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Research Article

Laboratory Evaluation on Performance of Fiber-Modified Asphalt Mixtures Containing High Percentage of RAP

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In recent years, the significant demand for sustainable paving materials has led to a rapid increase in the utilization of reclaimed asphalt pavement (RAP) materials. When RAP is mixed with virgin asphalt concrete, particularly when its percentage is high, performance of the binder and asphalt concrete can be adversely affected. For this reason, different types of additives need to be identified and evaluated beforehand to mitigate the adverse effects. In this study, different types of fiber materials were identified and selected as binder/mixture additives, including lignin fiber (LF), polyester fiber (PF), and basalt fiber (BF). Various samples of fiber-modified binders and asphalt mixtures with different RAP contents (0%, 20%, and 40%) were prepared and were evaluated using two sets of laboratory testing: (i) dynamic shear rheometer (DSR) and bending beam rheometer (BBR) tests were performed to study the rheological properties of fiber-modified binders; (ii) the wheel tracking test, bending creep test, moisture susceptibility test, fatigue test, and self-healing fatigue test were conducted to characterize the laboratory properties of fiber-modified RAP mixtures. Test results for the modified binders show that the BF-modified binder has the greatest positive effect on the high-temperature performance of the asphalt binder, followed by PF- and LF-modified binders. However, the virgin asphalt shows the best low-temperature property than the fiber-modified asphalt binder. Test results for the whole RAP mixtures show that all fibers have a significant effect on the properties (including high- and low-temperature stability, moisture susceptibility, fatigue, and self-healing ability) of RAP mixtures. Among them, adding BF shows the greatest improvement in high-temperature stability, fatigue resistance, and self-healing ability of RAP mixtures. LF is found to significantly enhance low-temperature properties, and PF can greatly improve the resistance to moisture damage of RAP mixtures. For high percentage of RAP using on sites, adding multiple additives may further enhance its durability.

1. Introduction

In recent years, reclaimed asphalt pavement (RAP) materials have been widely used in asphalt pavements' construction and maintenance because of their environment and economic benefits (i.e., due to materials saving). However, RAP materials have gone through long-term aging during their past life cycles, and mechanical properties have been essentially changed. Hence, using RAP, particularly at a high percentage, can cause reduced performance for asphalt pavements.

From current engineering practices, RAP percentages in asphalt pavement are typically around 15%–20% (by total mass) [1]. Recently, transportation agencies and researchers have shown an interest in using a higher percentage of RAP and carried out several studies to explore the performance of high RAP content mixtures. For example, Mensching et al. [2] and McDaniel et al. [3] studied the performance of asphalt mixtures containing up to 40% of RAP. The results showed that the cracking resistance, including fatigue cracking and low-temperature cracking, and moisture susceptibility, reduced with an increasing RAP percentage. Sabouri et al. [4] found that using soft matrix asphalt and keeping the optimum binder content were effective methods to produce high-percentage RAP mixtures with similar performance. Diefenderfer and Nair [5] showed that if the production steps were followed properly, the mixtures containing 40% RAP could be constructed successfully to achieve desirable durability.

To achieve better performance, researchers have actively attempted to use different types of additives to improve the performance of asphalt mixtures, such as crumb rubber, polymers, or natural rubber [6–8]. Many researchers showed that fibers could improve the low-temperature performance and fatigue life of virgin asphalt mixtures [9, 10]. There are several kinds of fibers used in asphalt pavements, such as lignin fiber (LF), polyester fiber (PF), and basalt fiber (BF). LF is a type of plant fiber with good temperature and chemical stability, which has a light green or gray color with a cotton flocculent shape. LF also shows good acid-alkali corrosion resistance. Hassen et al. [11] studied the effect of adding LF in virgin asphalt mixtures. The results showed that LF improved the workability, construction quality, and performance of asphalt concrete. PF is usually milky white in appearance with silky luster, and it is advantageous in heat resistance. Yang et al. [12] studied the properties of PF-modified asphalt mixtures compared with the virgin asphalt mixtures. The results showed that the strength and stiffness of the PF-modified asphalt mixtures increased significantly, and the flexural stiffness increased by 142%. BF is a new type of synthetic material with stable mechanical and chemical properties. In addition, BF has a high temperature resistance ability, which could maintain appropriate performance at high temperatures (−260°C to 700°C) [13]. Hence, BF has been widely used to improve the performance of asphalt binders and mixtures. Wang et al. [14] investigated the tensile and fatigue property of basalt fiber-modified asphalt binders. The results showed that the tensile strength and fatigue life of basalt fiber-modified asphalt binders were significantly improved. Zhao [15] found that the resistance to low-temperature crack of asphalt mixtures was improved with the addition of basalt fibers.

