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Research on Performance of Asphalt Concrete and Microcosmic Analysis of Its Reinforcing Mechanism

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This paper provides guidance for the use of asphalt concrete materials through the study of the action mechanism of asphalt concrete materials and the specific test results. Fiber-asphalt concrete is selected as an example and different mixtures are used to conduct indoor tests. The results show that after 0.3% fiber is added to the asphalt concrete material, the dynamic stability of the material itself has been significantly improved, with an average increase of 20%. It can be found through the experiment that the addition of different mixtures has different effect on the overall performance of the asphalt concrete material and the performance of the concrete has been significantly improved with the addition of fiber. The enhancing effect of fiber material on the performance of dense-graded concrete material is the most significant.

1. Introduction

At this stage, the domestic economy and society are developing in a fast speed and the development of economy and society puts forward new requirements for the field of road transportation. At present, over 95% of the domestic expressways are asphalt roads, and due to the influence of material properties, various factors such as temperature, rain, and vehicle load will affect the use of asphalt roads. Although there are many researches in the field of fiber asphalt concrete material at home and abroad, there are tremendous limitations on the whole, which basically focus on one type of mixed material while researches concerning the comparative study on different mixed materials are relatively few.

In this paper, combined with the use of fiber in asphalt concrete materials, several different fiber materials are selected. Through various stages of laboratory tests, various performance of fiber asphalt concrete material is studied combined with experimental results, hoping to provide a certain reference for future highway project practice.

2. Literature review

The main influencing factors of asphalt pavement water damage are: aggregate characteristics and mineral composition, chemical and physical properties of asphalt, asphalt usage, asphalt mixture characteristics, climate and traffic conditions. While Warm Mix Asphalt (WMA) has attracted wide attention as a green road-building technology for energy conservation and emission reduction. Its technical characteristics of reducing the mixing and compaction temperature of asphalt mixture make its water stability problem more complex than that of hot mix asphalt (HMA). Therefore, it has gradually received widespread attention from the industry.

Foreign researchers have done a lot of research work on the water stability of warm mix asphalt. Abdullah et al. showed that Evotherm-WMA is more water-sensitive than Hot Mix Asphalt (HMA) (Abdullah et al., 2016). However, studies by Liu et al. showed that Sasobit-WMA reduces the construction temperature and has little effect on water stability. Buss et al. pointed out that foamed WMA has better water stability than other WMAs. Raghavendra et al. studied the water stability of warm-mixed SMAs with three warm mixes (Aspha-min, Sasobit, and Evotherm). The results showed that even if slaked lime is added, 32% of the warm-mixed SMA water is still unsatisfactory (Raghavendra et al., 2016). Aliha et al. used TSR and dynamic modulus tests to determine the water stability of foamed-WMA spiked with 50-nm (NHL) and 100-nm (RHL) slaked lime. The results showed that the foamed-WMA mix is more susceptible to water damage than the HMA mix (Aliha et al.,

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2017). However, the results of Jones et al. found that there was no significant change in the residual stability and residual strength ratio of asphalt mixture after the addition of warm mix. However, Xiao et al. 's study also showed that WMA water stability with Aspha-min and Sasobit added under the same conditions was not significantly different from HMA. Mogawer et al. pointed out that most warm mixes have good resistance to water damage. Cucalon et al.'s study showed that the water stability of WMA added with Evotherm, Sasobit, Aspha-min depends mainly on the chosen warm mix technology and experimental conditions (Cucalon et al., 2016). Autelitano et al. performed freeze-thaw splitting tests on warm mix asphalt and hot mix asphalt mixtures under different aging conditions and found that the warm mix asphalt mixture after short-term aging exhibited relatively better water stability than hot mix asphalt mixture (Autelitano et al., 2017).

Water damage is one of the main diseases of asphalt pavement. It is considered that the water damage of the asphalt mixture is mainly caused by the cohesive failure inside the asphalt and the adhesion failure between the asphalt and the aggregate. There are currently two general methods for characterizing the water stability of asphalt mixtures: the first category is the qualitative characterization method represented by boiling and water leaching. And the second category is an indirect quantitative characterization method represented by freeze-thaw cleavage and water-immersed Marshall tests. The first method is influenced by subjective judgment ability of the experimenter, and the second method also has disadvantages such as insufficient theoretical basis and poor scene reproducibility. Amelian et al. used surface free energy theory to verify that hydrated lime as an anti-stripping agent facilitates the improvement of the water stability of the asphalt mixture (Amelian et al., 2018).

