Effects of Fiber Type on the Mechanical Properties of the Open-Graded Friction Course Mixture

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ABSTRACT: The open-graded friction courses (OGFCs) have a large number of interconnected voids, which may cause serious water damage to the pavement. Hence, the road performance needs to be investigated. In this study, the mechanical properties of OGFCs containing two different fibers (lignin and mineral fiber) were investigated. Based on the procedure proposed by the Chinese specification JTG F40-2004, OGFCs were designed with the asphalt content between 4.1 and 4.7 wt % to find the optimal asphalt content (OAC). The mesh-basket draindown test was used to check the fiber’s stabilization and absorption of bitumen. OGFCs containing the lignin/mineral fiber with OAC would be preferred in terms of the bulk specific gravity. These results indicate that the fiber can bring higher air voids to the OGFCs, and the different specific gravities of fibers may primarily account for the result. Both the lignin and mineral fibers can bring much more asphalts padded in the pores of mineral aggregates and subsequently larger OAC in OGFCs due to their higher asphalt absorption. Performance experiments were carried out to check the dynamic stability and moisture susceptibility of OGFCs containing the lignin/mineral fiber. The study suggests that the lignin and mineral fiber can be used to adjust the internal environment of OGFCs, enhancing the moisture damage resistance and improving the rutting resistance of OGFCs at high temperatures.

1. INTRODUCTION

Open-graded friction courses (OGFCs) are widely used to improve the pavement surface friction and permeability and even lower road noise. OGFCs mostly contain an open gradation, that is, more coarse aggregates with a little fine aggregates. Generally speaking, 50−60 wt % of the aggregate particles are almost of the same size. Moreover, OGFCs typically possess 2−5 wt % filler passing through a sieve of 0.075 mm to ensure a higher proportion (20%) of internal air voids (AVs), which can result in continuous porosity as well to guarantee the high permeability of subsurface drainage. The subsurface water is discharged via the high fraction of AVs in OGFCs, which can enhance the wet weather friction and visibility.

However, the combination of a low filler content and uniform graded aggregates of OGFCs can enable the draining of the bitumen binder via gravity during storage, transportation, and pavement, that is to say, the draindown. The phenomenon can lead to a slim bitumen binder coating that is insufficient to prevent aggregate particles from being detached under road load. To overcome the draindown of the bitumen binder, stabilizing agents such as lignin fiber and mineral fiber are used. In our previous study, we studied the reinforcement effect of different fibers on bitumen mortars comprehensively and found the mechanism. Fibers can disperse in the bitumen and adsorb it, generating a strong binding forced "structure-bitumen" interlayer and three-dimensional interconnected frameworks. Inspired by the reinforcement effect of fibers on bitumen mortars, we propose a novel strategy to overcome the draindown of OGFCs by adding a rational fiber. Meanwhile, the fibers bind the aggregate particles within the matrix tightly and prevent them from moving, which makes the mixture stiffer.

The fibers dispersed in asphalt can adsorb the light components, forming an asphalt interface layer with strong adhesion and a three-dimensional space network structure. Therefore, the close bonding of the fiber and asphalt mixture can produce

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reinforcing, toughening effects and a higher tensile capacity and reduce the occurrence of asphalt pavement cracks, loose crushing, and other diseases. Therefore, the use of fibers in OGFCs is not only to overcome the draindown but also to improve the rutting performance and moisture susceptibility.\textsuperscript{13}

A lot of theoretical studies on OGFCs through the discrete element method simulation has been carried out. Hu et al. proposed a new methodology (three-dimensional discrete element simulation) to evaluate the degradation of air voids in the double-layer porous pavement under traffic loading.\textsuperscript{15} The study provided useful information for pavement engineering in the design of porous asphalt pavement. Kusumawardani and Wong studied nine aggregate gradations with variations in 2.36–4.75 and 6.3–9.5 mm fractions by the discrete element method algorithmic simulations.\textsuperscript{15} If these studies were combined with more laboratory experiments, the results would be more fruitful. Hence, laboratory experiments of OGFCs were carried out in this study.

Accordingly, this study investigated the volumetric and mechanical properties of OGFCs containing the lignin/mineral fiber. The mixtures were designed based on the Chinese specification JTG F40-2004 to find the optimal asphalt content (OAC) in OGFCs containing the lignin/mineral fiber.\textsuperscript{16} The volumetric properties of the OGFCs containing the lignin/mineral fiber were tested via laboratory tests, and the moisture susceptibility and dynamic stability were also evaluated to check the effect of the lignin/mineral fiber on the critical pavement performance.

2. RESULTS AND DISCUSSION

2.1. Absorption and Adhesion Effects of Fibers on Bitumen. The fiber in OGFCs can adsorb the asphalt binder, changing its rheological behavior and the subsequent OAC in the mixture design, and plays a significant part in the formation of an interface bond between asphalt and the fiber.\textsuperscript{17,18} The draindown test results are presented in Table 1. OGFC containing the lignin fiber shows lower asphalt drop and separation, in other words, a higher asphalt absorption and stabilization than that containing the mineral fiber. The different surface areas and lengths can primarily account for this phenomenon, as shown in Table 2. Although the mineral fiber possesses a higher surface area, the smooth surface (Figure 1) with lubrication can result in a lower soaking function, leading to a much weaker absorption and stabilization effect on bitumen. Compared with mineral fiber, the lignin fiber has a loose texture, including a rough and porous surface and more lateral branches, which makes it preferable for the adhesion of bitumen. Therefore, it can absorb and stabilize part of bitumen. Due to adhesion and absorption to bitumen and a higher surface area, the improvement effect of the lignin fiber on bitumen draindown is better than that of the mineral fiber.