From current research, many studies had shown that fibers could improve the performance of virgin asphalt mixtures. However, there is a gap in the research regarding how to use additives in asphalt mixtures with a high RAP percentage to achieve satisfactory performance levels and, moreover, how to conduct laboratory testing to evaluate their cracking performance (in terms of fatigue cracking and low-temperature cracking). But for the RAP mixtures, especially high content of RAP mixtures, the influence of fibers on the properties of RAP mixtures was not adequate investigated. For this reason, different fibers were selected to analyze their impacts on the performance of virgin binders and RAP mixtures. The results of this study could provide important implications on the use of high-percentage RAP in engineering practices.

2. Materials and Methods

2.1. Materials

2.1.1. Virgin Binder and Aggregate. The virgin binder used in this study was Shell 70# road asphalt binder. The main physical properties were provided by Shell Singapore, as shown in Table 1. The coarse aggregate was basalts, the fine aggregate was lime stone, and the mineral filler was limestone powder. According to the JTG E42-2005 [16] standard test method, the physical properties of coarse aggregate and filler were tested and shown in Table 2.

2.1.2. RAP. The RAP used in this paper was milled from the surface mixtures of an expressway in Hebei Province, China. According to JTG F41-2008 [17] standard test method, Abson method was used to determine the properties of RAP and the results are listed in Table 3. Generally, the RAP content exceeds 25% by weight of mixture can be considered as high RAP level. For evaluating the impacts on the mixtures with high RAP levels, the 0%, 20%, and 40% of RAP was selected in the design of various asphalt mixtures in this study.

2.1.3. Fibers. Three types of road fibers were used in this study, which included lignin fiber, basalt fiber, and polyester fiber. The lignin fiber and polyester fiber were bought from Luxian Building Materials Technology Co., Ltd, Shandong Province. The basalt fiber was bought from Shenzhen Teli New Material Technology Co., Ltd, Guangdong Province. The shape and appearance of the three types of fibers are shown in Figure 1, and its technical properties are listed in Table 4. According to the existing research on fiber-reinforced asphalt mixtures [18, 19], the amount of fibers was generally 0.2%~0.4% of the total mass of mixtures. For comparing the effects of three different fibers on the properties of asphalt mixture containing RAP, the fiber content was chosen as 0.3% of total mass of mixtures.

2.2. Testing Methods

2.2.1. Mixture Gradation and Optimum Asphalt Content. The Marshall design method [20] was conducted for the asphalt mixtures containing 0%, 20%, and 40% RAP. The gradations used in this study are listed in Table 5.

In this study, four kinds of asphalt binders were used to produce the RAP mixtures, including matrix asphalt, LF-modified asphalt, PF-modified asphalt, and BF-modified asphalt. The optimum asphalt content (OAC) was also determined by the Marshall design method [20], as shown in Table 6.

Table 1: Physical properties of base asphalt.

Test properties		Results	Requirement
Penetration (25°C, 100 g, 5 s)/0.1 mm		74.9	60~80
Softening point (°C)		46.7	≥46
Ductility (10°C) (cm)		68.5	≥100
Rolling thin film oven (RTFO)	Mass loss (%)	0.60	≤0.80
	Penetration ratio (%)	71.5	≥61.0
	Ductility (10°C) (cm)	9.8	—

Table 2: Physical properties of aggregate and filler.

Test properties		Results	Requirement
Coarse aggregate	Crushed value (%)	11.8	≤26
	Los Angeles wear value (%)	10.6	≤28
	Polished stone value/ PSV	43	≥42
Fine aggregate	Apparent relative density	2.679	≥2.50
	Angularity (s)	42.7	≥30
Filler	Apparent density (g·cm^{-3})	2.761	≥2.50
	Water content (%)	0.4	≤1

2.2.2. Binder Testing. Binder testing and analysis were conducted on matrix asphalt and fibers-modified asphalt in this study. Dynamic shear rheometer (DSR) and bending beam rheometer (BBR) testing were used to assess the high-temperature and low-temperature properties of different asphalt binders, respectively.

