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Evaluation of Biomass Solid Waste as Raw Material for Preparation of Asphalt Mixture

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ABSTRACT

At present, the resource utilization of solid waste in China is facing prominent problems such as high production intensity, insufficient utilization, and low added value of products. The preparation of biomass composites from biomass solid waste and plastic solid waste reduces not only environmental pollution and energy consumption but also promotes the high-value utilization of solid waste. So, the characterization and preparation experiments of samples with two different biomass are carried out. The wheat straw fiber and corn straw fiber were added into the bio-asphalt mixture with the content of 0.1%, 0.2%, 0.3%, and 0.4%, respectively, with the content of 9% and 12% bio-heavy oil. The physical properties and rheological properties of asphalt were analyzed and evaluated by three indexes and a dynamic shear rheological test. Through the rutting test and immersion Marshall test, high-temperature performance and biological asphalt mixture's water stability were evaluated. The results show that straw fiber can improve bio-asphalt mixture's road performance, especially the performance of high-temperature rutting. When the fiber content of bio-asphalt with 9% bio-heavy oil content is 0.3%, the physical properties and rheological properties of bio-asphalt are the best. Corn straw fiber's influence on bio-asphalt mixture was better than that of wheat straw fiber.

INTRODUCTION

The development of the circular economy is to reduce raw material consumption and carbon emissions from the source and the whole process. It is an important path and support to achieving carbon peak and carbon neutralization. To improve the processing and utilization level of renewable resources, there is an urgent need to break through several key common technologies of green recycling in the fields of comprehensive utilization of bulk solid wastes and high-quality recycling of renewable resources. At present, China's urban and rural areas produce 6.3 billion tons of organic waste such as agricultural waste and urban waste every year, which are largely treated by landfill and incineration, and the energy utilization rate is less than 5%. Therefore, improving the resource utilization level of waste has significant environmental, social, and economic benefits. Adopting innovative technology to improve the resource utilization level of waste, while controlling pollution, and transforming waste into high-value-added resources and products, in line with the concept of circular economy, is an important research direction to solve waste pollution. In this paper, typical biomass solid waste is used as raw material to prepare asphalt mixture to improve the resource utilization level of biomass solid waste. In recent years, scholars have done a lot of research on the application of waste biomass to road asphalt materials (Hill et al. 2013, Fini 2013, Yang et al. 2014, Zhang et al. 2014, Gai et al. 2015.

Yang et al. (2003) found that the porous structure of lignin fibers can improve its absorptivity to asphalt, showing high residual stability and improving water damage resistance. At the same time, fiber adsorption increases the bonding ability of asphalt and plays a role in reinforcement in asphalt concrete, and the lubricating ability is weakened. Therefore, the anti-rutting performance of the fiber-asphalt mixture is improved, and it is pointed out that the fiber-asphalt has a good application prospect. Peng (2005) also added lignin fibers into the asphalt mixture. It showed that when the optimum dosage is 0.25% to 0.4%, the adsorption capacity of the mixture to asphalt increased slightly due to the increase of the specific surface area of the fiber after pretreatment, and it also better mechanical properties and stronger water stability in the Marshall test and water stability test. The fiber skeleton network composed of complex interlaced wood fibers increases the strength and stiffness, elasticity deformation restorability, and tensile strength of the mixture, and improves low-temperature crack resistance and the high-temperature anti-rutting resistance of the mixture greatly. Based on an understanding of the basic technical properties of cotton stalk fiber, Lei et al. (2016) studied the proportioning design of cotton stalk fiber AC-13 and SMA-13 asphalt mixture. Ma et al. (2020) evaluated the effects of modified KTLG2 and KTLF1 composite fibers on the road performance of asphalt mixtures. The test results showed that cotton straw fiber improved low-temperature crack resistance and the high-temperature performance of the asphalt mixture significantly, and the composite fiber's water stability greatly improved. Lv (2001) pointed out that the type of fiber will affect the properties of the asphalt concrete mixture, but wood fiber will only increase the amount of asphalt in the SMA-type mixture, and cannot play a role in internal reinforcement. Gao et al. (2008) incorporated basalt fiber and lignin fiber into SMA asphalt mixtures and measured the performance of the two fiber asphalt mixtures through the Cantabro abrasion test, leakage test, water stability, and rutting test. The results showed that basalt fiber can significantly improve asphalt concrete's water stability and was better than lignin fiber, but significantly worse than basalt fiber in terms of bonding and tackifying effect. Because lignin fiber has a large specific surface area, its adsorption capacity and strength to asphalt are better than those of basalt fiber. Fu and Chang (2020) used a composite reinforcing agent composed of high polymer and lignin fiber to improve the asphalt mixture's road performance and prepared three graded asphalt mixtures of AC-13, AC-16, and AC-20. The results showed that when the optimal dosage of the composite reinforcing agent is 1.0%, the improvement effect of the high and low-temperature performance is remarkable.

