International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Annales de Chimie: Science des Materiaux
Vol. 43, No. 2, April, 2019, pp. 81-88
Journal homepage: http://iieta.org/journals/acsm

Experimental Analysis on Flexural-tensile Performance of Polyester Fiber Asphalt Concrete

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https://doi.org/10.18280/acsm.430203

Received: 15 January 2019
Accepted: 2 April 2019

Keywords:
polyester fiber asphalt concrete, flexural-tensile strength, fiber aspect ratio, fiber volume ratio, fiber content feature parameter (FCFP)

ABSTRACT

Taking the AC-13F mixture as the matrix, this paper carries out beam bending tests on fiber asphalt concrete, using the optimal asphalt content (OAC) determined by Marshall test. The test parameters include temperature, fiber volume ratio and fiber aspect ratio. Based on the test results, the author systematically explored how the three parameters affect the flexural performance of asphalt concrete. In addition, the fiber content feature parameter (FCFP) was introduced to describe the combined effect of fiber volume ratio and fiber aspect ratio on the flexural performance of asphalt concrete, and an FCFP-based model was set up to calculate the flexural performance of polyester fiber reinforced concrete beams at different temperatures. The results show that the flexural-tensile strength of fiber asphalt concrete increases first and then decreases with the rising temperature; the failure strain of fiber asphalt concrete increases with temperature; under different temperatures, the flexural-tensile strength of polyester fiber asphalt concrete increases first and then decreases with the growth in fiber volume ratio or fiber aspect ratio; the optimal FCFP of polyester fibers is 1.13. The research findings shed important new light on flexural-tensile performance of polyester fiber asphalt concrete.

1. INTRODUCTION

The cracking of asphalt concrete pavement may occur due to the lack of flexural-tensile strength or the accumulation and development of meso-structure deformation. In this case, water will penetrate through the cracks and erode the interface between the asphalt and the aggregate. Prolonged exposure to moisture can de-bond the aggregate from the asphalt, which is a major cause of early damage of asphalt concrete pavement.

The asphalt concrete beam bending test offers an important way to study the low-temperature crack resistance of asphalt concrete [1, 2]. A comprehensive index system has been developed for the bending tests on intact and pre-cracked asphalt concrete beam at different temperatures, and adopted to explore how the low-temperature crack resistance of asphalt concrete is affected by temperature, grading, asphalt-aggregate ratio and loading rate. The index system mainly involves indices like the flexural-tensile strength, the strain and stiffness modulus at flexural-tensile failure (hereinafter referred to as failure stiffness modulus and failure strain), the J-integral, and the critical strain energy density [3-5]. With the development of computer technology, the bending test results have been simulated on finite-element, discrete-element and boundary element analysis software, aiming to disclose the correlation between the meso-structure and macroscopic mechanical performance of asphalt concrete [6].

Fiber asphalt concrete has received more and more attention, thanks to its excellent pavement performance and mechanical performance. Some progress has been made in the research of the flexural performance of this type of asphalt concrete. For instance, Reference [7] examines the impact of fiber type on the low-temperature crack resistance of fiber asphalt concrete through beam bending test. Reference [8] evaluates the resistance of glass fiber reinforced asphalt overlay to cracking and crack propagation, in light of fracture potential and critical strength. Reference [9] carries out a low-temperature beam bending test to disclose the effects of fiber content on low-temperature performance of fiber asphalt concrete. The mechanism for the low-temperature crack resistance of fiber asphalt concrete has also been discussed, and the low-temperature performance of fiber asphalt concrete has been evaluated based on the bending test index system [10-16].

Nevertheless, the existing studies have not tackled the following issues: the temperature induced-variations in the load at flexural-tensile failure (hereinafter referred to as the failure load), flexure-tensile strength, failure stiffness modulus and failure strain of fiber asphalt concrete; the relationship between bending test parameters of fiber asphalt concrete and the ratio of fiber volume to the volume of asphalt mixture (fiber volume ratio, V_f); the impact from the ratio of mean fiber length to mean fiber diameter (fiber aspect ratio R_a) to the flexural performance of asphalt concrete; the combined effect of fiber volume ratio and fiber aspect ratio on the flexural performance of asphalt concrete.