(1) DSR Test. The DSR test was carried out to study the rheological properties of asphalt with different fibers. According to the ASTM D7175-15 [21] standard test method, the test samples are fabricated to 25 mm diameter and 1 mm thickness. DSR tests were performed at 10 rad/s angular velocity. During the test, the samples were conducted at 52, 58, 64, 70, 76, and 82°C, respectively, by under a thermally controlled environment. The rutting factor $G^*/\sin\delta$ was selected as the parameter to assess the high-temperature rheological properties of different binders. Three replicates were performed at each test, and the final results were the average of every experiment.

(2) BBR Test. The BBR test is used to evaluate the low-temperature performance and flexural creep stiffness in terms of the relaxation capabilities and stiffness. According to the ASTM D6648-08 standard [22], an asphalt sample (127 mm in length, 6.35 mm in width, and 12.7 mm in height) was placed in the test device, and a constant load 980 ± 50 mN was applied on the midpoint of the sample. The test temperatures are −12 and −18°C. The creep stiffness (S) and creep rate (m) were obtained at 60 s to assess the low-temperature crack resistance of asphalt. The larger the m value is, or the lower the S value is, the better the anti-cracking ability will be. Three replicates were performed at each test, and the final results were the average of every experiment.

2.2.3. Mixture Testing. Binder characterization is not adequate to fully represent mixture performance; hence, some mixture evaluation methods were conducted in this section. To study the comprehensive properties of different RAP mixtures, five main mixture tests were performed, including the wheel tracking test, bending creep test, moisture susceptibility test, fatigue test, and self-healing test. Detailed descriptions for the tests are as follows:

(1) Wheel tracking test. the wheel tracking test was performed based on T 0719-2011 of JTG E20-2011 [20]. The specimens (thickness of 50 mm and length and width of 300 mm) were prepared using a rolling wheel compactor. The wheel tracking test system was used to test the specimens. The loading time of the wheel (solid rubber) conducted on the specimen was 60 min with the pressure of 0.7 MPa. The test temperature was 60°C, and the running speed of the wheel was 42 cycle/min. Each kind of mixture has three replicates.

(2) Bending creep test. low-temperature cracking is the main form of early damage of asphalt pavement with high percentage RAP. According to the test method of T 0728-2011 in JTG E20-2011 [20], the bending creep test was conducted on different mixtures. The specimens were sawed from the slab specimen made by a rolling wheel compactor. The dimension of a specimen is 30 mm in width, 35 mm in height, and 250 mm in length. The test temperature is controlled at −10°C, and the loading rate is 50 mm/min. During the test, the deflection and load are recorded by the testing machine for obtaining the flexural tensile strength and flexural strain of different asphalt mixtures. Each kind of mixture has three replicates.

(3) Moisture susceptibility test. the immersion Marshall test and freeze-thaw splitting test were used to assess the moisture susceptibility of asphalt mixtures. The immersed Marshall test is conducted according to T0709-2011 in JTG E20-2011 [20]. The specimens in a treated group of the immersion Marshall test were immersed in water at 60°C for 48 h. The specimens in a controlled group were only immersed in water for 30 min at 60°C. The Marshall stability of all specimens were tested, and the retained stability was calculated and used as an evaluation index of moisture susceptibility. The freeze-thaw splitting test was similar to the immersion Marshall test. The specimens in the treated group were vacuumed in water, kept at 18°C for 16 h, and thawed in water at 60°C for 24 h. After that, all specimens in the two groups were placed in a water bath at 25°C for 2 h. The tensile strength ratio (TSR) was calculated as an index of moisture susceptibility. Each kind of mixture has three replicates.

Table 3: Experiment results of RAP.

Test properties		Result	Requirements
RAP	Water content (%)	0.32	—
	Asphalt content (%)	4.0	—
	Sand equivalent (%)	79	>55
	Theoretical maximum density (g·cm^{-3})	2.569	—
Asphalt properties in RAP	Penetration (25°C, 100 g, 5 s)/0.1 mm	33	>20
	Softening point (%)	63	—
	Ductility (10°C) (cm)	3.1	—

(a) (b) (c)

Figure 1: Images of different types of fiber: (a) lignin fiber, (b) basalt fiber, and (c) polyester fiber.

Table 4: Technical properties of different types of fibers.

