Fatigue Performance Of High-Modulus Basalt Fiber-Reinforced Asphalt Mixture

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An effective way to improve the rutting resistance of asphalt pavement is to increase the modulus of the middle surface layer of the asphalt mixture. However, the fatigue performance of high-modulus asphalt mixtures hinders this development. In this study, we enhanced the fatigue property of high-modulus asphalt mixtures by adding basalt fiber. Marshall tests were performed to evaluate the effect of the basalt fiber and a high-modulus modifier on various Marshall test results. The results were analyzed and compared with the performance of SBS-modified (Styrene-Butylene-Styrene) asphalt mixes. Adding basalt fiber increased the asphalt-aggregate ratio, decreased the density, and reduced air voids in the mixture. The stability also slightly increased, and the flow slightly decreased. Moreover, 0.2% basalt fiber increased the fatigue resistance of high-modulus asphalt mixture 1.9 times, and this improvement increases with the increasing basalt content. The elastic modulus of basalt fiber is considerably higher than that of asphalt; therefore, the proportion of stiffer components in the asphalt mastic was higher after mixing. Furthermore, basalt fiber absorbs oil (asphalt); accordingly, the increased asphalt content slightly enhanced the fatigue resistance of the mixture.

Keywords: Basalt fiber, fatigue performance, high-modulus asphalt mixture, mixture ratio design

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1. Introduction

According to the French NFP98140 /141 standard, high-modulus asphalt concrete generally refers to road asphalt concrete with a complex modulus $(15°\text{C}, 10\ \text{Hz}) \geqslant 14,000\text{MPa}$ [1, 2]. The main principle is to reduce the tensile stress and strain of the asphalt pavement structure layer under the driving load by increasing the modulus of asphalt concrete, thereby improving the rutting resistance of pavement while also reducing the thickness of pavement. At present, three main technical methods can be used to increase the modulus [3–5]: adding a high-modulus agent, mixing natural asphalt, and using a low-grade hard asphalt binder. The process of adding a high-modulus agent is simple and inexpensive and has been studied by several researchers.

Among them, British researchers [6] have conducted a series of studies on using high-modulus asphalt mixture as the middle and lower layers. The results demonstrate that using EME (Epoxy Molding Compound) high-modulus asphalt mixture makes the road exhibit the advantages of low engineering cost in the whole life cycle. Lee et al. [7] of South Korea prepared a high-modulus asphalt mixture by adding an SBS modifier and an oil with a high boiling point to ordinary asphalt. Their findings showed that the high-temperature stability and water stability were improved, but the low-temperature performance did not change significantly. Yu [8] determined the reasonable dosage range of a PRM (PR PL.AST.M) high-modulus agent and an SBR (Styrene Butadiene Rubber) admixture. Meanwhile, Ren et al. [9] studied different macroscale mechanical properties and the microscale dispersion state of a high-modulus admixture before and after grinding. However, in both research and engineering practice, high-modulus asphalt concrete is often used in the middle surface course of asphalt pavement, but increasing the modulus of the structural material of a single layer will inevitably lead to great changes in the stress in the pavement. In particular, the flexural tensile stress at the bottom of the structural layer will considerably fluctuate, which will directly affect the fatigue life of asphalt pavement [10–14]. Therefore, a method that considerably improves the fatigue performance of high-modulus asphalt mixture while ensuring excellent rutting resistance is urgently required.

Fiber is an additive that can enhance the road performance of asphalt mixtures. Mixing fiber into an ordinary asphalt mixture inevitably changes its road performance. Qin et al. [15], Ma and Gao [16], Wu et al. [17], and Wang et al. [18] found through indoor tests that basalt fiber can not only adsorb oil but also stabilize, reinforce, and increase the viscosity of ordinary asphalt mixtures, which can effectively improve the fatigue resistance of asphalt pavement. Thus, methods for the preparation and construction of basalt fiber asphalt mixtures have been systematically proposed.

In summary, according to the performance characteristics of high-modulus asphalt mixtures, this study examined the fatigue performance of high-modulus asphalt mixture mixed with basalt fiber in order to enrich and improve the performance improvement technical measures of high-modulus asphalt pavement. The findings will provide a reference for the popularization and application of high-modulus asphalt mixtures in China.