Taking the AC-13F mixture as the matrix, this paper carries out beam bending tests on fiber asphalt concrete, using the optimal asphalt content (OAC) determined by Marshall test. The test parameters include temperature, fiber volume ratio and fiber aspect ratio. Based on the test results, the author systematically explored how the three parameters affect the flexural performance of asphalt concrete. In addition, the fiber content feature parameter (FCFP) was introduced to describe the combined effect of fiber volume ratio and fiber aspect ratio on the flexural performance of asphalt concrete, and an FCFP-based model was set up to calculate the flexural performance of polyester fiber reinforced concrete beams at different temperatures.

2. MATERIALS AND TESTS

Figure 1. Bending test of small beam

Our tests use China's No.70 A-grade petroleum asphalt, and polyester fibers with a mean diameter of 18.5 μm. To disclose the effects of fiber volume ratio and fiber aspect ratio, the polyester fibers were tested at different aspect ratios (i.e. 162, 486 and 649) at the same volume ratio (0.35 %), and also tested at different volume ratios (i.e. 0.17 %, 0.35 %, 0.52 % and 0.69 %) at the same aspect ratio (324). The aggregate was sieved, cleaned, dried and then mixed with limestone powder, using the median value of AC-13F grading. Then, the OACs [17] of the base asphalt mixture and the fiber asphalt mixture were determined through Marshall test. In light of the OACs, the mixture was compacted into 300 mm × 300 mm × 500mm asphalt concrete slabs, which was then cut into 250 mm × 30 mm × 35 mm specimens. As shown in Figure 1, 3-point bending tests were carried out on a multi-functional material testing machine at temperatures of -30 ℃, -20 ℃, -10 ℃, 0 ℃ and 15 ℃ and the loading rate of 50 mm/min. In each group of tests, four specimens were tested in parallel and the measured data were averaged as the final test result.

According to the bending test results, the flexural-tensile strength R_B, the failure strain ε_B, and the failure stiffness modulus S_B [17]:

$$R_B = \frac{3LP_B}{2bh^2} \tag{1}$$

$$\varepsilon_B = \frac{6hd}{L^2} \tag{2}$$

$$S_B = \frac{R_B}{\varepsilon_B} \tag{3}$$

where P_B is the failure load (N); h and b are the height and width of mid-span section of the specimen (mm); d is the mid-span deflection at flexural-tensile failure (mm); L is the span of the specimen (mm).

From formulas (1)-(3), the bending test results on fiber asphalt concrete at different temperatures, fiber volume ratios and fiber aspect ratios were obtained. The next step is to analyze how temperature, fiber volume ratio and fiber aspect ratio affect the flexural performance of asphalt concrete, according to the test results in Table 1.

Table 1. Bending test results

Mixture type	R_a	V_f/%	T/°C	R_B/MPa		$\varepsilon_B/\mu\varepsilon$		S_B/MPa	
				Test value	calculated value	Test value	calculated value	Test value	calculated value
			-30	7.616	7.700	3203	3200	2378	2373
			-20	8.188	8.150	3518	3515	2328	2315
AC-13F	0	0	-10	9.224	9.050	4095	4098	2253	2203
			0	9.624	9.420	4778	4868	2015	1913
			15	6.114	5.990	8348	7943	732	737
			-30	8.465	9.045	2993	2895	2829	3082
			-20	8.996	9.518	3255	3153	2764	3020
	162	0.35	-10	9.437	10.264	3728	3594	2532	2854
			0	9.878	10.878	4515	4068	2188	2689
			15	6.400	7.154	10710	13616	598	527
			-30	8.865	9.027	3098	2899	2862	3073
			-20	9.453	9.500	3413	3156	2770	3012
		0.17	-10	9.567	10.244	3728	3595	2567	2847
			0	9.682	10.855	4043	4071	2395	2681
			15	7.037	7.140	11288	13567	623	528
			-30	9.135	8.872	2835	2936	3222	3125
PFAC-13F			-20	9.771	9.368	3098	3297	3155	3048
		0.35	-10	10.661	10.437	3518	4031	3031	2910
	324		0	11.355	11.012	3780	4670	3004	2893
			15	7.747	6.903	15750	11136	492	537
			-30	8.906	8.252	2940	3006	3029	3236
			-20	9.461	8.769	3255	3421	2907	2841
		0.52	-10	10.539	9.607	3885	4057	2713	2516
			0	11.151	10.874	4463	4597	2499	2080
			15	6.971	6.305	13073	14919	533	550
			-30	8.669	8.499	2993	3002	2897	2723
		0.69	-20	9.078	8.738	3413	3522	2660	2799
			-10	10.237	9.794	4305	4572	2378	2371