Properties	Lignin fiber	Polyester fiber	Basalt fiber
Diameter (μm)	45 (average)	20–25	10–13
Length (mm)	<5	5–7	6–7
Tensile strength (MPa)	>300	>600	3000–4000
Elongation at break (%)	15–20	25–40	3.1
Density (g/cm^3)	0.8	0.95	2.7

(4) Fatigue test. the midpoint bending test was conducted to study the fatigue properties of different asphalt mixtures under the stress-controlled mode. According to the method T0739-2011 in JTG E20-2011 [20], the sinusoidal load was applied at a frequency of 10 Hz in the test. Stress loading was set as 0.5, 0.6, and 0.7, respectively. The test temperature was 15°C. Each kind of mixture has three replicates. The relationship between fatigue life and stress ratio in double logarithmic coordinates can be expressed by the following equation:

$$\lg N_{\mathrm{f}} = A - n \lg \sigma_t, \tag{1}$$

where N_{f} is the number of repeated loading before failure, times; A is a material-related regression constant; n is a regression constant, which is related to both the material property and test conditions; and σ_t is the loading stress, MPa.

(5) Self-healing test. the fatigue-healing-fatigue test was conducted to study the self-healing property of different asphalt mixtures through the midpoint bending test. The testing consists of sinusoidal loading of 10 Hz controlled by stress. The test temperature was 15°C. Each kind of mixture has three replicates. The specific test steps were as follows. First, a stress ratio of 0.5 was selected as the test load. According to the previous part of fatigue results, the fatigue lives (FN_{f}) of different mixtures were obtained under a stress ratio of 0.5. 20% of fatigue life was chosen as the control point of the first fatigue test, which was recorded as N_1. Then, the specimens were placed at room temperature for 48 h as the healing interval. After that, the second fatigue test was conducted on the specimen until the specimen was fully damaged. The number of second fatigue tests was recorded as N_2. The self-healing property of different asphalt mixtures can be assessed by the healing rate (H), which was shown as follows:

$$H = \frac{N_1 + N_2 - N_{\mathrm{f}}}{N_{\mathrm{f}}}. \tag{2}$$

3. Results and Discussion

3.1. Binder Testing Analysis

3.1.1. DSR Testing Results. The DSR test results of different types of fiber-modified asphalt are shown in Figure 2. The rutting factor $G^*/\sin\delta$ reflects the rutting resistance of asphalt binders. The $G^*/\sin\delta$ values of fiber-modified asphalt are greater than those of matrix asphalt binders, which means that the rutting resistance of asphalt is improved by adding fibers. It is because fiber-modified asphalt has higher viscosity than matrix asphalt. Moreover, with the increase in temperature, the $G^*/\sin\delta$ of all kinds of asphalt decreases, which indicates that asphalt has strong temperature sensitivity. For the three kinds of fiber-modified asphalt, the

Table 5: Asphalt mixture 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 rate (%)	Upper limit	100	90	76	60	34	20	13	9	7	5	4
	Lower limit	100	100	92	80	62	48	36	26	18	14	8
	0% RAP	100	94.8	85.2	68.5	49.0	34.1	24.8	15.8	11.5	8.8	6.4
	20% RAP	100	95.7	85.9	69.4	49.2	34.6	25.3	16.2	11.9	8.8	6.7
	40% RAP	100	95.8	85.9	69.6	49.6	34.8	25.6	16.4	11.5	9.1	6.8

Table 6: The optimum asphalt content of different asphalt mixtures.

Asphalt type	Optimum asphalt content (%)		
	0% RAP	20% RAP	40% RAP
Matrix asphalt	4.5	4.2	4.0
LF-modified asphalt	4.8	4.6	4.5
PF-modified asphalt	4.9	4.5	4.3
BF-modified asphalt	4.8	4.5	4.4

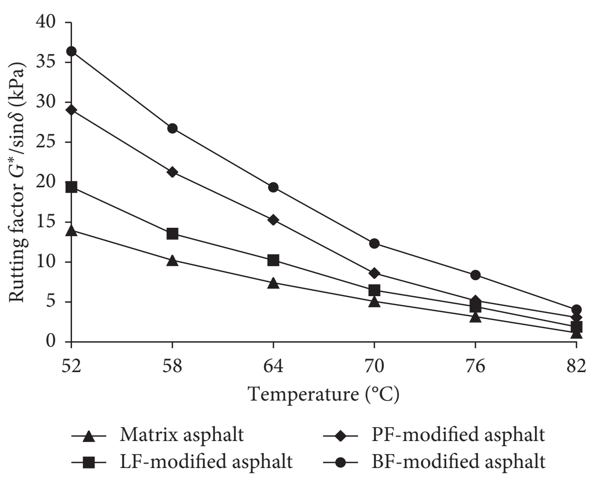

Figure 2: DSR results of the asphalt binder.