Above all, scholars have made some achievements in the study of bio-asphalt and fiber-asphalt mixtures respectively, but there are few studies on bio-asphalt fiber-asphalt mixtures. So, this paper adopts bio-asphalt with bio-heavy oil accounting for 9% and 12% of the matrix asphalt respectively. The mixing ratio is designed through the AC-13 type mineral grading, and the wheat straw and corn straw fibers with the mineral mass fraction of 0.2%, 0.3%, and 0.4% are added respectively. Bio-asphalt's physical and rheological properties are analyzed and evaluated through three major indexes and dynamic shear rheological tests. Through the rutting test and water immersion Marshall test, the high-temperature performance and biological asphalt's water stability as an asphalt mixture are evaluated. These provide the bio-asphalt straw fiber asphalt mixture's application as a reference.

MATERIALS AND METHODS

The Raw and Processed Materials

The Matrix Asphalt

The test selects 70# asphalt as the research object (after this referred to as matrix asphalt), and the technical index of asphalt is shown in Table 1.

Biomass Heavy Oil

In the experiment, waste biomass, including wheat and corn straw is used as raw material to undergo high-temperature cracking in a high-temperature cracking furnace. And then the waste is obtained by distillation, oxidation, and other treatment processes. It is solid, black, and brown and lighter than traditional petroleum asphalt at room temperature. The technical index of bio-heavy oil is shown in Table 2.

Table 1: Technical index of asphalt.

Technical indicators	Technical requirements	Test results
Penetration [25°C, 5s, 100 g]/[0.1 mm]	60~80	62
penetration index PI	-1.5 ~ + 1.0	-1.27
Softening point [°C]	≥ 46	47.1
Ductility [10°C, 5 cm.min^{-1}]	≥ 15	36
Ductility [15°C, 5 cm.min^{-1}]]	≥ 100	> 100
Residues after TFOT		
Weight changing [%]	-0.8 ~ + 0.8	-0.158
Residual needle penetration ratio (25°C), [%]	≥ 61	61.4
Residual ductility [10°C]	≥6	6.3

Table 2: The technical index of bio-heavy oil.

Technical indicators	Density [g.cm^{-3}]	Lighting [^{o}C]	Viscosity [Pa.s^{-1}]
Test result	0.899	240	121

Table 3: The oil absorption result of fiber.

Fiber type	Fiber [mass.g^{-1}]	Mixture [mass.g^{-1}]	oil absorption rate [%]
Wheat straw	10.0	14.87	48.7
Corn stover	10.0	14.21	42.1

Table 4: Mass heat loss percentage of fiber under constant temperature heating.

Temperature [°C] Fiber type	120	140	160	180
Wheat straw	6.2	7.4	8.1	8.3
Corn stover	5.4	6.3	7.5	7.6

Basic Technical Properties of Straw Fiber

In the experiment, wheat and corn straws were selected, and fiber materials were obtained by mechanical crushing, and then dried and screened. According to the test standard, the average length of the fiber satisfies is <6mm, the oil absorption rate is >5%, and the pH is between 6.5 and 8.5. The oil absorption and heat resistance of the two fibers were evaluated by the dropping test and the constant temperature heating test, respectively.

Oil Absorption

Using the dropping test, we weighed 10 g of the asphalt, put it on the mesh basket, and then, slowly poured the molten asphalt, and placed it at 160°C for 30 min. Then we weighed the fiber and asphalt mixture to determine the oil absorption rate. The oil absorption results of the two kinds of straw fibers are shown in Table 3.

Heat Resistance

Using the constant temperature heating test, the two fibers were set in an oven for 2 h at 50°C, and 10 g of the two samples were weighed and set in an oven at 120°C, 140°C, 160C, and 180°C for 5 h. By measuring the absorption of two kinds of straw, the mass heat loss percentage of fiber under constant temperature heating is shown in Table 4.

The oil absorption and heat resistance of the fiber meets the requirements.

Technology Properties of Aggregate

Thick and fine matrix materials are all from limestone, and the ore powder is finely ground limestone. After testing, all indicators meet the specification's requirements. Fig. 1 shows the AC-13 asphalt mixture gradation.