		0	10.735	9.485	5093	5846	2108	2017
		15	6.008	6.372	10658	11654	564	532
		-30	7.690	7.182	2940	3322	2616	2600
		-20	8.645	7.700	3360	3547	2573	2547
486	0.35	-10	9.722	9.568	3833	3910	2537	2432
		0	10.09	9.821	4253	4673	2373	2326
		15	6.824	6.238	11498	11502	594	568
		-30	7.355	7.950	3045	3059	2415	2472
		-20	8.482	8.491	3623	3711	2341	2352
649	0.35	-10	9.184	8.942	3938	4047	2332	2262
		0	9.845	8.286	4830	4904	2038	2145
		15	6.629	6.535	9188	10632	721	736

3. EFFECTS OF TEMPERATURE ON FLEXURAL-TENSILE PERFORMANCE OF FIBER ASPHALT CONCRETE

3.1 Flexural-tensile strength

It can be seen from Table 1 that, as the temperature changed from -30 ℃ to 15 ℃, the flexural-tensile strengths of the base asphalt concrete (AC-13F) and polyester fiber asphalt concrete (PFAC-13F) both increased first and then decreased, and peaked at the temperature of 0 ℃. Under this temperature, both types of asphalt concretes obviously softened under stress [18]. This is because temperature can change the mechanical performance of the asphalt, and thus determine the flexural-tensile failure mode of asphalt concrete. With the temperature growth from -30 ℃ to 15 ℃, the brittle asphalt becomes viscoelastic and then plastic. The 0 ℃ is the division point between the brittle phase and the viscoelastic phase.

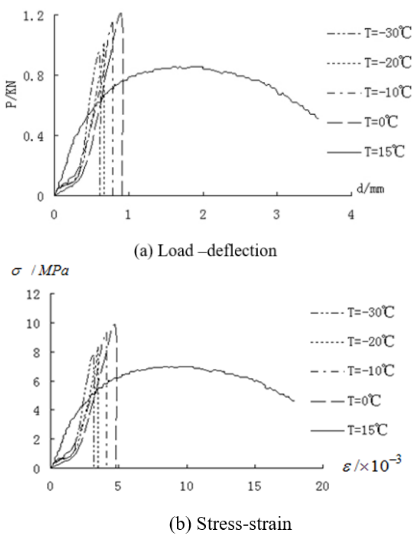

Figure 2. Ordinary asphalt concrete bending process

As shown in Figure 2, there was no obvious descending segment in the load-deflection curve and the stress-strain curve, when the temperature was below 0 ℃. During flexural-bending failure, brittle fractures appeared on the asphalt concrete. The lower the temperature, the more obvious the brittleness of the asphalt, and the poorer the resistance of asphalt concrete beam to flexural-tensile deformation. That is why fiber asphalt concrete beam had low flexural-tensile strength and failure load, when the temperature was at a low level. When the temperature was above 0 ℃, the asphalt became viscous, and the asphalt concrete suffered from bending plastic failure, as evidenced by the clear descending segments in the load-deflection curve and the stress-strain curve at the temperature of 15 ℃. The higher the temperature, the weaker the fiber asphalt concrete in the viscoelastic phase, and the smaller the flexural-tensile strength and failure load.

As the temperature changed from -30 ℃ to 15 ℃, the flexural-tensile strength of the fiber asphalt concrete increased first and then decreased. This trend can be illustrated as a quadratic curve:

$$R_B = a_0 + a_1 T + a_2 T^2 \tag{4}$$

The bending test data on fiber asphalt concretes were fitted nonlinearly to obtain the model parameters of formula (4) (Table 2) for fiber asphalt concretes of different fiber volume ratios and fiber aspect ratios. Next, the brittle temperatures of fiber asphalt concretes were derived from these model parameters. It can be seen that fiber asphalt concretes had a lower brittle temperature than base asphalt concretes; the lower the brittle temperature, the stronger the low-temperature crack resistance of fiber asphalt concrete; the optimal low-temperature crack resistance was observed on the fiber asphalt concrete with the fiber aspect ratio of 324 and the fiber volume ratio of 0.35 %.