2. Experimental section

2.1. Material properties

Sinopec A 70# asphalt was selected as the base asphalt, and Shell SBSI-D was used as modified asphalt. Limestone was selected as the coarse and fine aggregates. Technical indicators of the base asphalt, SBS-modified asphalt, aggregates, and mineral powder were investigated via specific tests to ensure that they satisfy their corresponding specification requirements. Rutting is primarily associated with the middle layer of the pavement; therefore, AC- 20C was selected as the asphalt mixture aggregate gradation; the grading range is presented in Table 1.

The high-modulus admixture refers to the various polymers and polar additives added to the asphalt mixture to enhance its rutting resistance [19]. In this study, Lu Bao high-modulus admixture was used with a dosage of 0.4%, as recommended by the manufacturer and in a previous study [20, 21]. Basalt fiber was produced by melting pure natural basalt at $1450 - 1500°C$. Short-cut basalt fiber manufactured by Zhejiang Shijin Basalt Fiber Co., Ltd. was used, with a fiber monofilament length of $17 \mu m$ and a short-cut fiber length of 6 mm. The measured basalt fiber performance indexes are listed in Table 2.

2.2. Experimental design

Marshall test and four-point bending beam fatigue tests (T0739-2011) were performed on seven types of mixtures: ordinary asphalt mixture (AC-20C), basalt fiber asphalt mixture (BF), high-modulus asphalt mixture (HM), SBS-modified asphalt mixture, and HM with 0.2%, 0.4%, and 0.6% basalt fiber additions. The specific sample labels and compositions are listed in Table 3. The influence of basalt fiber and high-modulus admixture on the road performance of common asphalt mixes and basalt fiber-reinforced HM was investigated. The mechanisms underlying these effects were also examined.

2.2.1. Test methods

At present, domestic and international fatigue testing is categorized into four types. The first is the fatigue damage testing of actual pavement under real vehicle loads, which is typically performed according to the AASHTO specifications in the United States. The second is fatigue testing under the action of a simulated vehicle load with a footprint pavement structure such as ring road tests, straight road tests, and accelerated loading tests. The third is the test plate method. Finally, the fourth is indoor small-scale fatigue testing. The first three tests are costly and time-consuming. Regarding the fourth category, SHRP scholars analyzed the convenience of the test, the repeatability of the data, and the consistency of the stress condition of pavement materials. They found that the four-point bending trabecular test is closer to the actual situation, and the test data can also be directly applied to the design of asphalt pavement. They thus concluded this was the most reliable fatigue testing scheme. Therefore, four-point bending beam fatigue testing was selected to study the fatigue performance for its short cycle and low cost.

2.2.2. Loading mode

Phenomenological fatigue testing consists of two loading modes, namely, stress- and strain-controlled modes [22–24]. Depending on the selected loading mode, different findings can be obtained. When microcracks start forming on a test specimen under stress control, the crack expansion gradually accelerates with the decreasing material stiffness modulus under constant stress. However, under strain control, a decrease in the strength modulus of the asphalt mixture reduces the stress on the specimen. Consequently,

Table 1. AC-20C asphalt mixture grading range

Sieve Size (mm)	Percent Passing (%)										
	19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Mixture Gradation	97.5	88.5	75.5	66.5	48.7	37	27.8	20	14	10.8	6

Table 2. Performance indexes and corresponding test results of basalt fiber

Physical Characteristics	Technical Standard	Test Results
Tensile strength (MPa)	≥ 1500	2326
Elongation at rupture (%)	≤ 3.1	2.57
Oil absorption (%)	≥ 50	51.2
Combustible content (%)	$0.1 - 1.0$	0.5
Water content (%)	≤ 0.2	0.09
Heat resistance, fracture strength retention (%)	≥ 85	93

Table 3. Test samples and their compositions

Gradation Type	Sample label	Fiber content (%)	High modulus content (%)	SBS modifier (%)
ordinary asphalt mixture	AC-20C	/	/	/
SBS-modified asphalt mixture	5% SBS	/	/	5
basalt fiber asphalt mixture	0.4%BF	0.4	/	/
high-modulus asphalt mixture	0.4%HM	/	0.4	/
basalt fiber and high modulus admixtures	0.2%BF+0.4%HM	0.2	0.4	/
	0.4%BF+0.4%HM	0.4	0.4	/
	0.6%BF+0.4%HM	0.6	0.4	/

the crack expansion decelerates, thus extending the fatigue life. In this study, the strain-controlled loading mode was adopted for fatigue testing because it is more in line with the fatigue characteristics of the actual pavement structure.

