Comparative Study on Asphalt Mixtures for the Surface Course of Semi-rigid Base Pavements of High-grade Highways

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Abstract: This study focuses on the surface course of semi-rigid base pavements of high-grade highways. Three types of asphalt mixtures are designed and compared: traditional lignin-fiber SMA-13, AC-13, and basalt-fiber SMA-13. Starting from aspects such as material selection, mix proportion design, and performance testing, the applicability of different types of asphalt mixtures is comprehensively evaluated. Through experiments, the physical and mechanical properties of these mixtures are analyzed, their stability under different environmental conditions is assessed, and their cost-effectiveness is compared. The experimental results show that basalt-fiber SMA-13 performs excellently in terms of high-temperature stability, low-temperature crack resistance, and water-damage resistance, and its optimal asphalt content is significantly lower than that of lignin-fiber SMA-13. The economic benefit analysis indicates that AC-type asphalt mixtures have an obvious price advantage. However, in the long run, due to its excellent performance and lower material cost, basalt-fiber SMA-13 may be more economical. This study provides a scientific basis for the design, construction, and maintenance of semi-rigid base pavements. Meanwhile, while ensuring pavement performance, efforts are made to reduce the overall construction cost, achieving a win-win situation of economic and social benefits.

Keywords: Semi-Rigid Base; Lignin Fiber; Basalt Fiber; SMA Asphalt Mixture

1. Introduction

With the rapid development of China's economy, the construction of expressways and urban roads has been accelerating. The semi-rigid base pavement structure has been widely applied in road engineering due to its good mechanical properties and economic benefits [1-5]. However, during long-term use, it has been found that semi-rigid base pavements are prone to problems such as reflective cracks, water damage, and fatigue failure. These issues seriously affect the service life of the road and driving comfort [6-9].

The increasing road traffic load poses higher requirements for the pavement structure [10-11]. The materials need to be able to withstand greater loads and more frequent stress cycles. Environmental factors such as high temperature, low temperature, and moisture have a significant impact on the performance of pavement materials, demanding good adaptability and weather resistance. With the continuous emergence of new materials and technologies, new challenges have been raised for the performance of traditional asphalt mixtures. It is necessary to find better material solutions through research.

This study will focus on the performance characteristics of asphalt mixtures, starting from aspects such as material selection, mix proportion design, and performance testing, to comprehensively evaluate the applicability of different types of asphalt mixtures. The physical and mechanical properties of different asphalt mixtures will be analyzed, the stability of the mixtures under different environmental conditions will be evaluated, and the cost-effectiveness of different mixtures will be compared, including material costs, construction costs, and maintenance costs. The purpose of this study is to provide a scientific basis for the design, construction, and maintenance of semi-rigid base pavements. At the same time, by paying attention to the economy of the pavement structure, efforts are made to reduce the overall construction cost while ensuring pavement performance, achieving a win-win situation of economic and social benefits.

2. Design of Surface Course Mixtures

For the surface course of semi-rigid base pavements of high-grade highways, this study designed three types of asphalt mixtures: traditional lignin-fiber SMA-13, AC-13, and basalt-fiber SMA-13. Basalt was selected as the aggregate, and SBS modified asphalt was used. All the raw materials used in the experimental research were qualified materials from actual engineering projects. The design process adhered to the relevant standards and requirements of the "Technical Specifications for Construction of Highway Asphalt Pavements" (JTG F40-2004), and the test methods followed the "Test Procedures for Asphalt and Asphalt Mixtures" (JTG E20-2011). The specific experimental results are shown in Table 1 and Table 2:

Table 1. Gradation Proportions of Asphalt Mixtures

Gradation Items	Aggregate Specification					
	11-18mm	6-11mm	3-6mm	0-3mm	mineral powder	fiber
SMA-13 (lignin fiber)	35	40	/	14	11	0.3
SMA-13 (basalt fiber)	35	37	/	16	12	0.4

Table 2. Volume Index of Asphalt Mixtures

test index	lignin fiber SMA-13	basalt fiber SMA-13	AC-13
Asphalt content, %	5.9	5.1	4.9
Maximum Theoretical Density, g/cm^3	2.631	2.656	2.674
Bulk Volume Density, g/cm^3	2.531	2.543	2.559
Voids Volume (VV), %	3.8	4.3	4.3
Stability, kN	11.89	11.08	12.8
Schellenberger Bitumen Drain-down Test	0.07	0.07	/
Cantabro Abrasion Test	6.7	5.9	/

3. Performance Analysis of Surface-Layer Asphalt Mixtures

The physical and mechanical properties of the three mixtures were studied through high-temperature stability, low-temperature crack resistance, and water-damage resistance. Corresponding tests were carried out to explore the advantages and application scenarios of different mixtures in terms of their respective performances.