Table 2. Model parameters of formula (4)

Mixture type	R_a	V_f /%	a_0	a_1	a_2	Peak point temperature /℃
AC-13F	0	0	8.90	-0.067	-0.0097	-3
PFAC-13F	162	0.35	9.19	-0.093	-0.0065	-7
	324	0.17	9.28	-0.088	-0.0087	-5
		0.35	10.55	-0.093	-0.0061	-8
		0.52	10.26	-0.103	-0.0078	-7
		0.69	9.77	-0.105	-0.0088	-6
	486	0.35	9.52	-0.088	-0.0075	-6
	649	0.35	9.21	-0.072	-0.0071	-5

3.2 Failure strain

It can be seen from Table 1 that the failure strain of fiber asphalt concrete increased with temperature. This trend can be attributed to the following facts: When the temperature is below 0 ℃, the asphalt is highly brittle, and the fiber asphalt concrete exhibits obvious elasticity. The lower the temperature, the more elastic the fiber asphalt concrete, and the smaller the deflection and strain at flexural-tensile failure. When the temperature is above 0 ℃, the asphalt is highly viscous, and the fiber asphalt concrete exhibits obvious viscoelasticity. The higher the temperature, the more viscoelastic the fiber asphalt concrete, and the greater the deflection and strain at flexural-tensile failure.

When the temperature was equal to or smaller than 0 ℃, the failure strain of fiber asphalt concrete increased linearly with the rising temperature. The linear relationship can be expressed as:

$$\varepsilon_B = a + bT \tag{5}$$

where a and b are two parameters about the relationship between the failure strain of fiber asphalt concrete and temperature.

The bending test data on polyester fiber asphalt concretes were fitted nonlinearly to obtain the model parameters of formula (5) for fiber asphalt concretes. The results show that a and b first increased and then decreased with the growth in fiber volume ratio and fiber aspect ratio. The two parameters minimized at the fiber volume ratio of 0.35 % and the fiber aspect ratio of 324. In this case, the time-failure strain curve of polyester fiber asphalt concrete remained at a low level, indicating that the polyester fibers fully restrain deformation at low temperatures and that polyester fiber asphalt concrete is not sensitive to temperature changes.

Table 3. Model parameters of formula (5) and brittle temperatures

Mixture type	R_a	V_f/%	a	b	R^2
AC-13F	0	0	4694	53.2	0.9757
PFAC-13F	162	0.35	4379	50.4	0.9481
	324	0.17	4043	34.5	0.9989
		0.35	3796	32.6	0.9907
		0.52	4416	52.0	0.9825
		0.69	5030	71.9	0.9809
	486	0.35	4258	44.1	0.9994
	649	0.35	4709	56.7	0.9640

3.3 Failure brittleness modulus

It can also be seen from Table 1 that the failure brittleness modulus of polyester fiber asphalt concrete is negatively correlated with temperature. The negative correlation was obviously linear when the temperature was below 0 ℃, and was extremely significant when the temperature was above 0 ℃. A possible reason is provided as follows: When the temperature was below 0 ℃, the flexural-tensile failure of fiber asphalt concrete was clearly elastic. The lower the temperature, the smaller the failure deformation of the fiber asphalt concrete in the elastic phase, and the greater the failure brittleness modulus. When the temperature was above 0 ℃, the flexural-tensile failure of fiber asphalt concrete was clearly viscoelastic. The higher the temperature, the greater the failure deformation of the fiber asphalt concrete in the viscoelastic phase, and the smaller the failure brittleness modulus.

4. EFFECTS OF FIBER VOLUME RATIO ON FLEXURAL-TENSILE PERFORMANCE OF FIBER ASPHALT CONCRETE

4.1 Flexural-tensile strength

As shown in Table 1, the flexural-tensile strength of polyester fiber asphalt concrete increased first and then decreased with the growth in fiber volume ratio, when the temperature remained the same, and peaked at the fiber volume ratio of 0.35 %. There are two causes of this particular trend.

First, it can be seen from Figure 3 that the fiber asphalt concrete mainly cracked along the interface between particles during flexural-tensile failure. The flexural-tensile resistance of asphalt concrete mainly depends on the strength of the asphalt-aggregate interface [11]. The proper addition of fibers to the base asphalt mixture increases the OAC and the thickness of the asphalt membrane. Meanwhile, the fibers can adsorb and infiltrate the light components of the asphalt, and form chemical bonds with these components. In this way, the fibers enhance the asphalt-aggregate interface, and thus improving the flexural-tensile strength of asphalt concrete [14].