Preparation of Bio-Asphalt

Heat the matrix asphalt to the molten state, and the biomass heavy oil was mixed into the matrix asphalt according to 9% and 12% proportion of the total matrix asphalt at 130°C and 2000 R/min, and prepare the biological asphalt after mixing for 20 min under the action of the high-speed shear instrument.

Test Method

Physical Property Test

The basic physical characteristics of asphalt are represented by its three indexes, ductility, penetration, and softening point, which also indicate its flexibility, temperature sensitivity, heat resistance, and other characteristics. The test is conducted to determine the ductility, penetration degree, and the composite modified asphalt's softening point according to the Test Rules for Highway Engineering Asphalt and Asphalt Mixture (JTG E20-2011).

Dynamic Shear Rheological Test

To analyze asphalt's dynamic viscoelasticity, the instrument model MCR302&CR102 dynamic shear rheological instrument is selected for the test. The shear rheological test was carried out in the temperature control mode, where the loading frequency was 1.59 Hz, the temperature was controlled between 40 and 80°C, the type of the parallel plate is PP25, and the spindle is 1 mm.

Pavement Performance Tests

According to the asphalt mixture's design method, the Test Rules for Highway Engineering Asphalt and Asphalt Mixture (JTG E20-2011), Marshall test, rutting test, and immersion Marshall test are carried out to evaluate asphalt mixture's road performance.

RESULTS AND DISCUSSION

Physical Performance

The ductility and penetration of bio-asphalt are higher

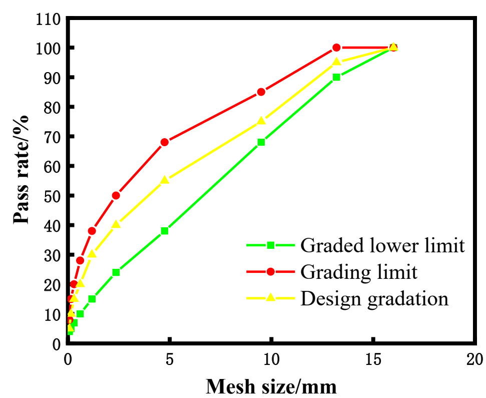

Fig. 1: Marshall grading.

Table 5: Physical performance test results.

Technical indicators Heavy oil content [%]	Penetration [25°C, 5 s, 100 g]/[0.1 mm]	Softening point [°C]	Ductility [10°C, 5cm. mm^{-1}]
9%	11.78	49.3	121
12%	12.05	45	133

compared to matrix asphalt, as shown in Table 5's three key indexes. It shows that bio-asphalt's low-temperature performance is significantly better than that of matrix asphalt. The main reason is that with the addition of the light components in heavy oil, the asphalt becomes softer gradually, but the high-temperature performance and shear failure resistance are weakened. Considering the utilization rate and performance of bio-heavy oil, two levels of bio-asphalt of 9% and 12% were finally selected to prepare the asphalt mixture.

Rheology Performance

As shown in Fig. 2, with the temperature's increasing, the asphalt's fluidity rises, and the composite shear modulus of the three asphalts decreases. The variation trends of the three asphalt phase angles are the same, and the viscoelastic properties of the bio-asphalt with 9% heavy oil content are more similar. As shown in Fig. 3, the rutting resistance of 12% bio-asphalt is worse than that of matrix asphalt, and the rutting resistance of 9% bio-asphalt is a little stronger than that of matrix asphalt.

Pavement Performance

Bio-asphalt with 9% and 12% bio-heavy oil content was comprehensively selected from the aspects of utilization and performance. The asphalt mixture's optimum oil-to-stone ratio is 5.2% to laboratory experiments' results. Under the above conditions, wheat and corn straw fiber were added at 0.2%, 0.3%, and 0.4% of the total mass of aggregate and mineral powder, respectively, and the road performance test was carried out.

Marshall Test

Fig. 4 and Fig. 5 show Marshall stability and flow values results. When the level of bio-asphalt was the same, the stability of the mixture gradually improved with the increase of wheat and corn straw fiber content. If the fiber content is the same, the effect of the two types of fibers on the stability and flow value is close to the same, but the corn stover fiber is slightly stronger than the wheat stover fiber. The addition of straw fibers forms a stiffening structure inside, which enhances the bearing capacity of the bio-asphalt mixture. The flow value of 0.3% fiber content becomes

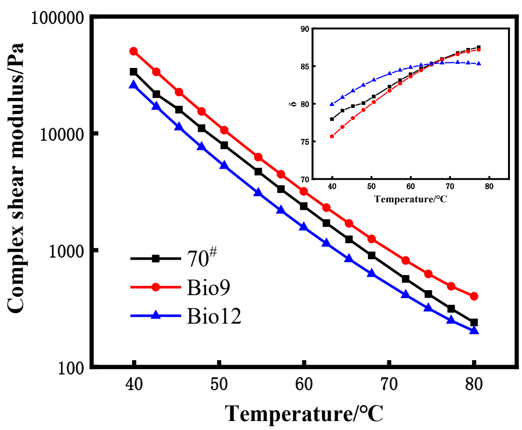

Fig. 2: Relationship between complex shear modulus, δ, and temperature.