Table 7: Bending creep property of the asphalt binder.

Asphalt type	−12°C		−18°C	
	S (MPa)	m	S (MPa)	m
Matrix asphalt	60.1	0.535	268	0.412
LF-modified asphalt	64.5	0.525	295	0.375
PF-modified asphalt	98.5	0.435	349.5	0.330
BF-modified asphalt	62.5	0.532	272	0.406

For creep rates, the matrix asphalt shows the highest m value than the others at both −12°C and −18°C. The reason is that the interfacial transmission and the blocking effect caused by fibers could obstruct the creep behavior of asphalt. Overall, the ranking of the four kinds of asphalt is matrix asphalt ≈ BF-modified asphalt > LF-modified asphalt > PF-modified asphalt.

BF-modified asphalt shows the optimal performance of rutting resistance, followed by PF and LF modified asphalt. The reason is that BF and PF have good adsorbability with asphalt, and thousands of monofilament fibers can form a stable 3D network with asphalt. However, the volume percentage of LF is lower than that of BF and PF at the same content, which limits the improvement of rutting resistance.

3.1.2. BBR Testing Results. The BBR test results are shown in Table 7. It can be seen from Table 7 that with a decrease in temperature, the S values of various asphalt increase significantly, which shows the temperature sensitivity of asphalt. At the same temperature, the S values of fiber-modified asphalt are higher than those of the matrix asphalt. In particular, the S value of the PF-modified asphalt is 63.9% greater than that of the matrix asphalt. The reason is that fibers can restrict the creep behavior of asphalt at a lower temperature, which leads to a decrease of deformation and increase in the creep modulus. It is worth noting that the S values of the matrix asphalt and the BF-modified asphalt are approximately equivalent at −12°C and −18°C.

3.2. Mixture Testing Analysis

3.2.1. Wheel Tracking Test Results. The dynamic stability and rut depth were used to assess high-temperature stability of different asphalt mixtures, and the results are shown in Figures 3 and 4. The results show that the addition of different fibers can improve dynamic stability and reduce rut depth. Among them, the dynamic stability of the BF-modified asphalt mixture with 40% RAP reaches 4,012 times/mm, whereas the rut depth is only 1.41 mm. Compared with the matrix asphalt with the same RAP percentage, the dynamic stability increased by 54.9% and the rut depth decreased by 22.5%.

In addition, the high temperature stability of LF- and PF-modified asphalt mixture has also been improved compared with the matrix asphalt mixture. The reason is that when the fibers are fully dispersed in asphalt, the stiffness of the asphalt mortar increases. Fully dispersed fibers can shape a 3D network structure in asphalt mixtures and act as reinforcement. Furthermore, the fibers have an effect in bridging macrocracks and improving cohesiveness within asphalt mixtures, which can improve their high-temperature performance. Moreover, the mixtures containing 40% RAP have a higher dynamic stability and lower rut depth. Compared with all mixtures containing 20% RAP and 0% RAP, the average increase in dynamic stability was observed to be 11.1% and 16.1% and the average decrease in rut depth was 8.3% and 15.6. The reason is that adding more RAP caused the mixture to become stiffer, which is more capable of resisting deformation under a high temperature. Among the three fiber-modified asphalt mixtures containing RAP, the LF-modified asphalt mixture has the lowest dynamic

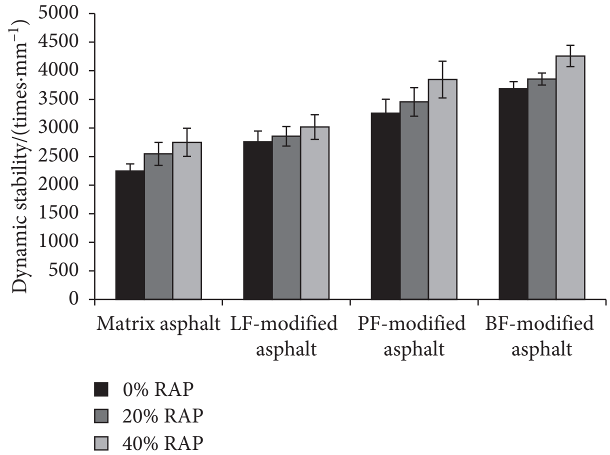

Figure 3: Dynamic stability results of different asphalt mixtures.