3.1 High-Temperature Performance

he high-temperature performance is generally evaluated by the rutting test. This test simulates the anti-deformation ability of asphalt mixtures when they are under repeated loading at high-temperature conditions. Under the condition of 60°C, the deformation of the test specimens is measured after a certain number of load cycles. As shown in Figure 1.

From the rutting test, it was found that SMA asphalt mixtures exhibit excellent high-temperature performance, making them more suitable for high-grade highways. Compared with lignin-fiber SMA asphalt mixtures, basalt-fiber SMA asphalt mixtures have even better high-temperature performance. In SMA asphalt mixtures, lignin fibers mainly play the roles of reinforcement and asphalt absorption. The advantage of lignin-fiber SMA asphalt mixtures lie more prominently in their fatigue-resistance performance, and the function of asphalt absorption is crucial. Basalt fibers have a relatively low oil-absorption rate and mainly provide reinforcement in asphalt mixtures. Due to their excellent tensile strength and anti-aging properties, basalt-fiber SMA asphalt mixtures have higher high-temperature stability.

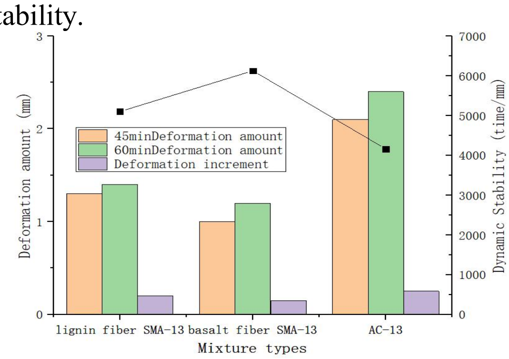

Figure 1. Results of the Rutting Test for Asphalt Mixtures

3.2 Crack Resistance

The low-temperature performance is evaluated through the beam bending test. The test specimens undergo three-point bending at-10°C until fracture, and the strain value at the moment of fracture is recorded. The specific experimental results are shown in Figure 2:

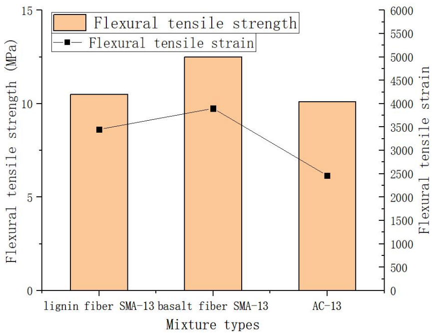

Figure 2. Results of the Bending Test for Asphalt Mixtures

Through the low-temperature beam bending test, it was found that the AC-13 asphalt mixture has a lower asphalt content, so its low-temperature performance is inferior to that of SMA. Although the asphalt content of the basalt-fiber SMA asphalt mixture is significantly lower than that of the lignin-fiber SMA asphalt mixture, due to the material properties of basalt fibers, the basalt-fiber SMA asphalt mixture exhibits more excellent flexural-tensile strength, and at the same time, it has a larger flexural-tensile strain. Therefore, the addition of basalt fibers can effectively improve the modulus and elastic deformation ability of the asphalt mixture.

3.3 Water Damage Resistance

The water damage resistance is evaluated through the freeze-thaw splitting test. The specimens first undergo a certain number of freeze-thaw cycles in a water-saturated state, and then a splitting test is carried out to measure the strength ratio after splitting. The main focus is to study the damage to the internal structural strength of the water-retaining mixture caused by frost heave after the freeze-thaw cycle. The specific experimental results are shown in Table 3.

Table 3. Results of Freeze-Thaw Splitting Test for Asphalt Mixtures

Type of mixture	Splitting strength after freeze-thaw cycles RT2 (MPa)	Splitting strength without freeze-thaw cycles RT1 (MPa)	Freeze-thaw splitting strength ratio TSR (%)	Technical specifications
lignin fiber SMA-13	0.80	0.91	87.91	≥80
basalt fiber SMA-13	0.85	0.99	85.86	
AC-13	0.97	1.17	82.9	

Through the freeze-thaw splitting test, it was found that among the three types of asphalt mixtures, in terms of the freeze-thaw splitting strength ratio, the order is lignin-fiber SMA > basalt-fiber SMA > AC-13. Moreover, all three types of asphalt mixtures meet the relevant technical requirements in the specification JTG F40-2004. As the asphalt content increases, the water-damage resistance of the asphalt mixture is significantly enhanced.

When comparing the freeze-thaw splitting strengths of various types of asphalt mixtures, the AC asphalt mixture without fiber addition has a lower asphalt content, resulting in relatively less asphalt mastic. However, its splitting strength is higher. When comparing the SMA asphalt mixtures with fiber addition, due to the relatively lower asphalt content in the basalt-fiber SMA asphalt mixture and the obvious reinforcement effect of basalt fibers, its anti-splitting strength is superior to that of the lignin-fiber SMA asphalt mixture.