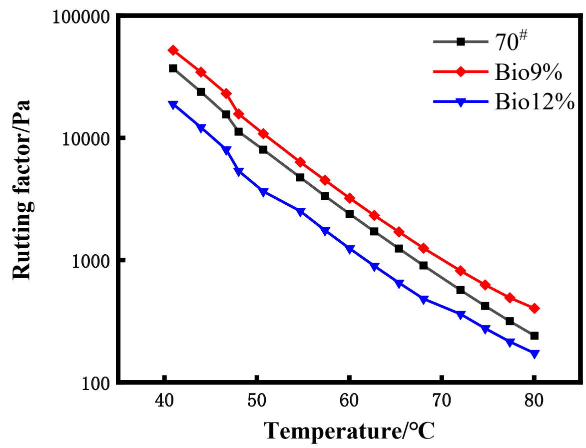

Fig. 3: Relationship between rutting factor and temperature.

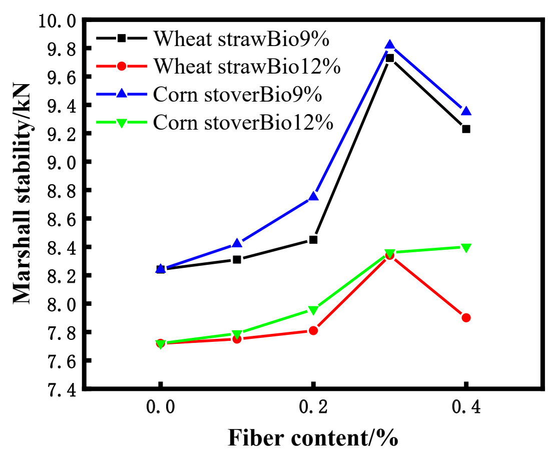

Fig. 4: Marshall stability test results (kN).

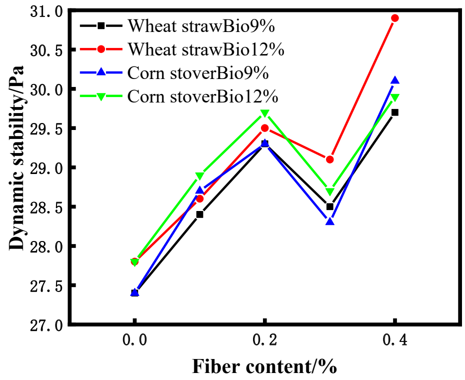

Fig. 5: Flow value test results (0.1mm).

smaller, which may be due to the strong adsorption of fiber to asphalt, which enhances the deformation resistance of the bio-asphalt mixture. While the fiber content is 0.4%, the Marshall stability decreases, and the flow value increases. It shows that the breaking strength of the asphalt mixture under high-temperature conditions decreases, and the deformation increases during failure. This conclusion is consistent with the article (Ma et al. 2019).

Rutting Test

According to JTG E20-2011, the mixture's high-temperature performance was evaluated by the rutting test. As shown in Fig. 6 and Fig. 7, with the fiber content's rise, the bio-asphalt's dynamic stability at the same level is enhanced, the relative deformation is also gradually reduced, and the rutting resistance of the mixture is enhanced. Among them, under the condition of 9% heavy oil level bio-asphalt, 0.3% and 0.4% wheat straw fiber content can improve the dynamic stability of the mixture by 14.6%, 16.2%, 22.3%, and 20.3%. Under the condition of 12% heavy oil level bio-asphalt, 0.3%, 0.4% wheat straw fiber content can improve the mixture's dynamic stability by 24.3%, 26.2%, and 39.6%. Although the fiber improves the dynamic stability of the bio-asphalt mixture with 12% bio-heavy oil content significantly, its overall value is low. This indicates that the two kinds of straw fibers can enhance the asphalt mixture's high-temperature performance and make up for the poor high-temperature performance of bio-asphalt. This conclusion is consistent with the optimal result of 0.3% fiber content in Li et al. (2019). There are two main reasons why straw fiber can improve high-temperature stability. First, the presence of fibers will adsorb "free asphalt", which increases the "structural asphalt" in the mixture. Structural asphalt binds aggregates in the mixture to form skeleton support, which enhances the ability of asphalt pavement to resist deformation. Second, the corn stalk fibers obtained by crushing and extraction are of different lengths, dispersed in the mixture to build a network constitution, and overlapped with each other. When the pavement is under load, the fiber can play the role of transmitting the load and preventing the structural damage caused by the stress concentration (Li et al. 2019).

