Effect of Fibers on the Performance of a Porous Friction Course

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ABSTRACT: In this paper, the preparation of a porous friction course (PFC) with styrene–butadiene–styrene (SBS)-modified asphalt and fibers instead of a high-viscosity-modified asphalt was investigated. The aggregate gradation B was chosen to prepare the PFC, and the optimal asphalt content in the PFC containing lignin or basalt fibers was determined to be 4.5% by the Cantabro abrasion experiment and Schellenberg draindown experiment. The freeze-thaw split experiment and immersed Marshall experiment indicated that with the addition of the fiber, the residual stability increased by 7.6 and 2.4% for the PFC with the lignin and basalt fibers, respectively, indicating that fibers can enhance the moisture damage resistance of the PFC. Furthermore, the dynamic stability increased by 17.9 and 6.0% for the PFC with the lignin and basalt fibers, respectively, indicating that fibers can significantly enhance the rutting resistance of the PFC at high temperatures. These results prove that the PFC prepared by SBS-modified asphalt and lignin/basalt fibers reaches the standard of pavement performance.

1. INTRODUCTION

Over the past 20 years, new materials, structures, and technologies have been widely used in highway construction, especially some new pavement materials, such as the porous friction course (PFC), an excellent road material. The PFC is a kind of open-graded bitumen mixture with a higher proportion (18–25%) of internal air voids (AVs), which can also bring enough consecutive voids to supply higher permeability in case of subsurface drainage. The residual water on the PFC asphalt pavement surface can be removed through the high proportion of AVs, enhancing the wet weather visibility and safety and reducing the noise of the pavement.1,2 Therefore, the PFC is also known as a draining asphalt pavement, porous wearing course, open-graded friction course, and so forth. Since the advent of the PFC, it has been most commonly used in the United States, Europe (Germany, France, and the Netherlands), and Asia (China, South Korea, and Japan) for decades.3

Scientists have conducted a lot of theoretical research on the PFC via discrete element method simulations. Hu et al. evaluated the effect of the traffic level on AV reduction of the specimen and found that the coarse aggregates in realistic shapes were rebuilt as virtual aggregates and established a three-dimensional coarse aggregate database with physical and mechanical parameters by discrete element method simulations.4 The results offer a path to predict AV degradation of the double-layer PFC with traffic loading, which is beneficial to the design of the PFC. Zhu et al. studied the aggregate structure of the PFC of the gradation-based framework and found aggregate structure parameters by discrete element method simulations.5 If these studies can be combined with more laboratory tests, it will be more illustrative. Therefore, this paper focuses on the PFC laboratory test.

Due to its high percent of AVs, low strength, and poor durability, the PFC is usually prepared with an asphalt binder with an outstanding performance, for example, a tafpack-super (TPS)-modified asphalt binder with high viscosity and elasticity. However, this kind of asphalt binder is very expensive, which restricts the popularization and application of the PFC to some extent. In our previous study, we found that the ordinary styrene–butadiene–styrene (SBS)-modified bitumen can meet the technical standard of a highly viscous bitumen binder by adding the rational fiber.6,7 The PFC has less fine aggregates but more coarse aggregates, and the specific surface area of aggregates is relatively small, which results in the drain of the bitumen binder due to gravity during storage, transportation, and pavement. First, adding the fiber to the SBS-modified asphalt binder enhances the material strength, antifatigue, and ductility due to its inherent compatibility.8 Second, the fiber can provide a high surface area which is beneficial for the adsorption...
of more asphalt; as a result, it can stabilize asphalt to prevent it from leaking during pavement construction. More importantly, the SBS-modified asphalt–fiber mixture is much cheaper than the TPS-modified asphalt binder. However, few studies are found on the SBS-modified bitumen mixed with the fiber based on the literature review. Following up on our recent studies on pavement materials, we propose a novel strategy for the rational design of the PFC with SBS-modified asphalt and a rational fiber instead of a highly viscous asphalt binder to reduce the construction cost. In this paper, the aggregate gradation, AVs, and optimal asphalt content (OAC) were determined to prepare the PFC with the lignin or basalt fiber, and then, the mixture was evaluated by the immersed Marshall experiment, freeze-thaw split experiment, and high-temperature rutting experiment to find the water stability and pavement performance at high temperatures. This study not only opens new avenues for the application of SBS-modified bitumen and the fiber in the PFC at low costs but also sheds light on the popularization and application of the PFC.