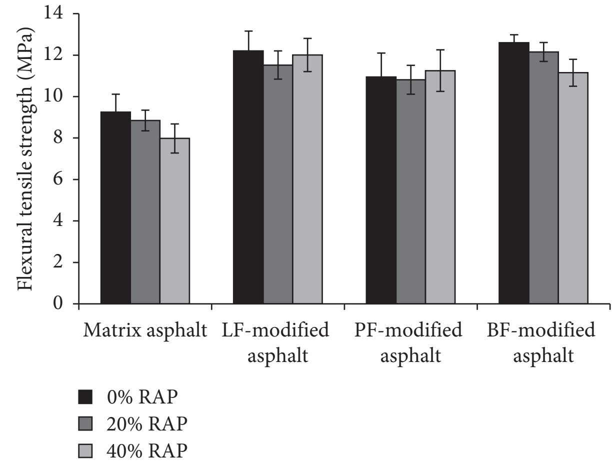

Figure 5: Flexural tensile strength results of different asphalt mixtures.

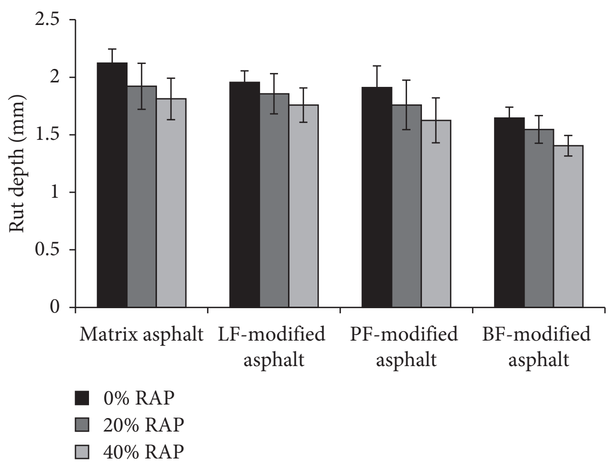

Figure 4: Rut depth results of different asphalt mixtures.

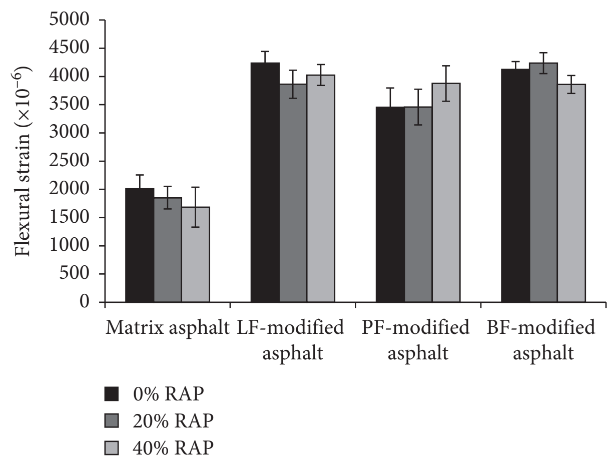

Figure 6: Flexural strain results of different asphalt mixtures.

stability and the highest rut depth. This is because BF and PF have better physical and mechanical properties than LF. In addition, BF and PF can form an effective network in asphalt mixtures, which prevents the interfacial slip and significantly improves the shear strength of asphalt mixtures. Therefore, the BF- and PF-modified asphalt mixtures have better rutting resistance.

3.2.2. Bending Creep Testing Results. The bending creep test results are shown in Figures 5 and 6. Figure 5 shows the flexural tensile strength for each of the twelve mixtures. As can be seen in Figure 5, the flexural tensile strength of the fiber-modified RAP mixtures increased significantly compared with the matrix RAP mixtures. Similar information for flexural strain of different mixtures is presented in Figure 6. Both figures show that the fibers can improve the low-temperature property of the mixtures. For the mixtures with 0% RAP, the BF-modified asphalt mixtures exhibit the very high value of flexural strain and flexural tensile strength. Compared with the matrix asphalt mixture, the maximum flexural strain and flexural tensile strength increased by 105.1% and 36.2%.