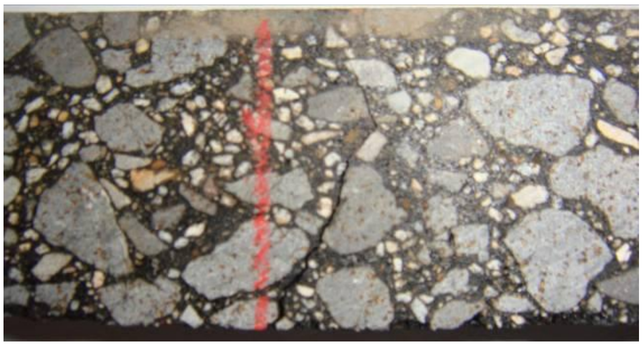

Figure 3. Bending failure crack development form

Second, the fibers of a proper volume ratio can disperse uniformly in the asphalt concrete, creating a 3D fiber network. The density of the fiber network bears on how much the fibers can restrain the flexural-tensile deformation of asphalt concrete. Within a proper range, the greater the fiber volume ratio, the denser the fiber network, the greater the restraining effect, and the stronger the asphalt concrete. Of course, the fiber volume ratio should not surpass the maximum number of fibers that can be contained in the fiber network. Otherwise, the fibers will become less dispersive and accumulate in local areas of the fiber network, forming bundles and cakes. These defects will lower the flexural-tensile strength of the asphalt concrete. During our tests, the flexural-tensile strength of fiber asphalt concrete was lower than that of base asphalt concrete, when the polyester fiber reached the fiber volume ratio of 0.69%.

4.2 Failure strain

It can be seen from Table 1 that, when the temperature remained unchanged below 0 °C, the failure strain of fiber asphalt concrete decreased first and then increased with the growth in fiber volume ratio, and the fracture-tensile failure of fiber asphalt concrete was minimized at the polyester fiber volume ratio of 0.35 %; when the temperature stood at 15 °C, the failure strain of fiber asphalt concrete increased first and then decreased with the growth in fiber volume ratio, and the fracture-tensile failure of fiber asphalt concrete was maximized at the polyester fiber volume ratio of 0.35 %. Below are the possible explanations of these trends.

When the temperature is below 0 °C, brittle fractures emerge on the asphalt concrete during the flexural-tensile failure, while the fibers are mainly broken under the tensile force [14]. Within a proper range, the greater the fiber volume ratio, the denser the fiber network, the greater the restraining effect of fibers on the flexural-tensile deformation of asphalt-concrete. However, an excessively high fiber volume ratio will reduce the strength of asphalt concrete and weaken the restraining effect of fibers, such that the failure strain of fiber asphalt concrete increases during low-temperature brittle failure.

When the temperature remains at 15 °C, the fiber asphalt concrete is highly viscoelastic, the fiber asphalt concrete beam mainly suffers from plastic damages during flexural-tensile failure, and the fibers are mostly damaged by slippage. During interface slippage, the fibers can prevent crack extension. The extent of fibers is positively correlated with the failure strain and the resistance of fiber asphalt concrete to flexural-tensile failure. The crack arresting ability of fibers mainly depends on the fiber volume ratio. Within a proper range, a high fiber volume ratio means more fibers per unit volume of asphalt concrete, and a high density of the uniformly distributed fiber network. As a result, there will be many longitudinal fibers on the beam section under flexural-tensile failure, under a high fiber volume ratio. The fibers will bear a high tensile stress as they slide along the interface, thereby slowing down the crack extension and pushing up the failure strain of asphalt concrete. If the fiber volume ratio is too high, however, the fibers will accumulate in local areas of the fiber network and form defects in the asphalt concrete. The flexural-tensile stress will concentrate in these defected places, reducing the bearing capacity of the asphalt concrete. That is why the failure strain of asphalt concrete decreased in our tests.

4.3 Failure stiffness modulus

It can also be seen from Table 1 that, when the temperature was below 0 °C, the failure stiffness modulus of fiber asphalt concrete increased first and then decreased with the growth of fiber volume ratio, and peaked at the polyester fiber volume ratio of 0.35 %; in this case, the fiber asphalt concrete exhibited good low-temperature crack resistance. When the temperature was at 15 °C, the failure stiffness modulus of fiber asphalt concrete decreased first and then increased with the growth of fiber volume ratio, and minimized at the polyester fiber volume ratio of 0.35 %; in this case, the fiber asphalt concrete boasted good flexural and tensile performance.