## 2. RESULTS AND DISCUSSION

### 2.1. Target AVs

The excellent drainage performance of the PFC is mainly realized by its larger AV, and the water permeability is generally characterized by the permeability coefficient. The permeability coefficient of the PFC is linearly correlated with the AV, and relatively speaking, more AVs mean a larger permeability coefficient and better water permeability. However, more AVs can cause a decrease in the high-temperature stability, water stability, and mechanical properties of the PFC. Therefore, a suitable AV is the key factor affecting the performance of the PFC. Considering the heavy load of vehicles and large amount of rainfall in South China, the PFC was designed according to JTG F40-2004, which had an AV of 18–20%.

### 2.2. Initial Mineral Aggregate Gradation

The asphalt mixture is made of asphalt and a suitable proportion of fillers, fine aggregates, and coarse aggregates, and these components are in accordance with the prescribed mineral aggregate gradation. The performances of asphalt mixtures vary greatly with different mineral aggregate gradations. According to the requirements of the standard mineral aggregate gradation in specification JTG F40-2004, the PFC was prepared, and the mineral aggregate gradations are shown in Table 1.

A large number of studies have shown that the percentage passing for a sieve size of 2.36 mm has a great influence on the AV of the PFC; therefore, the percentage passing for a sieve size of 2.36 mm was chosen as the characteristic change point in this paper. Based on some successful projects, three initial mineral aggregate gradations were designed with different percentage passings for a sieve size of 2.36 mm, and the curves of three different mineral aggregate gradations were obtained and are shown in Figure 1.

## Table 1. Mineral Aggregate Gradations of the PFC

| sieve size/mm | 10–15 mm/% | 5–10 mm/% | 0–3 mm/% | mineral powder/% | gradation A | gradation B | gradation C | range/% |
|---------------|------------|-----------|----------|------------------|-------------|-------------|-------------|--------|
| 16            | 100        | 100       | 100      | 100              | 100.0       | 100.0       | 100.0       | 100    |
| 13.2          | 85         | 100       | 100      | 100              | 93.3        | 93.3        | 93.3        | 90–100 |
| 9.5           | 25         | 99.7      | 100      | 100              | 66.1        | 66.1        | 66.2        | 60–80  |
| 4.75          | 3.2        | 8.2       | 99.3     | 100              | 21.5        | 25.8        | 28.5        | 12–30  |
| 2.36          | 1.5        | 1.1       | 55.1     | 100              | 10.5        | 12.8        | 15.2        | 10–22  |
| 1.18          | 1.2        | 0.9       | 27.4     | 100              | 7.0         | 6.5         | 8.4         | 6–18   |
| 0.6           | 1.1        | 0.9       | 20.8     | 100              | 6.0         | 5.5         | 6.8         | 4–15   |
| 0.3           | 1.0        | 0.9       | 14.9     | 99.8             | 5.0         | 4.5         | 5.3         | 3–12   |
| 0.15          | 1.0        | 0.8       | 12.6     | 99.2             | 4.6         | 4.1         | 4.7         | 3–8    |
| 0.075         | 0.8        | 0.7       | 10.7     | 93.8             | 4.1         | 3.6         | 4.1         | 2–6    |
| gradation A   | 45         | 38        | 15       | 2.0              | 100         |             |             |        |
| gradation B   | 45         | 38.5      | 15       | 1.5              | 100         |             |             |        |
| gradation C   | 45         | 30        | 24       | 1.0              | 100         |             |             |        |

### Figure 1.

Mineral aggregate gradation profiles of the PFC.
is 14 μm, as shown in other literature. After calculation, the initial asphalt contents of three initial mineral aggregate gradations A, B, and C are \( P_A = 4.1\% \), \( P_B = 4.3\% \), and \( P_C = 4.5\% \), respectively.

2.4. Final Mineral Aggregate Gradation. Based on the results obtained above, the asphalt-aggregate ratios of the three initial mineral aggregate gradations A, B, and C are calculated, and the results are 4.3, 4.5, and 4.7%, respectively. Using the SBS-modified asphalt as a binder, we prepared standard Marshall specimens with 50 times double-sided compaction by the Marshall compaction method (specification T 0702-2011). The AVs of the specimens were calculated by the volume method via specification T 0708-2011 and are shown in Table 2.