2.2.3. *Test conditions*

The fatigue performance of the asphalt mixtures was evaluated using the four-point bending beam fatigue test in accordance with the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011). The test temperature was maintained at 15°C, with a loading frequency of 10 Hz. The strain-controlled partial sine wave loading mode was used, and the test was considered to have ended when the stiffness modulus of the asphalt mixture specimen decreased to 50% of the initial modulus. The asphalt mixture specimen slab was wheel-rolled in the laboratory with the following dimensions: length $= 380 \pm 5$ mm, width $= 63.5 \pm 5$ mm, and height $= 50 \pm 5$ mm. In this study, five strain control levels, namely $400, 500, 600, 700$, and $800\mu\varepsilon$, were tested for fatigue resistance as per specifications.

3. Test results and analysis

3.1. Comparative analysis of Marshall metrics

3.1.1. *Effect of basalt fiber on Marshall index*

Table 4 compares the results of Marshall tests, including the gross volume relative density, theoretical maximum density, void ratio, mineral aggregate gap ratio, and other indexes. Adding basalt fiber and HM both decreased the relative densities of AC-20C; however, they increased the air voids (VVs). This is because basalt fibers transfer a small amount of energy when the Marshall specimen is compacted, which makes the further compaction more difficult under the same amount of work, resulting in reduced density. Furthermore, basalt fibers disperse to form a comprehensive interlocking spatial structure, and the fibers themselves occupy space. This increases both the number of VVs and the mineral interstitial rate. However, the stability and flow indexes reveal that the addition of basalt fibers slightly enhanced the stability and reduced the flow. These findings may be attributed to the spatial structure formed by the basalt blocking the slip of aggregate to some extent.

3.1.2. *Effect of high-modulus admixture on Marshall index*

As can be inferred from Table 4, oil absorption within the high-modulus admixture increased the HM asphalt-aggregate ratio. After adding this admixture, the gross volume relative density and theoretical maximum density decreased, while volume indexes such as the VV ratio and the mineral interstitial ratio increased slightly. In addition, the stability and flow indexes demonstrate that the asphalt mixture was considerably more stable than the $AC - 20C$, BF, and SBS-modified asphalt mixtures. This is

Table 4. Marshall test results of different asphalt mixtures

Gradation Type	Optimal Aggregate Ratio (%)	Gross Volume Density (g/cm^3)	Theoretical Maximum Density (g/cm^3)	Air Voids VV (%)	Voids in Mineral Aggregates VMA (%)	Voids Filled with Asphalt VFA (%)	Stability MS (kN)	Flow Value FV (0.1 mm)
AC-20C	4.3	2.426	2.539	4.21	13.3	69.2	12.28	32.3
5%SBS	4.5	2.428	2.539	4.19	13.3	69.3	13.76	31.9
0.4%BF	4.6	2.418	2.534	4.32	13.6	69	12.36	32.2
0.4%HM	4.5	2.424	2.533	4.25	13.5	69.3	15.16	29.4
0.2%BF+0.4%HM	4.7	2.419	2.528	4.33	13.7	69.8	15.21	29.2
0.4%BF+0.4%HM	4.8	2.413	2.522	4.38	13.9	70.9	15.35	28.9
0.6%BF+0.4%HM	5.0	2.411	2.519	4.43	14.1	70.5	15.41	28.6

mainly attributed to the fact that high-modulus admixture addition modified the asphalt, enhancing asphalt adhesion. It also resulted in physical interactions with the hot aggregate, thereby forming a molten state, which filled the voids of the aggregate skeleton. Furthermore, in the high-modulus admixture, flocculent, fibrous, and flake deformations were produced by the hot aggregate when extruded and subsequently participated in cementation, reinforcement, and embedding in the aggregate skeleton after cooling. Thus, the high-modulus admixture hindered sliding between the mineral particles in the asphalt mixture. For this reason, the interactions between the mixture strengthened, and the structure became more compact, creating a high-modulus asphalt mix with higher stability and decreased flow.

3.2. Effect of basalt fibers on HM fatigue performance

Fatigue tests were conducted on the seven asphalt mixtures as per specifications, and the results are presented in Table 5 and Figs. 1 to 3.