The reason is that, when the fiber asphalt concrete is brittle at low temperature, a proper fiber volume ratio helps restrain the deformation of the asphalt concrete. The restraining effect increases with the fiber volume ratio, but declines when the fiber volume ratio is excessively high. As mentioned before, too many fibers will accumulate in local areas, forming cake-shaped defects, and these defects will reduce the effect of fibers on restraining deformation.

When the temperature reaches 15 °C, the fiber asphalt concrete may suffer from plastic damages under flexural-tensile stress. In this case, the fibers mainly prevent crack extension with the tensile stress from interface slippage. The greater the prevention ability, the larger the failure strain of fiber asphalt concrete beam. Under the same fiber aspect ratio, the prevention ability increases with the fiber volume ratio, but decreases when there are too many fibers. As a result, the failure stiffness modulus in our tests increased first and then decreased with the growth of fiber volume ratio.

5. EFFECTS OF FIBER ASPECT RATIO ON FLEXURAL-TENSILE PERFORMANCE OF FIBER ASPHALT CONCRETE

5.1 Flexural-tensile strength

As can be seen from Table 1, the flexural-tensile strength of polyester fiber asphalt concrete increased first and then decreased with the growth of fiber aspect ratio, when the temperature remained the same. The maximum flexural-tensile strength appeared at the fiber aspect ratio of 324, under which the fiber asphalt concrete showed good flexural-tensile performance. These results can be explained by the following facts.

When the fiber diameter and fiber volume ratio remain constant, the fibers tend to be longer and point to different directions under a high fiber aspect ratio. In this case, the fibers are highly likely to curl in the asphalt concrete, forming cake-shaped defects [14], which dampens the enhancement effect of fibers. Under the same conditions, a small fiber aspect ratio means each fiber is relatively short, and more fibers exist per unit volume of asphalt concrete. Then, the fibers will become less dispersive and form cake defects in the asphalt concrete, which reduces the enhancement effect of fibers. Under the polyester fiber aspect ratio of 324, the fibers will neither curl into cakes due to the excessive length nor form cake defects due to the numerous fibers per unit volume of concrete. As a result, the fiber asphalt concrete will achieve a good flexural-tensile performance when the fiber aspect ratio is 324.

5.2 Failure strain

It can be seen from Table 1 that, when the temperature remained unchanged below 0 °C, the failure strain of fiber asphalt concrete decreased first and then increased with the growth in fiber aspect ratio, and reached the minimum at the fiber aspect ratio of 324; in this case, the fiber asphalt concrete enjoyed a good flexural-tensile performance. When the temperature stood at 15 °C, the failure strain of fiber asphalt concrete increased first and then decreased with the growth in fiber aspect ratio, and reached the maximum at the fiber aspect ratio of 324; in this case, the fiber asphalt concrete also enjoyed a good flexural-tensile performance.

When the temperature is below 0°C, brittle fractures form on the asphalt concrete during the flexural-tensile failure. The flexural-tensile deformation of the asphalt concrete is restrained by the fibers, which bear lots of tensile stress. Under the fixed fiber volume ratio and fiber diameter, each fiber is relatively long at a high fiber aspect ratio. In this case, there will be relatively few fibers per unit volume of asphalt concrete, and thus limited number of longitudinal fibers on the beam section under flexural-tensile failure. Therefore, the fibers' restraining effect on the flexural-tensile deformation of asphalt concrete will decrease. The high fiber aspect ratio also means the fibers tend to point to different directions, making it easy for fibers in the asphalt concrete to curl into cakes and reduce the restraining effect of the fiber network.

Under the fixed fiber volume ratio and fiber diameter, each fiber is relatively short at a low fiber aspect ratio. In this case, there will be many fibers per unit volume of asphalt concrete, leading to nonuniform dispersion of the fibers. It is highly likely for fibers to accumulate in local areas of the fiber network in the asphalt concrete, which undermines the restraining effect of the fiber network on concrete deformation. In addition, the tensile strength of short fibers often exceeds the interface strength. The fibers are pulled out along the interface, causing slippage damages. Thus, the fibers will become less efficient in restraining concrete deformation. The optimal restraining effect appears at the fiber aspect ratio of 324, which corresponds to the minimum failure strain of fiber asphalt concrete.

When the temperature remains at 15°C, the fiber asphalt concrete beam mainly suffers from plastic damages during flexural-tensile failure, and the fibers are mostly damaged by slippage along the interface. During interface slippage, the fibers' ability to prevent crack extension is positively correlated with the failure strain of the fiber asphalt concrete. If the fiber aspect ratio is high, each fiber will be relatively long and bear a high tensile stress in interface slippage, and will be more likely to break. If the fiber aspect ratio is low, each fiber will be relatively short and get pulled out early in interface slippage. Once pulled out, the fiber will no longer bear the tensile stress. Then, the cracks will propagate quickly, causing flexural-tensile failure of the asphalt concrete.