Table 2. AVs for the PFC without Fibers

| gradations | asphalt-aggregate ratio/% | \( G_{\text{mm}} \) | \( G_{\text{mb}} \) | AV/% |
|------------|--------------------------|-------------------|-------------------|------|
| A          | 4.3                      | 2.624             | 2.064             | 21.3 |
| B          | 4.5                      | 2.611             | 2.131             | 18.4 |
| C          | 4.7                      | 2.599             | 2.169             | 16.5 |

According to the data in Table 2, the relationship between the percentage passing for a sieve size of 2.36 mm and the AV can be obtained, as shown in Figure 2. The AV of the PFC mixture decreases with the increase in fine aggregates. As discussed in the target AV, the desired AV of the PFC is in the range of 18–20%. Hence, only the mineral aggregate gradation B (AV = 18.4%, percentage passing for a sieve size of 2.36 mm = 12.8%) can meet the requirement. Subsequently, the mineral aggregate gradation B was selected to prepare the PFC for further research.

2.5. Target OAC. The Cantabro abrasion test and Schellenberg draindown test of different PFCs were conducted to calculate the initial bitumen content based on the optimal mineral aggregate gradation, and then, the OAC was determined. The Cantabro abrasion test results of the PFC with or without fibers are shown in Table 3. According to the specification, a Cantabro loss of less than 20% is desired. It can be seen that for the PFC without fibers, the Cantabro loss (C.L.) (21.3%) cannot meet the requirement, while for the PFC with 0.3 wt % lignin fibers or 0.35 wt % basalt fibers, the C.L. (14.2, 16.1%) can meet the requirement. Therefore, the addition of lignin/basalt fibers to the PFC can meet the design requirements in view of the Cantabro abrasion test. Meanwhile, for both PFCs with lignin/basalt fibers, the asphalt-aggregate ratio is 4.5%.

Table 3. Cantabro Abrasion Results of Different PFCs

| PFC               | asphalt-aggregate ratio/% | \( G_{\text{mm}} \) | \( G_{\text{mb}} \) | AV/% | C. L./% |
|-------------------|---------------------------|-------------------|-------------------|------|---------|
| no fiber          | 4.5                       | 2.611             | 2.131             | 18.4 | 21.3    |
| lignin fiber      | 4.5                       | 2.609             | 2.100             | 19.5 | 14.2    |
| basalt fiber      | 4.5                       | 2.617             | 2.100             | 19.7 | 16.1    |

According to the optimal mineral aggregate gradation, the Schellenberg draindown test of PFCs with the lignin/basalt fibers was carried out, and the results are shown in Table 4.

Table 4. Schellenberg Draindown Test Results of the PFC with Fibers

| PFC               | lignin fiber | basalt fiber |
|-------------------|--------------|--------------|
| asphalt-aggregate ratio/% | 4.5          | 4.5          |
| draindown/%        | 0.11         | 0.13         |

According to the specification, a Schellenberg draindown of less than 0.3% is desired. It can be seen that for PFCs with 0.3 wt % lignin fibers or 0.35 wt % basalt fibers, the Schellenberg draindown (0.11%, 0.13%) can also meet the requirement, indicating that the introduction of lignin/basalt fibers to the PFC meets the design requirements in view of the Schellenberg draindown experiment. Therefore, a conclusion can be drawn that an initial bitumen binder content of 4.5% can meet both the requirements of the Cantabro abrasion test and the Schellenberg draindown test. Thus, the bitumen binder content was determined to be 4.5% and will be used for the following tests.

2.6. Moisture Sensitivity of PFCs with the Lignin/Basalt Fibers. The moisture damage in bitumen pavements is the reduction of the adhesion between the aggregate and bitumen binder under the action of wheel dynamic loads or in the presence of water, especially the freeze-thaw and frost heave effect of water in the freezing winter. The water stability of the PFC refers to the ability of the aggregate and asphalt binder to resist the spalling of the asphalt film caused by moisture damage. In addition to the rainfall and heavy load of vehicles, the antimoisture damage ability of the bitumen mixture is the fundamental factor in the water stability of the PFC. Compared with the dense-graded asphalt pavement, surface water is discharged from the internal structure of the PFC mixture, which makes moisture damage more likely to occur and requires higher water stability. Many methods are established to test the water stability of the PFC mixture, including the immersed Marshall experiment and freeze-thaw splitting experiment. The immersed Marshall experiment can find the antispalling ability of the bitumen mixture when it is damaged by water to test the water stability of the PFC mixture, which is suitable for evaluating the water stability of PFC asphalt mixtures thoroughly.