In recent years, more and more researchers have tried to use surface free energy theory to find a direct quantitative characterization method for the water stability of asphalt mixtures. Goli et al. used the surface free energy of asphalt and aggregates to analyze the relationship between the surface energy index and macroscopic indicators of asphalt mixture water stability. It is considered that the surface free energy method can be used to characterize the water damage resistance of asphalt mixtures (Goli et al., 2017); Abbas et al systematically expounded the surface free energy testing method of asphalt based on Wilhelmy hanging plate method from the aspects of test solution selection, validity verification of contact angle data and surface free energy calculation (Abbas et al., 2016); recently, nanotechnology has been applied to the study of the microstructure and mechanical properties of asphalt. Tarefder et al. used AFM to determine the nanoscopic adhesion of polymer-modified asphalt and matrix asphalt respectively, and the results showed that the former had relatively better adhesion performance. Based on atomic force microscopy, Nazzald et al. studied the effects of different warming agents on the nanoscopic morphology, cohesion and adhesion of asphalt. The results showed that Sasobit warming agents make the width of the “bee-like” structure in the asphalt smaller, while other warming agents have no significant effect on this. Through the force spectrum test, it is found that the adhesion of warm mix asphalt is significantly higher than that of matrix asphalt before soaking; after soaking, there was no significant difference in the adhesive force between the warm mix asphalt and its corresponding matrix asphalt except for Sasobit (Zhang et al., 2018). In addition, both the Sasobit and Advera warming agents reduce the cohesion of the asphalt in water soaking conditions, which is detrimental to the water stability of the asphalt. Huang et al. tested the bonding properties of eight different types of asphalt with various methods including AFM. The results showed that the water sensitivity of asphalt is related to the concentration of polyaromatic hydrocarbons. Lyne et al. used AFMONM to obtain the apparent morphology of the matrix asphalt and studied the mechanical properties of the asphalt. Studies have shown that the adhesion force measured in the area around and inside the “bee structure” inside the asphalt is smaller than that measured in the smooth area.

There are also related studies in China. Wei Jianming measured the surface energy of different matrix asphalts. The comparison between the obtained asphalt cohesion function and its Pull-off strength shows that there is a good correlation between the cohesion function and the Pull-off strength; Han Sen and others focused on the influence of surface energy characteristics of raw materials on the interfacial adhesion of asphalt-aggregate systems. The results show that the adhesion function produced by the larger Lewis acid base force and the smaller van der Waals force is beneficial to the improvement of the interfacial adhesion performance of the asphalt-aggregate system; Chen Yanjuan believes that the exfoliation function based on the surface energy method can more intuitively characterize the adhesion properties of the asphalt-aggregate system; Ma Feng et al. analyzed the surface free energy of natural asphalt modified asphalt. The results show that the formation of polar functional groups and network structures in natural asphalt can work together to improve the surface free energy of natural asphalt and modified asphalt; Ji Jie et al. explored the effects of water and warm mixes on the adhesion properties of asphalt-aggregate systems by establishing adhesion models for asphalt-aggregates, asphalt-warming agents-aggregates.

In summary, the above-mentioned research work has mainly studied the water sensitivity of WMA and the water stability of asphalt. However, these macro-scale tests can’t distinguish between adhesion failure and cohesive failure within the WMA system, and can’t explain the mechanism of WMA water damage, resulting in many studies reaching different conclusions. Therefore, based on the above research status, new research methods to clarify and quantify the adhesiveness of warm-mix asphalt and aggregate system are mainly adopted, and AFM is used to characterize the water stability of asphalt mixture.

3. Study on the performance of fiber asphalt concrete material

In order to study the improvement effect of fiber on the performance of asphalt mixture road, the high temperature performance, low temperature performance and water stability performance of fiber asphalt mixture are studied through laboratory tests.

3.1 Raw materials

(1) Fiber
The lignin fiber is used, which is a kind of plant fiber with light green color or gray floc structure. This fiber material usually has good high temperature and chemical stability. Also, compared with other mixed materials, it has better chemical corrosion resistance. Table 1 shows the main technical indicators of lignin fiber material:

Table 1: Lignin fiber material main technical indicators

Fiber type	The average diameter (mm)	Length (mm)	Melting temperature (℃)
Lignin fiber	0.045	<5.0, average value1.1	250

(2) Asphalt
The asphalt specification used for the study in this paper is the Zhonghai No. 70 matrix asphalt. The technical indicators are shown in Table 2:

Table 2: Base asphalt technical indicators

Technical indicators		Specification value	Test value
Penetration25℃/0.1mm		60-80	72
Softening Point/℃		≥46	50.1
Delay,10℃/cm		≥20	40.3
Delay,15℃/cm		≥100	112
Film oven test quality changes		±0.8	0.36
Remains	Delay,10℃/cm	≥6	7.3
	Delay,15℃/cm	≥15	18.5

(3) Mixture
In the design of the mix ratio of asphalt mixture, basalt is selected as the coarse aggregate; limestone is used as the fine aggregate; and the ore is prepared from limestone; the mixture type of AC-13, SMA-13 and OGFC-13 is selected. According to engineering experience, the lignin fiber content is selected to be 0.3% and the test results of mixture volume indicator are shown in Table 3:

Table 3: Asphalt Mixture Technical Index Test Results

Mixture type	Fiber content/ %	The best ratio of oil /%	Gross bulk density/ ($g.cm^{-1}$)	Porosity /%	Mineral material gap /%	Asphalt saturation /%	Stability /KN	Flow value /0.1mm
AC-13	0	5.2	2.428	4.4	13.9	68.4	7.4	44
	0.3	5.4	2.419	4.2	14.4	69.9	8.4	46
SMA-13	0	5.9	2.458	3.8	16.5	76.9	11.6	32
	0.3	6.2	2.443	3.8	16.9	77.5	12.2	36
OGFC-13	0	4.7	2.058	20.1			5.1	38
	0.3	4.9	2.081	19.8			5.6	32

From the above table, it can be seen that the optimal asphalt-aggregate ratio and stability of the asphalt mixture increase with the addition of fiber and the porosity of the other two mixtures decreases except that the porosity of SMA-13 remains unchanged. This is mainly because the lignin fiber has a large specific surface area and the surface can adsorb a large amount of asphalt, thereby increasing the amount of structural asphalt and increasing the strength of the mixture.

3.2 High temperature performance

According to the requirements of the rutting test in the “Test Procedure for Asphalt and Asphalt Mixtures for Highway Engineering” (JTG E20-2011), the 30cm×30cm×5cm rut plate specimen is prepared using the above-mentioned gradation and oil-stone ratio, the rutting test is conducted at the temperature of 60° and finally the impact of fiber addition on the high temperature performance of asphalt mixture is evaluated with the rutting depth and dynamic stability indicators. Through the rutting tester, the vertical deformation of asphalt mixture at a specified time interval is recorded and the dynamic stability is calculated using formula (1):

$$D_s = \frac{(t_2 - t_1) \times N}{d_1 - d_2} \times C_1 \times C_2 \tag{1}$$

In the formula: Ds is the dynamic stability index and the unit times/mm; d is the vertical deformation of asphalt mixture at time t and the t is usually 45min; N is the round-trip rolling rate of rubber tires and the specification is 42 times per minute, C1 is the correction coefficient of the testing machine and the value is 1.0 at this time; C2 is the coefficient of the test piece. When the width of the test piece is 30 cm, the value is 1.0.
The specific rutting test results and dynamic stability calculation results are shown in Table 4:

Table 4: Rutting test results and dynamic stability calculation results

Mixture type	Fiber content/%	Rutting depth d_1/mm	Rutting depth d_2/mm	Secondary stability / (mm^{-1})
AC-13	0	1.927	2.324	1 587
	0.3	1.855	2.119	2 386
SMA-13	0	1.859	2.101	2 603
	0.3	1.756	1.938	3 462
OGFC-13	0	2.862	3.312	1 400
	0.3	2.648	3.017	1 707

From Table 2, it can be seen that after adding 0.3% of fiber, the rutting depth of the above three asphalt mixtures at both times has decreased to some extent but the dynamic stability has increased. This is mainly because a network structure can be formed with the fiber addition into the mixture, which plays a role in reinforcing and toughening; at the same time, a large number of structural asphalt is formed with the surface adsorption, which improves the binding properties of asphalt to aggregate and thereby increases the high temperature performance of the mixture. The dynamic stability of the three materials AC-13, SMA-13 and OGFC-13 increases by 50.4%, 33.0%, and 22.0% respectively. This is mainly due to large amount of dense-graded fine aggregate and the fact that the coating and reinforcement effect of reticular fiber structure and structural asphalt of fine aggregate is superior to that of coarse aggregate; SMA-13 itself has good skeletal structure and mechanical property, so the enhancement effect is the secondary; OGFC-13 has large pores and large amount of coarse aggregate. The reinforcing and toughening effect of fiber and structural asphalt is the worst, so the enhancement effect of dynamic stability is the worst.

3.3 Low temperature performance

According to the requirements of the 3 point low-temperature trabecular bending test in the“Test Procedure for Asphalt and Asphalt Mixtures for Highway Engineering” (JTG E20-2011), the 30cm×30cm×5cm rut plate specimen is prepared using the above-mentioned gradation and oil-stone ratio with the rolling compaction method. After that, it is cut into the cuboid trabecular specimen with a length of 250mm ± 2.0mm, a width of 30mm ± 2.0mm and a height of 35mm ± 2.0mm. The trabecular specimen is placed the in a constant temperature cabinet at -10°C for 4 hours and then the MTS tester is used to conduct the three-point cold trabecular bending test at the loading speed of 50 mm/min. The indicators of bending failure strain εB, bending failure strength RB and stiffness modulus SB are used to evaluate the low temperature performance of concrete, which can be calculated using the following formula:

$$R_B = \frac{3LP_B}{2bh^2}$$
$$\varepsilon_B = \frac{6hd}{L^2} \quad (2)$$
$$S_B = R_B / \varepsilon_B$$