5.3 Failure stiffness modulus

It can also be seen from Table 1 that, when the temperature was below 0 ℃, the failure stiffness modulus of fiber asphalt concrete increased first and then decreased with the growth of fiber aspect ratio, and peaked at the fiber aspect ratio of 324; in this case, the fiber asphalt concrete demonstrated good flexural-tensile performance. When the temperature was at 15 ℃, the failure stiffness modulus of fiber asphalt concrete decreased first and then increased with the growth of fiber aspect ratio, and minimized at the fiber aspect ratio of 324; in this case, the fiber asphalt concrete also displayed good flexural-tensile performance.

The reason is that, when the temperature is below 0 ℃, the asphalt concrete may suffer from low-temperature brittle damages under the flexural-tensile stress. The fibers can bear a part of the stress to restrain the concrete deformation. Within a proper range, the restraining effect increases with the fiber aspect ratio. If the fiber aspect ratio is excessively high, however, the fibers will curl into cake defects, and become less effective in restraining the flexural-tensile deformation. That is why the failure stiffness modulus of fiber asphalt concrete increased first and then decreased with the growth of fiber aspect ratio, when the temperature was below 0 ℃.

When the temperature reaches 15 ℃, the fiber asphalt concrete, which belongs to the viscoelastic phase, may suffer from plastic damages under flexural-tensile stress. In this case, the fibers mainly prevent crack extension with the tensile stress from interface slippage. The greater the prevention ability, the larger the failure strain of fiber asphalt concrete beam. Under the same fiber volume ratio, the fibers tend to slip along the interface at a small fiber aspect ratio and rupture at a large fiber aspect ratio. In either case, the fibers will become less efficient in restraining crack extension, dragging down the resistance of fiber asphalt concrete to flexural-tensile deformation. As a result, the failure stiffness modulus of fiber asphalt concrete decreased first and then increased with the growth of fiber aspect ratio, when the temperature was at 15 ℃.

6. FCFP-BASED CALCULATION OF FLEXURAL-TENSILE PERFORMANCE OF ASPHALT CONCRETE

The above analysis shows that fiber volume ratio and fiber aspect ratio both have significant impacts on the flexural-tensile performance of asphalt concrete, and their influence laws are basically consistent. As shown in Table 1, the test results agree well with the fitted results. Therefore, the FCFP $\lambda_f = V_f \times R_a$ was introduced to describe the combined effect of fiber volume ratio and fiber aspect ratio on the flexural-tensile performance of asphalt concrete. Whichever the temperature, fiber volume ratio and fiber aspect ratio, the flexural-tensile strength of polyester fiber asphalt concrete always increases and then decreases with the growth of the FCFP. Through the nonlinear fitting of our test results, the relationship between the flexural-tensile strength of polyester fiber asphalt concrete and the FCFP can be expressed as:

$$\boldsymbol{R_B = 7.7 + 3.71\lambda_f - 2.36\lambda_f^2} \quad \text{T=-30°C} \tag{12}$$

$$\boldsymbol{R_B = 8.15 + 3.75\lambda_f - 2.36\lambda_f^2} \quad \text{T=-20°C} \tag{13}$$

$$\boldsymbol{R_B = 9.05 + 3.06\lambda_f - 1.62\lambda_f^2} \quad \text{T=-10°C} \tag{14}$$

$$\boldsymbol{R_B = 9.42 + 3.74\lambda_f - 2.06\lambda_f^2} \quad \text{T=0°C} \tag{15}$$

$$\boldsymbol{R_B = 5.99 + 3.30\lambda_f - 2.20\lambda_f^2} \quad \text{T=15°C} \tag{16}$$