Figure 3 shows the results of the immersed Marshall experiment for residual stabilities of PFC bitumen mixtures, and the results indicate that the Marshall residual stabilities of these PFC bitumen mixtures meet the requirements of the specification. Furthermore, with the addition of fibers, the residual stability increased to 7.6 and 2.4% for PFCs with the lignin and basalt fibers, respectively, indicating that fibers can enhance the moisture damage resistance of the PFC bitumen.
mixture. Meanwhile, the water stability of the PFC bitumen mixture was also effectively enhanced with the introduction of different fibers. The reason is that the adsorption of fibers can improve the thickness of the bitumen film coated on the aggregate surface and greatly reduce the erosion damage of water to the asphalt mortar, enhancing the resistance of the asphalt mortar to damage from the natural environment. Simultaneously, a better adhesion between the asphalt and fiber improves the load-carrying ability of the bitumen−fiber binder, which also reduces the possibility of moisture damage of the asphalt pavement.\textsuperscript{13–27} Since the proportion of structural asphalt in PFCs with the lignin/basalt fibers increases with the incorporation of fibers, the interfacial effect between the structural asphalt and aggregate increases, which enhances the water stability of the PFC bitumen mixture.

The freeze-thaw splitting experiment of the PFC with or without fibers was carried out, and the results are shown in Figures 4 and 5. The tensile strength of the PFC with or without fibers is shown in Figure 4. The tensile strength of the PFC increases with the introduction of the fiber, and it can be ranked in the following decreased order: lignin fiber (0.57, 0.44 Mpa) > basalt fiber (0.56, 0.39 Mpa) > no fiber (0.49, 0.31 Mpa). After the freeze-thaw cycling test, the PFC asphalt mixtures showed a sharp decrease in the tensile strength, for example, 36.7, 30.4, and 22.8% for PFCs without fibers and with the basalt fiber and the lignin fiber, respectively. The fibers can effectively hinder the decrease in tensile strength of the freeze-thawed PFC, and the lignin fiber shows a better hindrance effect than the basalt fiber. In the splitting test, the internal sample is mainly subjected to tensile stress, and the splitting tensile strength of the sample is mainly defined by the bond of the asphalt binder and the friction between mineral aggregates. The reinforcement of the fiber can enhance the cohesion between aggregates and even the cohesion between bitumen and the aggregate, thereby improving the antislipping ability of the PFC bitumen mixture. Since the pores of the PFC asphalt mixture were filled with water, it could freeze and induce volume expansion at $-18$ °C, which resulted in a frozen-heave stress to the pores of the PFC asphalt mixture and the expansion of the pores and even the original cracks. As the temperature rose, ice melted into water, which further weakened the adhesion between bitumen and the aggregate. Therefore, after freeze-thaw cycles, the tensile strength reduced. The number of AVs of the PFC with basalt fibers (21.0%) is higher than that of the PFC with lignin fibers (19.6%), which results in a higher frozen-heave stress to the pores of the PFC with basalt fibers, resulting in a less excellent hindrance effect than that with lignin fibers. The higher the tensile strength ratio (TSR) is, the more difficult the asphalt binder is to peel off from the PFC mixture when it meets water, that is to say, a better water stability.\textsuperscript{13} With the introduction of fibers to the PFC, the TSR increased, for example, from 63.3 to 69.6% and 77.2%, as shown in Figure 5, indicating the improvement effect of fibers on the water stability of the PFC. Meanwhile, lignin fibers showed a better improvement effect on the water stability than basalt fibers.

2.7. High-Temperature Performance. Figures 6 and 7 show results of the rutting experiment for different PFCs, and the results indicate that the Marshall dynamic stabilities (DSs) of these PFC bitumen mixtures can reach the standard of the PFC specification. As shown in Figure 6, due to the introduction of different fibers, the DSs of PFC bitumen mixtures increase,
indicating that fibers enhance the rutting resistance of the PFC bitumen mixture at high temperatures. Furthermore, the DS of the PFC with lignin fibers increased by 17.9% compared with that of the PFC without fibers, while the DS of the PFC with basalt fibers increased by only 6.0%, indicating the better improvement effect of lignin fibers on the DS than that of basalt fibers. Meanwhile, with the addition of fibers, the deformation rate of PFC asphalt mixtures decreased, as shown in Figure 7, that is, 14.3% or 7.1% for the PFC with lignin or basalt fibers, suggesting a more excellent hinder effect of lignin fibers on the deformation rate than that of basalt fibers.