In the formula: b is the mid-span cross-section width of the trabecular specimen; h is the mid-span cross-section height of the trabecular specimen; L is the span of the trabecular specimen; PB is the failure load of the trabecular specimen; d is the failure deflection of the trabecular specimen.
The test results are shown in Table 5:

Table 5: Low temperature bending test results

Mixture type	Fiber content/%	Disrupt the strain /×10^{-3}	Destruction strength /MPa	Stiffness modulus /MPa
AC-13	0	2.713	10.24	3774.42
	0.3	3.791	12.67	3342.13
SMA-13	0	3.045	11.57	3799.67
	0.3	4.208	14.18	3369.77
OGFC-13	0	2.537	9.65	3803.71
	0.3	3.381	10.86	3212.07

From the above table, it can be seen that the failure strain and failure strength of the three-point low temperature bending test of the asphalt mixture with the addition of fiber have both increased and the stiffness modulus at the time of failure has decreased. The superior sequence of the failure strength and stiffness modulus of the mixture before and after the addition of fiber is SMA-13>AC-13>OGFC-13. This is mainly because the larger the pore of the mixture and the larger amount of coarse aggregate, the more uneven the internal structure. Therefore, more cracks are more likely to appear; the porosity of the OGFC-13is the largest among these three types of mixture and SMA has the optimal skeleton structure. It also shows that the asphalt mixture with the addition of fiber can effectively improve its low temperature performance, improve the crack resistance of asphalt roads and extend the service life of asphalt roads.

3.4 Water stability

According to the speciation of the “Test Procedure for Asphalt and Asphalt Mixtures for Highway Engineering” (JTG E20-2011), the immersion Marshall test and freeze-thaw splitting test are used to study the water stability of fibers-reinforced asphalt mixture. In order to study the reinforcing effect of fibers, the 0 and 0.3% of fiber content is selected as for comparison:
(1) Immersion Marshall Test
The standard Marshall specimens which are molded on both sides of each specimen with 75 strokes are selected. One set of specimens is placed in a 60°C water bath for 48 hours. The field group is placed in a 60°C water bath for 30 minutes. The stability of two groups of are tested immediately after being taken out. At the same time, formula (3) is sued to calculate the stability of immersion residual stability:

$$MS_0 = \frac{MS_3}{MS} \times 100 \quad (3)$$

Table 6: Immersion Marshall test results

Mixture type	Fiber content/%	Standard stability/kN	Immersion Marshall stability/kN	stability/%
AC-13	0	7.8	6.7	85.9
	0.3	9.1	8.4	92.3
SMA-13	0	11.5	10.2	88.7
	0.3	12.8	11.6	90.6
OGFC-13	0	5.5	4.7	85.5
	0.3	6.3	5.7	90.5

In the formula: MS0 is the immersion Marshall residual stability and MS1 is the immersion Marshall stability. The specific test results are shown in Table 6:

From the above table, it can be seen that the standard stability, the immersion Marshall stability and the immersion residual stability of the asphalt mixture all increase after the addition of the fiber, which are all are above 90%, indicating that the fibers-reinforced asphalt mixture has good water stability.

4. Conclusion

The addition of fibers to the asphalt mixture can play a role in adsorption, stabilization and “reinforcement”. From improving road performance of the mixture, huge number of fibers are randomly distributed in three dimensions in asphalt concrete, forming spatial network structure in the asphalt mixture. The load on the asphalt mixture can be transmitted to the fiber through the fiber asphalt interface. Due to the high modulus and high tensile strength characteristics of the reinforcing fibers, it can play a reinforcement effect in the asphalt mixture similar to that of rebar, improving the functional performance of the mixture. The fiber has a very small diameter and a large specific surface area and the addition into the asphalt mixture can form a spatial network structure and form a structural asphalt on its surface, which can play a role of adsorption, stabilization and reinforcement” and improve the road performance of mixture. The indoor experiment shows that adding 0.3% of fiber can effectively improve the high temperature performance, low temperature performance and water stability performance of the asphalt mixture and the enhancing effect of fiber material on the road performance of dense-graded concrete material is the most significant. In actual projects, the compaction degree and road surface performance of the fiber asphalt concrete road can meet the requirements, which is suitable for constructing asphalt roads.

Although there are many theoretical theories about the performance enhancement mechanism of fibers-reinforced asphalt mixture, the improvement mechanism for different asphalt mixture is not the same. Therefore, the improvement mechanism of different fibers still needs to be treated differently and new improvement theories should be actively explored through rigorous experiments.

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