Immersion Marshall test

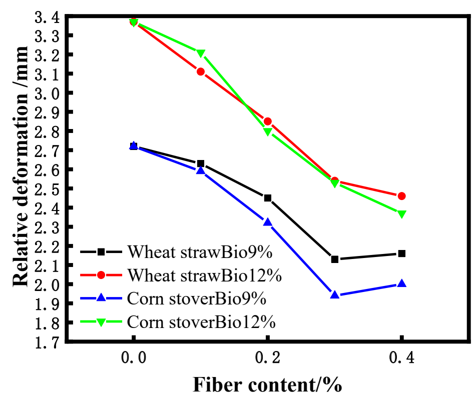

Fig. 7: Relationship between relative deformation and fiber content.

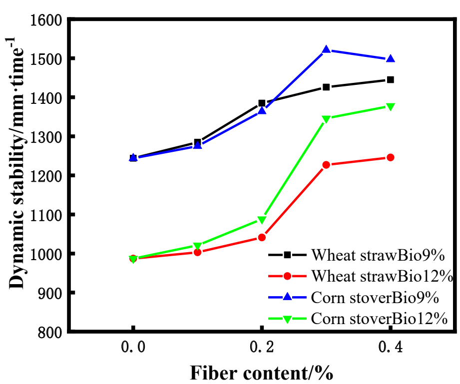

Fig. 6: Relationship between dynamic stability and fiber content.

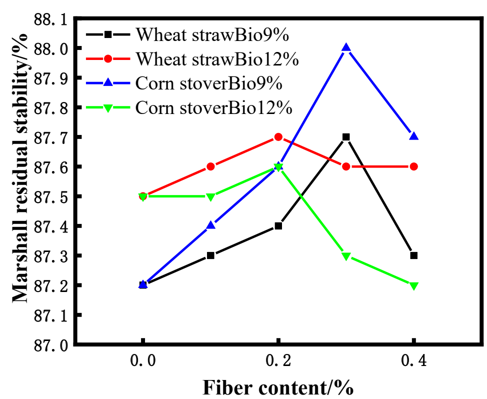

Fig. 8: Relationship between immersion Marshall test and fiber content.

The water immersion residual stability of the Marshall specimen is calculated by the the following formula and the results are shown in Fig. 8.

$$MS_0 = MS_1/MS$$

In the formula:

MS_0 - Specimen immersion residual stability (%)

MS_1 - Immersion residual stability in 48h (kN)

MS - Immersion residual stability in 30 min

Bio-heavy oil significantly improves the asphalt mixture's water stability, and the straw fibers' addition can also improve asphalt mixtures' water stability. However, fiber content above 0.3% will make the bio-asphalt mixture's water stability worse. The conclusion that the bio-asphalt mixture's water stability is enhanced is consistent with Zhu et al. (2020). The bio-asphalt mixture with 9% bio-heavy oil content has the largest residual stability value when the corn stover fiber content is 0.3%. This indicates that corn stalk fiber's water stability enhancement effect on bio-asphalt mixture is better than that of wheat stalk fiber.

CONCLUSION

Taking biomass solid waste as the main raw material, this paper develops high value-added green biomass asphalt mixture, realizes the high-value utilization of solid waste, reduces solid waste environmental pollution and energy consumption, and gives full play to the negative carbon effect of biomass, which is conducive to the national goal of carbon peak and carbon neutralization. The conclusions of this paper are as follows:

(1) Considering the physical properties and rheological properties of bio-asphalt, the bio-asphalt's high-temperature performance is poor, and its mixture cannot meet the requirements of road use. However, the addition of straw fibers can improve the bio-asphalt mixture's road performance, especially the high-temperature rutting resistance. Combining the effects of two kinds of straw fibers on the high-temperature performance and bio-asphalt mixture's water stability, the effect of corn straw fiber on the bio-asphalt mixture's road performance is greater than that of wheat straw fiber.

(2) Considering the performance of bio-asphalt and straw fiber mixture's road performance, it is suggested that the content of bio-heavy oil should be about 9% and the content of corn straw fiber between 0.3% and 0.4%.

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