Figures 6 and 7 show that with the introduction of different fibers, the DSs of PFC asphalt mixtures increased sharply, whereas the deformation rate decreased significantly, and the improvement in the PFC containing lignin fibers is better than that in the PFC containing basalt fibers. The lignin fiber is made up of ribbons with porous and relatively flat cross sections, and many lignin filaments are torn apart, giving rise to the small increase in surface area. The surface area of the lignin fiber is more than 10 times higher than that of the basalt fiber, which is only 0.13 m$^2$/g, as shown in Table 10. The microstructure of the basalt fiber is different from that of the lignin fiber due to the quite round cross sections with a smooth surface texture and smaller surface area. The surface properties can account for the higher efficiency of the lignin fiber in binding bitumen. It can be seen that the introduction of fibers can improve the PFC pavement resistance to rutting at high temperatures. The reasons are as follows: the fiber dispersed in bitumen can absorb bitumen over the surface to form a monolayer, leading to a powerful bond between the “fiber–bitumen” interfacial layers and a three-dimensional interconnected framework. The framework will not be destroyed at high temperatures, which brings a thick mastic coating without bitumen draining down. Meanwhile, both lignin fibers and basalt fibers can absorb the light fraction in bitumen, increasing the viscosity of the bitumen binder. Hence, the fiber can enhance the shear strength of the bitumen binder. Furthermore, the higher tensile strength of fibers can wrap more bitumen and prevent flowing and crack propagation more significantly. It is also noted that the introduction of the fiber improves the high-temperature performance of the PFC bitumen mixtures.

2.8. Mechanism of the Fiber Modifier in the PFC. Scanning electron microscopy (SEM) can be used to find the surface morphology and other information of the sample; hence, the microstructures of the lignin fiber and the basalt fiber were detected using a Hitachi S-4800 SEM instrument with an accelerating voltage of 5 kV. The SEM images of these samples are shown in Figure 8.

The difference in the fiber microstructure leads to the different adsorption capacities of bitumen. SEM images indicate that the basalt fiber is regular cylindrical with a smooth surface. The basalt fiber presents a lower specific surface of 0.13 m$^2$/g, resulting in a weaker bitumen adsorption capacity. By contrast, the microstructure of the lignin fiber is flocculent, irregular, and rough, and the specific surface area can reach 1.8 m$^2$/g. These characteristics make it coat more bitumen and increase the thickness of the bitumen film. Therefore, it can improve the optimal asphalt–aggregate ratio in the bitumen mixture, enhancing the pavement performance.

The different surface properties of fibers bring about the physical property difference of the bitumen mortar. Regarding the fiber–bitumen mortar as the organic–inorganic hybrid, the difference can also be reflected in the rheology. In order to study the influence of the fiber on the rheological properties of the bitumen mortar, the dynamic shear rheometer test was carried out, and the procedure was performed as reported. The results are shown in Figures 9 and 10. Compared with those of the pure
bitumen mortar (no fibers), the rutting factor increases while the phase angle decreases in the fiber—bitumen mortar, indicating that the addition of the fiber improves the high-temperature stability of the bitumen mortar. Meanwhile, different fibers have different improvement effects on the high-temperature rheological properties of the bitumen mortar, and the lignin fiber presents a better improvement effect than the basalt fiber. More importantly, the phase angle of the lignin fiber—bitumen mortar decreases obviously, suggesting that the lignin fiber has an obvious effect on the elastic components in the bitumen mortar. The fiber can improve the high-temperature rheological properties of the bitumen mortar through its tackifying effect to a certain extent.

The adsorption of bitumen to the fiber is related to the surface property of the fiber. A higher absorption capacity of bitumen means more bitumen in the mixture. After fully contacting with the fiber, the adsorbed bitumen can produce physical infiltration and adsorption on the fiber surface to form a solid bitumen interface layer, which improves the adhesion of bitumen and the consequent rutting resistance of the bitumen pavement. The interface energy between the fiber and bitumen can reach a maximum only when they are fully infiltrated, and a new phase is formed at the interface with a reduction in the surface Gibbs free energy. Generally, there are three adsorptions between the fiber and bitumen: physical adsorption, selective adsorption, and chemical adsorption. When bitumen is in the liquid state, the temperature is high. Then, the fiber is inserted in bitumen, and selective adsorption and physical adsorption are strong, while the chemical adsorption is weak. The stronger the fiber adsorption capacity, the higher the bitumen mixture stability.

The fiber absorption capacity of bitumen can be evaluated as reported by our group at 170 °C, and the results are shown in Table 5. The adsorption of bitumen to the fiber is related to the surface property of the fiber, and a higher absorption capacity of bitumen is beneficial for reducing the flushing and segregation of the bitumen mixture at high temperatures. Table 5 shows that the maximum mass of bitumen adsorbed by the lignin fiber is 9 times its own weight, indicating a higher absorption capacity and stabilization of bitumen. By contrast, the value of the basalt fiber is 6, slightly lower than that of the lignin fiber. The result is related to the larger specific surface area of the lignin fiber. When bitumen is in the liquid state, adsorbed bitumen over the fiber can infiltrate the fiber and form an interface layer which has a great impact on the absorption capacity of bitumen to the fiber.