In the elastic phase, the failure strain of fiber asphalt concrete decreases first and then increases with the growth of the FCFP. In the viscoelastic phase, however, the failure strain of fiber asphalt concrete increases first and then decreases with the growth of the FCFP. Through the nonlinear fitting of our test results, the relationship between the failure strain of polyester fiber asphalt concrete and the FCFP under different temperatures can be expressed as:

$$\boldsymbol{\varepsilon_B = 3200 - 842.04\lambda_f + 537.20\lambda_f^2} \quad \text{T=-30°C} \tag{17}$$

$$\boldsymbol{\varepsilon_B = 3515 - 1084.22\lambda_f + 786.57\lambda_f^2} \quad \text{T=-20°C} \tag{18}$$

$$\boldsymbol{\varepsilon_B = 4098 - 1719.03\lambda_f + 1463.94\lambda_f^2} \quad \text{T=-10°C} \tag{19}$$

$$\boldsymbol{\varepsilon_B = 4868 - 2647.00\lambda_f + 2180.09\lambda_f^2} \quad \text{T=0°C} \tag{20}$$

$$\boldsymbol{\varepsilon_B = 7943 + 17195.57\lambda_f - 12680.79\lambda_f^2} \quad \text{T=15°C} \tag{21}$$

In the elastic phase, the failure stiffness modulus of fiber asphalt concrete increases and then decreases with the growth of the FCFP. In the viscoelastic phase, however, the failure stiffness modulus of fiber asphalt concrete decreases first and then increases with the growth of the FCFP. Through the nonlinear fitting of our test results, the relationship between the failure stiffness modulus of polyester fiber asphalt concrete and the FCFP under different temperatures can be expressed as:

$$\boldsymbol{S_B = 2373 + 1926.98\lambda_f - 1192.00\lambda_f^2} \quad \text{T=-30°C} \quad (22)$$

$$\boldsymbol{S_B = 2315 + 2016.99\lambda_f - 1364.07\lambda_f^2} \quad \text{T=-20°C} \quad (23)$$

$$\boldsymbol{S_B = 2203 + 1936.18\lambda_f - 1391.24\lambda_f^2} \quad \text{T=-10°C} \quad (24)$$

$$\boldsymbol{S_B = 1913 + 2312.85\lambda_f - 1666.18\lambda_f^2} \quad \text{T=0°C} \quad (25)$$

$$\boldsymbol{S_B = 737 - 653.08\lambda_f + 497.95\lambda_f^2} \quad \text{=15°C} \quad (26)$$

From formulas (12)-(26), it can be seen that the polyester fiber asphalt concrete enjoys good flexural-tensile performance when the FCFP amounts to 1.13.

7. CONCLUSIONS

The following conclusions were drawn from our bending tests on polyester fiber asphalt concretes:

(1) The flexural-tensile strength of fiber asphalt concrete increases first and then decreases with the rising temperature, and peaks at the temperature of 0 ℃. Under this temperature, the fiber asphalt concrete obviously softens under stress. Through nonlinear fitting, the author obtained the relationship between flexural-tensile strength of fiber asphalt concrete and temperature, which shows that the fibers can reduce the brittle temperature of the asphalt concrete.

(2) The failure strain of fiber asphalt concrete increases with temperature. When the temperature is below 0 ℃, the failure strain has an obvious linear relationship with temperature, while the failure stiffness modulus decreases with the rising temperature.

(3) Under different temperatures, the flexural-tensile strength of polyester fiber asphalt concrete increases first and then decreases with the growth in fiber volume ratio or fiber aspect ratio. When the fiber asphalt concrete suffers from low-temperature brittle damages, the failure strain decreases first and then increases with the growth in fiber volume ratio or fiber aspect ratio, while the failure stiffness modulus increases first and then decreases with the growth in fiber volume ratio. When the fiber asphalt concrete suffers from plastic damages under flexural-tensile stress, the failure strain increases first and then decreases with the growth in fiber volume ratio or fiber aspect ratio, while the failure stress modulus decreases first and then increases with the growth in fiber volume ratio.

(4) The FCFP was introduced to describe the combined effect of fiber volume ratio and fiber aspect ratio on the flexural-tensile performance of asphalt concrete. The correlations of the FCFP with the flexural-tensile strength, failure strain and failure stiffness modulus of polyester fiber asphalt concrete can be expressed respectively by formulas (12)-(16), formulas (17)-(21) and formulas (22)-(26). The test results and theoretical analysis show that the optimal FCFP of polyester fibers is 1.13.

The future research will probe deeper into the FCFP, a parameter reflecting the combined effect of fiber volume ratio and fiber aspect ratio on the flexural-tensile performance of asphalt concrete.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support of the project from the Colleges and Universities Key Scientific Research Projects of Henan Province (Grant No. 17B580003) and Horizontal Research Project of Xuchang University (Grant No. 2017HX029 and 2019HX005).

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