4. Economic Benefit Analysis of Surface-Layer Asphalt Mixtures

Evaluate the material costs of different mixtures and their long-term economic benefits. The material cost analysis will consider the costs of asphalt, aggregates, mineral powder, and fiber reinforcement materials. The long-term economic benefit analysis will be based on the time of appearance of reflective cracks, the attenuation of the fatigue performance of asphalt mixtures, the maintenance of anti-skid performance, and the life-cycle cost. Through comprehensive evaluation, it will provide a basis for proposing the mixture scheme with the highest economic benefit.

4.1 Mixture Cost Analysis

Analyze the material costs of different surface-layer asphalt mixtures. This includes investigating the market prices and consumption of SBS modified asphalt, aggregates, mineral powder, and fiber reinforcement materials. By calculating the unit cost of these materials, we will obtain the total material cost of each mixture. Since the construction cost does not vary significantly among different mixtures, this paper will focus on the comparison of material costs to evaluate the initial economic investment of different mixtures. The market research on various material prices is shown in Table 4.

Table 4. Prices of Raw Materials for Asphalt Mixtures

Material Name	Unit Price, ¥/t
Basalt Coarse Aggregate	220
Basalt Fine Aggregate	100
Asphalt	4100
Mineral Powder	200
Lignin Fiber	5000
Basalt Fiber	8000

By using the prices of raw materials obtained from the above market research and calculating according to the corresponding mix ratios, the cost of SMA-13 (lignin fiber) is 457.90 ¥/t; the cost of SMA-13 (basalt fiber) is 439.50 ¥/t; and the cost of AC-13 is 382.20 ¥/t. The AC type asphalt mixture has an obvious price advantage, followed by the basalt fiber asphalt mixture. The main price difference between the basalt fiber and lignin fiber asphalt mixtures is 32.8 ¥/t.

4.2 Long-term Economic Benefit Analysis of Mixtures

This section focuses on discussing the long-term economic benefits of mixtures, which involves the performance maintenance and maintenance costs of mixtures during actual use. It is necessary to evaluate the time when reflective cracks appear on the semi-rigid base layer and analyze the impact of different mixtures on delaying the appearance of cracks. Based on the results of fatigue tests, the attenuation of fatigue performance and anti-skid performance of mixtures will be explored, and their service lives will be predicted. By combining the initial material costs and long-term maintenance costs, a comparative analysis of the full life-cycle costs will be carried out.

Combined with previous engineering experience and relevant research at home and abroad, reflective cracks will appear on semi-rigid base asphalt concrete pavements within 3-5 years. Therefore, preventive maintenance will be required once cracks occur. If preventive maintenance is not carried out in a timely manner, the cracks will inevitably develop into diseases such as base layer loosening, such as slurry accumulation, and then progress to potholes and other diseases in the asphalt surface layer. The main advantage of conventional lignin fiber SMA asphalt mixtures lies in their excellent high-temperature performance and fatigue resistance. However, most SMA asphalt mixtures on highways do not take advantage of their fatigue resistance and will face major and medium repairs. The advantage of basalt fiber SMA asphalt mixtures is their excellent high-temperature stability and crack resistance. When applied to semi-rigid base asphalt pavements, they can delay the development of reflective cracks, and at the same time, the material cost of asphalt mixtures is also lower than that of lignin fiber SMA-13.

AC asphalt mixtures belong to the suspended dense structure, and their texture depth is usually 0.5-0.7mm, while the texture depth of SMA asphalt mixtures is usually 1.8-1.2mm, which is significantly higher than that of AC asphalt mixtures. Some studies have shown that the texture depth of AC asphalt mixtures decays faster under vehicle loads. Therefore, although the high-temperature performance can be improved by adding high-viscosity and high-elastic asphalt, its anti-skid performance decays rapidly, making it unsuitable for the surface layer of high-grade highways.

5. Conclusion

(1) Basalt fiber SMA-13 shows a lower optimum asphalt content in the mix design, and at the same time, it is comparable to lignin fiber SMA-13 in various mechanical properties, indicating its potential advantages in material cost and performance.

(2) Basalt fiber SMA-13 is superior to lignin fiber SMA-13 in terms of deformation resistance, flexural tensile strength, and flexural tensile strain under high-temperature conditions. The water damage resistance of all three mixtures meets the technical specifications, but the water damage resistance of AC-13 is relatively poor.

(3) The material cost analysis reveals that AC-type asphalt mixtures have an obvious price advantage. From the perspective of long-term economic benefits, basalt fiber SMA-13 may have higher economic efficiency in practical applications due to its excellent performance and lower material cost. Using basalt fiber SMA-13 in the surface layer of semi-rigid base pavements of high-grade highways can achieve the optimal balance between performance and economic benefits.

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