Adding fibers into the PFC can not only improve its high temperature performance but also improve its water stability. The reinforcement mechanism of fibers on the PFC can be summarized as follows.

1. The fiber can adsorb a large amount of bitumen, which increases the content of bitumen in the mixture and the thickness of the bitumen film wrapped over the aggregate. The fiber can also enhance the adhesion between bitumen and the aggregate while reducing the immersion of water in the interface between bitumen and the aggregate, thus increasing the water damage resistance of the bitumen pavement. The reinforcing effect of the fiber can enhance the adhesion between bitumen and the aggregate and improve the self-healing ability. After water immersion, the damage of the PFC is reduced, while the residual stability and the splitting resistance are improved.

2. The large specific surface area of the fiber can accommodate more light component in bitumen, thus increasing the viscosity and adhesion of bitumen. Meanwhile, the physical and chemical adsorption, diffusion, and bonding between bitumen and the fiber increase the thickness of the bitumen film, which produces a strong interfacial effect between the fiber—bitumen and aggregate and thus effectively enhance the rutting resistance of the PFC at high temperatures.

3. When the PFC cracks under the external force, the uniformly dispersed fibers play the role of “bridging” and “crack resistance”, thus effectively preventing the expansion of cracks. Meanwhile, they could also resist aggregate sliding at the interface, allocate stress, and reduce stress concentration, thereby improving the integral strength of the PFC.

4. A brittle fracture will occur at low temperatures if bitumen has a much higher viscosity. However, due to the higher modulus and extension deformation, the fiber possesses strong extensibility and effective stress distribution and crack resistance, which makes it still maintain a strong toughening effect at low temperatures and will not be broken when the pavement cracks.

3. CONCLUSIONS

In this paper, the preparation of the PFC with SBS-modified bitumen and lignin or basalt fibers instead of high-viscosity-modified bitumen was investigated. The immersed Marshall experiment and freeze-thaw split experiment results indicated that with the addition of fibers, the residual stability can be increased by 7.6 and 2.4% for PFCs with the lignin and basalt fibers, respectively, indicating that fibers can enhance the moisture damage resistance of the PFC. The reinforcing effect of the fiber can enhance the adhesion between bitumen and the

Table 5. Adsorption to Bitumen of Different Fibers

| Fiber      | Test | $m_{drained}/g$ | $m_{ads-or-bitumen}/g$ | $m_{ads-or-basalt}/g$ | $m_{wrapped-bitumen}/g$ | Multiple |
|------------|------|-----------------|------------------------|-----------------------|------------------------|----------|
| Lignin fiber | 1    | 4.1             | 40.0                   | 0.2                   | 35.7                   | 8.7      |
|            | 2    | 4.0             | 40.1                   | 0.1                   | 36.0                   | 9.0      |
| Basalt fiber | 1    | 4.2             | 40.2                   | 10.8                  | 25.2                   | 6.0      |
|            | 2    | 4.1             | 40.1                   | 11.2                  | 24.8                   | 6.0      |
aggregate and improve the self-healing ability. After water immersion, the damage of the PFC is reduced, while the residual stability and the splitting resistance are improved. Furthermore, the DS increased by 17.9 and 6.0% for PFCs with the lignin and basalt fibers, respectively, indicating that both fibers can enhance the rutting resistance of the PFC at high temperatures. The physical and chemical adsorption, diffusion, and bonding between bitumen and fibers increase the thickness of the bitumen film, which produces a strong interfacial effect between the fiber–bitumen and aggregate and thus effectively enhance the rutting resistance of the PFC at high temperatures.