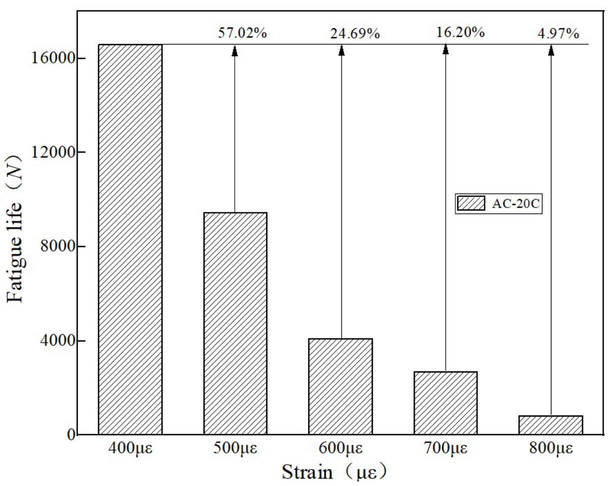

Fig. 1. Relationship between strain and fatigue life

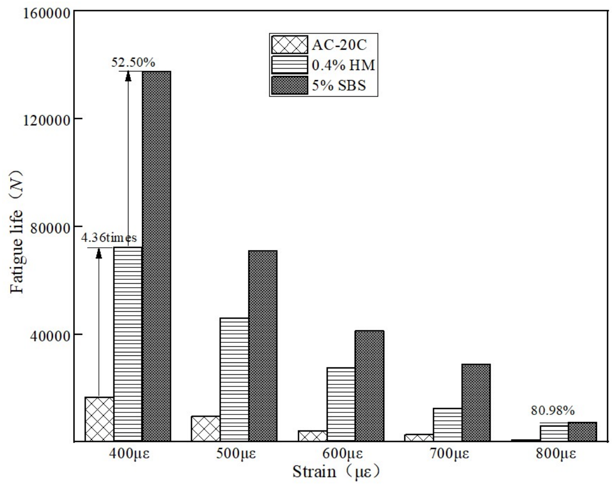

Fig. 2. Fatigue performance life of high-modulus asphalt mixture

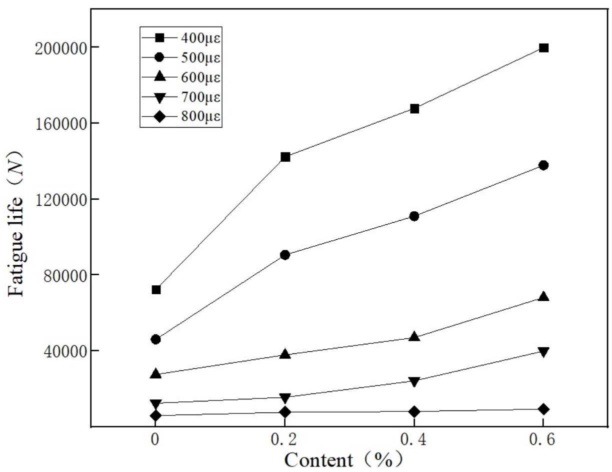

Fig. 3. Relationship between strain and fatigue life

Table 5. Asphalt mixture fatigue test results

Gradation Type	Fatigue Life (N)				
	$400\mu\varepsilon$	$500\mu\varepsilon$	$600\mu\varepsilon$	$700\mu\varepsilon$	$800\mu\varepsilon$
AC − 20C	16587	9459	4095	2688	824
5%SBS	137898	71087	41238	28909	7288
0.4%BF	28767	14823	5025	4077	1981
0.4%HM	72355	46096	27562	12435	5902
0.2%BF + 0.4%HM	142325	90550	37890	15580	7650
0.4%BF + 0.4%HM	167845	110979	47021	24198	8122
0.6%BF + 0.4%HM	199803	137822	68168	39902	9334

3.2.1. Effect of the strain level on fatigue performance

As shown in Table 5 and Fig. 1, the data from the same asphalt mixture reveal an evident association between the fatigue life and strain level. With increasing strain, the fatigue life decreased significantly. Considering the common asphalt mixture as an example, fatigue lives under strain levels of 800, 700, 600, and $500\mu\varepsilon$ accounted for 4.97%, 16.20%, 24.69%, and 57.02%, respectively, of their fatigue life at a strain of $400\mu\varepsilon$. Similar conclusions were obtained for the fatigue lives of other asphalt mixtures; for example, that fatigue life decreases rapidly even under high strain.