The next parameter of interest to be presented is the content of RAP in the mixtures. For the four kinds of mixtures, the relationship between RAP content with flexural strain and flexural tensile strength has no obvious rules to follow. For low-temperature property, LF-modified RAP mixtures seem to show the highest improvement among others, followed by BF- and PF-modified RAP mixtures. Therefore, the addition of fibers can significantly improve the low-temperature crack resistance of asphalt mixtures. This is due to the fact that the asphalt binder is the weakest mechanical part of the asphalt mixture and it is very easy to form stress concentration, produce cracks, and eventually lead to the failure of the entire asphalt pavement structure. Fibers can effectively bind to asphalt materials and increase the content of structural strength in asphalt mixtures, thereby improving their mechanical properties. In addition, with the reinforcing and bridging effects of fibers, the stress concentration caused by crack initiation and propagation can be transferred to the other undamaged parts and can be released the stress effectively.

Table 8: Retained stability and TSR results of different asphalt mixtures.

Asphalt type	Retained stability (%)			TSR (%)		
	0% RAP	20% RAP	40% RAP	0% RAP	20% RAP	40% RAP
Matrix asphalt	87.2	86.5	84.5	79.2	78.5	76.8
LF-modified asphalt	90.5	90.2	89.5	80.1	79.8	79.2
PF-modified asphalt	94.6	94.4	93.8	88.2	87.6	86.8
BF-modified asphalt	92.4	92.3	92.5	87.2	86.8	85.5

Table 9: Fatigue results of different asphalt mixtures.

Asphalt type	Stress ratio	σ_t (MPa)	$\lg \sigma_t$	N_f (times)	$\lg N_f$	Relationship equation	R^2
Matrix asphalt	0.5	0.0625	−1.20	17252	4.23	$\lg N_f = -3.02 - 6.04 \lg \sigma_t$	0.975
	0.6	0.0728	−1.12	7569	3.85		
	0.7	0.0865	−1.05	2245	3.32		
LF-modified asphalt	0.5	0.0852	−1.08	25625	4.42	$\lg N_f = 1.02 - 3.16 \lg \sigma_t$	0.958
	0.6	0.1025	−1.01	17522	4.23		
	0.7	0.1167	−0.92	8568	3.95		
PF-modified asphalt	0.5	0.1025	−0.99	32152	4.50	$\lg N_f = 3.02 - 1.53 \lg \sigma_t$	0.963
	0.6	0.1235	−0.90	26558	4.43		
	0.7	0.1429	−0.83	19065	4.25		
BF-modified asphalt	0.5	0.1178	−0.93	35442	4.55	$\lg N_f = 3.64 - 0.99 \lg \sigma_t$	0.978
	0.6	0.1420	−0.84	30982	4.49		
	0.7	0.1650	−0.79	24968	4.40		

Table 10: Results of the self-healing property of asphalt mixtures.

Asphalt type	N_1 (times)	N_2 (times)	$(N_1 + N_2)$ (times)	N_f (times)	H (%)
Matrix asphalt	3450	15665	19115	17252	10.8
LF-modified asphalt	5125	24241	29366	25625	14.6
PF-modified asphalt	6430	31219	37649	32152	17.1
BF-modified asphalt	7088	35513	42601	35442	20.2

3.2.3. Moisture Susceptibility Results. The moisture susceptibility results for different asphalt mixtures are shown in Table 8. It can be seen from Table 8 that the retained stability and TSR of fiber-modified asphalt mixtures have been improved, compared with the matrix asphalt mixtures. Among the three types of fibers, PF-modified asphalt mixture shows the best moisture susceptibility. The retained stability and TSR of PF-modified asphalt mixture with 20% RAP are 1.07 and 1.13 times, respectively, more than the matrix asphalt mixture. With the RAP content increasing from 0% to 40%, the retained stability and TSR of different fiber-modified asphalt mixtures have slightly decreased, but the reduction is not significant.

There are two main reasons for the improvement of moisture susceptibility of the fiber-modified asphalt mixtures. On one hand, the OAC of asphalt mixtures increases after adding fibers, which directly leads to an increase of asphalt film thickness. On the other hand, the fibers could function as bridging and reinforcing agents in asphalt mixtures. Therefore, fiber-modified asphalt mixtures have better resistance to moisture damage. It can be also found that the LF-modified asphalt mixtures show the lowest improvement of resistance to moisture damage. The reason is that LF has strong water absorption ability, resulting in poor moisture susceptibility and durability.