4. EXPERIMENTAL SECTION

4.1. Experimental Materials. 4.1.1. Bitumen. The bitumen binder used in this paper is ordinary SBS-modified asphalt. Based on “technical specification for the construction of highway asphalt pavement” (specification JTG F40-2004) and actual engineering requirements, the physical properties of SBS-modified asphalt were checked, and the results are presented in Table 6.

| Table 6. Physical Properties of Ordinary SBS-Modified Asphalt |
|---------------------------------------------------------------|
| items | result | specification |
| 25 °C penetration/dmm | 55 | GB/T 4509 |
| softening point/°C | 78.5 | GB/T 4507 |
| 5 °C ductility/cm | 24 | GB/T 4508 |
| 60 °C viscosity/Pa.s | 15,506 | GB/T265 88 |
| TFOT mass loss/% | <0.12 | GB/T 5304 |
| TFOT retained penetration ratio/% | >80 | GB/T 4509 |
| 5 °C ductility/cm | 16 | GB/T 4508 |

4.1.2. Aggregates. The mineral aggregates, including fine aggregates and coarse aggregates used in this paper, are made in Zhangjiakou, China, and the physical properties are shown in Tables 7 and 8. It can be seen that the physical properties of aggregates meet the technical standard of specification JTG F40-2004, indicating that they can be used in the pavement.

| Table 7. Physical Properties of Zhangjiakou Mineral Fine Aggregates |
|---------------------------------------------------------------|
| items | 0–3 mm | requirement | specification |
| sand equivalent/% | 98 | ≥60 | GB/T 0334 |
| ruggedness (>0.3 mm)/% | 7 | ≤12 | GB/T 0340 |
| mud content (<0.075 mm)/% | 2.1 | ≤3 | GB/T 0333 |
| apparent specific gravity | 2.78 | ≥2.50 | GB/T 0328 |
| methylene blue value/g/kg | 5.7 | ≤25 | GB/T 0349 |

| Table 8. Physical Properties of Zhangjiakou Mineral Coarse Aggregates |
|---------------------------------------------------------------|
| items | 10–15 mm | 5–10 mm | requirement | specification |
| crushing value/% | 14.3 | 14.3 | ≤26 | GB/T 0316 |
| Los Angeles abrasion loss/% | 19.2 | 19.2 | ≤28 | GB/T 0317 |
| apparent specific gravity | 2.92 | 2.95 | ≥2.60 | GB/T 0304 |
| water absorption/% | 1.39 | 1.49 | ≤2.0 | GB/T 0304 |
| flat and elongated particle content/% | >9.5 mm | 6.1 | ≤12 | GB/T 0312 |
| | <9.5 mm | 6.0 | ≤18 | GB/T 0312 |
| | <0.075 mm | 0.3 | ≤1 | GB/T 0310 |

4.1.3. Mineral Powder. The mineral powder used in asphalt mixtures must be grounded with a hydrophobic rock, such as a strong basic rock like a limestone or magmatite. The mineral powder used in this paper is the Zhangjiakou limestone powder, and the physical properties are shown in Table 9. It can be seen that the physical properties of the limestone powder meet the technical standard of specification JTG F40-2004, indicating that it can be used in the pavement.

4.1.4. Fibers. The fibers used in this paper are basalt fibers and lignin fibers, and their physical properties are shown in Table 10. Both of the fibers possess a high tensile strength. The combination of the fiber and asphalt mixture can produce a reinforcing and toughening effect and improve the tensile capacity, thus reducing the cracks, loose and broken pavement, and other problems. The length to diameter ratio of the fiber determines the bituminous mixture strength and pavement engineering. When the ratio is too low, the reinforcing and toughening effect cannot be fully realized. By contrast, agglomeration and knotting in the mixing process will occur when the ratio is too high, which produces a heterogeneous distribution of the fiber. As shown in Table 10, both ratios of the fibers are moderate and meet the pavement requirements. Moreover, the melting point of the fibers is higher than the mixing temperature of the asphalt mixture (175–185 °C). Hence, the two fibers used in this paper meet the pavement requirements.

4.2. Experimental Methods. 4.2.1. Specimen Preparation. In this paper, the mineral aggregate gradation for the PFC mixture, a most commonly used mixture in South China, was selected based on the specification JTG F40-2004. The mixture design includes the selection of mineral aggregate gradation and mixing of aggregates and bitumen with or without the fiber. The lignin/basalt fiber was added to the PFC bitumen mixture with a content of 0.3 wt%/0.35 wt%, respectively. The lignin/basalt fiber was mixed with the aggregate completely and then heated when the ratio is too high, which produces a heterogeneous distribution of the fiber. As shown in Table 10, both ratios of the fibers are moderate and meet the pavement requirements. Moreover, the melting point of the fibers is higher than the mixing temperature of the asphalt mixture (175–185 °C). Hence, the two fibers used in this paper meet the pavement requirements.