3.2.2. Effect of the high-modulus admixture on fatigue performance

Fig. 2 shows that adding the high-modulus admixture improved the fatigue performance of high-modulus asphalt mixtures with respect to that of ordinary asphalt. At the strain of $400\mu\varepsilon$, the fatigue lives of the high-modulus asphalt mixtures were 4.36 times that of ordinary asphalt mixtures. This is mainly because the initial strength modulus of HM is considerably higher than that of ordinary asphalt mixtures, which in turn increases the number of load actions required to reach the damage threshold. The fatigue life of HM at $400\mu\varepsilon$ only accounts for 52.50% of that of the SBS-modified asphalt mixes. At $800\mu\varepsilon$, this gap is reduced; however, HM is only capable of reaching 80.98% of the SBS fatique life.

3.2.3. Effect of basalt fibers on fatigue performance

Table 5 summarizes that the addition of basalt fibers substantially increased the fatigue lives of both common and high-modulus asphalt mixtures. Under $400\mu\varepsilon$ of strain, the fatigue life of HM with 0.4% basalt fiber was 2.32 times higher than that of HM without fibers and 10.12 times higher than that of the common asphalt mixture. Its fatigue performance even surpassed that of the SBS-modified asphalt mix. In addition, as shown in Fig. 3, the fatigue life increased with the increasing basalt fiber dosage under the same strain conditions. The fatigue performance of the basalt fiber-reinforced high-modulus asphalt mixture was considerably more satisfactory than that of the asphalt mix with only basalt fiber or the high-modulus admixture without fiber. This is likely because the elastic modulus of the fiber is considerably higher than that of asphalt; thus, the proportion of elastic components in asphalt mastic increased after the mixing. After the fibers were mixed uniformly, the high-modulus admixture was added to increase the stiffness modulus. These two factors together significantly enhanced the fatigue performance of asphalt mastic. However, basalt fiber and the high-modulus admixture both absorb oil, which increased the oil-to-stone ratio of the mixture; as a result, increasing asphalt content improved the fatigue performance of the mixture. Furthermore, it increased the asphalt-aggregate ratio. An increase in the asphalt content can also improve the mixture fatigue performance.

4. Conclusion

1. Seven asphalt mixtures were prepared using AC-20C grading. Both the high-modulus admixture and basalt fiber absorb oil, so their optimum asphalt-aggregate ratio increased by 0.2% and 0.3% respectively. In the high-modulus asphalt mixture with basalt fiber, the asphalt-aggregate ratio tended to increase with the increasing fiber dosage.

2. After mixing with basalt fiber, the asphalt-aggregate ratio increased, density decreased, void ratio increased, stability slightly increased, and flow value slightly decreased. Adding the high-modulus admixture resulted in an increased asphalt-aggregate ratio, a slightly lower density, a slightly higher void ratio, and considerably increased stability. Moreover, the flow value decreased.

3. After the high-modulus admixture was added to the matrix asphalt, the fatigue life increased 4.36 times at the level of $400\mu\varepsilon$. However, this is only 52.5% of the fatigue life of SBS asphalt mixture, whereas at $800\mu\varepsilon$, the gap in the fatigue life decreased to 81%.

4. The fatigue lives of the high-modulus asphalt mixtures were significantly longer than those of the normal asphalt mixtures, but they were still lower than those of the SBS-modified asphalt mixture. With the addition of basalt fibers, the fatigue life of the mixtures increased substantially for both normal and high-modulus asphalt mixtures; however, the effect was not as prominent with the increasing strain level. Meanwhile, with increasing strain, the fatigue life of 0.4% basalt fiber high-modulus asphalt mixture was 2.32 times higher than that of the high-modulus asphalt mixture at $400\mu\varepsilon$. Under the same strain conditions, the basalt fiber-reinforced high-modulus asphalt mixture showed the best fatigue performance among all prepared samples.

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

All authors contributed to the study conception and design. All authors contributed to material preparation, data collection and analysis. The first draft of the manuscript was written by Jingjing Dai and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability statements

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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