3.2.4. Fatigue Testing Results. The fatigue results of different asphalt mixtures are shown in Table 9. It should be noted that only 40% RAP mixtures were considered. It can be seen from the column for N_f that the fatigue lives of different asphalt mixtures decrease with increases of stress ratios. In addition, the ranking of fatigue life under the same stress ratio is BF-modified asphalt > PF-modified asphalt > LF-modified asphalt > matrix asphalt. It also can be seen in Table 9 that the A value of the BF-modified asphalt mixture is 3.64, which is the greatest among the four asphalt mixtures. Moreover, the n value of the BF-modified asphalt mixture is 0.99, which is the lowest value among the four types of asphalt mixtures. Therefore, the BF-modified RAP mixture has better fatigue performance, the reason for which is similar to that of the low-temperature bending creep test that fibers can enhance the bond between the asphalt binder and aggregates. The fiber-modified asphalt mixtures have stronger deformation recovery ability under the fatigue load.

3.2.5. Self-Healing Testing Results. The self-healing test results were obtained based on the aforementioned test procedures and are shown in Table 10. It can be seen in Table 10 that the fatigue lives $(N_1 + N_2)$ of asphalt mixtures increase after the healing interval. This is because the asphalt mixtures can heal themselves through a time interval or under high-temperature conditions. Therefore, the fatigue lives of all asphalt mixtures have been extended. In addition, the BF-modified RAP mixture has the highest healing rate, nearly twice as much as that of the matrix RAP mixture. However, the mechanism of self-healing still needs investigations.

4. Conclusions

This study investigates the properties of fiber-modified asphalt binders and RAP mixtures through some of the laboratory tests, including DSR and BBR tests for asphalt binders, the wheel tracking test, bending creep test, moisture susceptibility test, fatigue test, and self-healing test for mixtures. According to the results obtained from the tests, the following conclusions were drawn:

(i) The rutting factor $G^*/\sin\delta$ of different binders obtained from the DSR test showed that all the three types of fibers could improve the high-temperature rutting resistance in comparison with the unmodified binder. This improvement in the rutting factor is thought to be a function of adsorbability between the fibers and asphalt, which could increase the high-temperature stability of asphalt. Among the three types of fibers, BF was found to be the most suitable for improving the rutting factor of asphalt binders. However, the BBR test showed that the virgin binder had the best low-temperature performance. The reason could be the blocking effect caused by fibers that obstruct the creep behavior of asphalt. It should be noted that the binder characterization could not be completely understood for the mixture properties.

(ii) The addition of fibers and RAP could both increase the rutting resistance. The BF-modified mixture containing 40% RAP had the highest dynamic modulus and lowest rut depth. Compared with the unmodified mixtures containing 40% RAP, the dynamic stability increased by 54.9% and the rut depth decreased by 22.5%. The bending creep results showed that with the addition of fibers, the low-temperature cracking resistance improved significantly. While for the parameter of RAP content, there is no obvious regularity in low-temperature property of different RAP mixtures. Among all RAP mixtures, LF-modified RAP mixtures showed the best low-temperature cracking resistance.

(iii) The moisture susceptibility test results showed that the PF-modified asphalt mixture with 0% RAP had the best resistance to moisture damage. For the increase of the RAP content, the moisture susceptibility did not change a lot.

(iv) The fatigue and self-healing properties of different RAP mixtures were obtained from the midpoint bending test. It should be noted that only 40% RAP mixtures were evaluated. The results showed that BF-modified RAP mixtures had better fatigue performance. Moreover, the healing rate was used to assess the self-healing property of RAP mixtures. The BF-modified RAP mixture showed the highest healing rate.

(v) Overall, the fiber-modified asphalt mixtures had better properties, including high-temperature and low-temperature stability, moisture susceptibility, fatigue, and self-healing properties, than matrix asphalt mixtures. The reason could be the fully dispersed fibers can shape a 3D network structure and act as the reinforcement in asphalt mixtures. Also, the fibers could improve the cohesiveness within asphalt mixtures, which can effectively improve the anti-cracking resistance. However, because of the lack of microscopic tests, the mechanism of fiber reinforcement on asphalt and asphalt mixtures cannot be observed directly. Further microscopic evaluation could be conducted for analyzing the influence of the fiber reinforcing effect on the properties of asphalt and asphalt mixtures.

Data Availability

The 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 article.

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