4.2.2. Air Void. The AV of the PFC asphalt mixture was obtained based on the specification JTG F40-2004. The maximum theoretical specific gravity (G_{mm}) of the uncompacted PFC bitumen mixture was measured via the vacuum saturation method and the bulk specific gravity (G_{mb}) of the compacted PFC bitumen mixture via the CoreLok method. Then, eq 3 was employed to calculate the AV.
Table 9. Physical Properties of the Limestone Powder

| items                   | results               | requirement | specification |
|-------------------------|-----------------------|-------------|---------------|
| bulk density/g/cm³      | 2.74                  | ≥2.50       | GB/T 0352     |
| water content/%         | 0.2                   | ≤1          | GB/T 0332     |
| particle size < 0.6 mm/% < 0.6 mm | 100               |             | GB/T 0351     |
| particle size < 0.15 mm/% | 97.7               | 90–100      | GB/T 0351     |
| particle size < 0.075 mm/% | 88.0               | 75–100      | GB/T 0351     |
| appearance              | no agglomeration      |             |               |
| hydrolipidic coefficient | 0.8                  | <1          | GB/T 0353     |
| plasticity index        | 2.1                   | <4          | GB/T 0354     |

Table 10. Physical Properties of the Lignin Fiber and Basalt Fiber

| items                   | lignin fiber | basalt fiber | specification |
|-------------------------|--------------|--------------|---------------|
| density/g/cm³           | 0.52–1.32    | 2.65–3.05    | ASTM D3800    |
| diameter/µm             | 12–15        | 13–16        | ASTM D2130    |
| length/mm               | 0.5–2.0      | 6.0          | ASTM D204     |
| surface area/m²/g       | 1.8          | 0.13         |               |
| melting point/°C         | <250         | 1600         | ASTM D276     |
| tensile strength/MPa     | 100–300      | 2500–3500    | ASTM D2256    |

\[ AV = \left(1 - \frac{G_{mb}}{G_{mm}}\right) \times 100\% \]  

(3)

4.2.3. Cantabro Abrasion Experiment. The Cantabro abrasion experiment was designed to characterize the raveling resistance of PFC mixtures as a result of the tire wear and environmental degradation. In this test, the compacted Marshall specimens were tested using the Los Angeles Abrasion machine at a speed of 33 rpm for 300 cycles according to the specification JTG E20 T 0733-2011. The loose mixture was removed, and the final weight of the sample was recorded. The percentage of weight loss, that is to say, the C.L. was calculated using eq 4. It is noted that the specimen with an OAC can possess C.L. no more than 20% of the unaged specimen.

\[ \text{C. L.} = \frac{A - B}{A} \times 100\% \]  

(4)

where C. L. is the percentage of Cantabro loss, %, and A and B are the initial and final weights of the specimen, respectively.

4.2.4. Schellenberg Draindown Experiment. The Schellenberg draindown experiment was used to test the draindown of the asphalt binder from the coarse aggregate skeleton of the PFC mixture during the storage and transportation. In this test, an ASTM wire basket, a Japanese criterion test pan, or a German and Chinese criterion beaker was generally used as the standard testing container. The Schellenberg draindown experiment procedure is done as reported, and the ASTM wire basket method is the most recommended.

The draindown test was performed according to the specification AASHTO T 283-14 and JTG E20 T 0729-2011. Prior to the test, the standard Marshall specimen was saturated in water after immersing in the water bath in vacuum for 15 min. Then, the saturated sample was put into a refrigerator at −18 °C for 16 h and finally transferred into the water bath at 25 °C for 2 h. The indirect tensile strength of the specimen was tested on a Marshall stability press at a rate of 50 mm/min. The tensile strength of the specimen was confirmed via the peak load and the specimen dimensions.

The freeze-thaw TSR is known as the ratio of the tensile strength of the water-conditioned specimen to that of the unconditioned specimen, and it can be calculated via eq 7. The TSR can be used as an indicator of water stability for the PFC bitumen mixture.

\[ \text{TSR} = \frac{S_2}{S_1} \times 100\% \]  

(7)

Here, \( S_1 \) is the average tensile strength of the unconditioned sample and \( S_2 \) is that of the conditioned sample.
The authors declare no competing financial interest.

\[ DS = \frac{42 \times 15}{d_{60} - d_{45}} \] (8)

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**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

Financial support from the National Natural Science Foundation of China (22078227), State Key Laboratory of Heavy Oil Processing (SKLOP201902005), Qing Lan Project of Jiangsu Province of China, Natural Science Foundation of Jiangsu Higher Education Institutions of China (22KBJB150040), Science and Technology Support Program (Social Development) of Taizhou (SSF20210021), and Research Foundation for Talented Scholars of Taizhou University (QD2016007 and QD2016012) is gratefully acknowledged.

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