2.2. OAC. The OAC for OGFCs is determined based on the Marshall design procedure, and the result is shown in Figure 2. With the addition of the mineral/lignin fiber, the OACs of OGFCs increase, and they can be ranked in an increasing order as follows: OGFC without fiber (4.3 wt %) < OGFC containing the mineral fiber (4.4 wt %) < OGFC containing the lignin fiber (4.5 wt %). The result indicates that fibers require more bitumen to wrap the surface as a result of the high surface area and their absorption of light components in bitumen.\textsuperscript{16,19} Since the lignin fiber with a higher surface area is loose and cross-linked (Figure 1 and Table 2), OGFC containing the lignin fiber presents a higher absorption of asphalt than that containing the mineral fiber, as shown in Table 1.

2.3. Bulk Specific Gravity and AVs. The bulk specific gravity $G_{mb}$ was tested based on the Chinese specification JTG E20-2011, and the result is demonstrated in Figure 3. The $G_{mb}$ of OGFCs is ranked as follows: OGFC containing the mineral fiber > OGFC containing the lignin fiber > OGFC without fiber. Different OACs and specific gravities of fibers can primarily account for this result. Increase of OAC requires more compaction effort to obtain the same density because of the relatively lower specific gravity of bitumen than that of aggregates or reduction in the density of OGFC at the same compaction effort. The OGFC containing the lignin fiber possesses the highest OAC followed by that containing the mineral fiber. A higher OAC can result in a lower $G_{mb}$ with the same compaction effect. Thus, the $G_{mb}$ of OGFC containing the lignin fiber is lower than that of the OGFC containing the mineral fiber. Simultaneously, this shows that the $G_{mb}$ of OGFCs with OAC is slightly higher than those using a bitumen content of 4.3 wt % (i.e., 0.82%/0.76% higher for OGFCs containing the lignin/mineral fiber, respectively). A higher $G_{mb}$ is desired based on the Marshall design method. Therefore, OGFC containing the lignin/mineral fiber with OAC would be preferred in terms of the $G_{mb}$ value.

The fiber generally has a diameter of less than 20 $\mu$m and a considerable surface area, which can reach no more than 10 $m^2/g$. The fiber is dispersed in the bitumen homogeneously, and the larger surface area produces an interface with plenty of absorbed bitumen, which can bring an important effect on the AVs of OGFCs. The AVs of three OGFCs with different bitumen contents are presented in Figure 4. The result shows that the AVs in OGFCs decrease with the increase of the bitumen content. For OGFCs without the fiber, the AVs vary between 16.2 and 20.5%, while AVs can reach 21.5%/22.0% for OGFCs containing the mineral/lignin fiber, respectively. OGFC containing the lignin fiber possesses the highest AV, while OGFC without the fiber has the lowest AV. These results indicate that the fiber can show higher AV to the OGFC, and the different adsorptions of fibers may primarily account for the result.
2.4. Voids in Mineral Aggregates (VMA) and Voids Filled with Asphalt (VFA). VMA is an air void between the aggregates of the compacted pavement, including the space packed with bitumen, and it is the available space to hold bitumen and the volume of air voids.\textsuperscript{21,22} The aggregate gradation, mineral powder content, bitumen content, and compacting power can significantly affect VMA.\textsuperscript{23,24} Figure 5 presents the VMAs of OGFCs containing different fibers. The results show that the VMAs were slightly different among the three mixtures, which decrease with the increase of the bitumen content at the same aggregate gradation. As bitumen has a lubricating effect, the VMA decreased with a higher content of bitumen in the studied range.

As shown in Figure 6, the VFAs of OGFCs with OAC increase with the addition of the lignin/mineral fiber. The OGFCs containing the mineral fiber possess higher VFAs than those with the lignin fiber, and the higher VMAs of OGFCs containing the mineral fiber with OAC can account for the result. However, when using the same asphalt content as ordinary mixtures, VFAs of OGFCs reduce since the VMAs decrease with the addition of the lignin/mineral fiber according to eq 2.

In addition, asphalt mixtures with OAC obviously possess higher VFAs than those using the same bitumen content as ordinary mixtures, 30.2%/26.1% higher for OGFCs containing the lignin/mineral fiber. On the basis of the interlock adhesion theory, a very low VFA cannot bring sufficient asphalt binder to the voids in aggregate particles to obtain stable interface adhesion, resulting in interfacial failure between the aggregate...
surface and the asphalt film.\textsuperscript{25,26} Hence, the fiber-modified OGFC with OAC can induce a higher interface adhesion than that with the same bitumen fraction as ordinary mixtures.

2.5. Marshall Stability and Moisture Susceptibility. The addition of a fiber stabilizer to the OGFC is carried out to fully absorb the superficial and internal bitumen; consequently, the content of bitumen increases and the bitumen film thickens, which can enhance the durability of the OGFC. The results suggest that with the addition of the lignin/mineral fiber, the residual stabilities of OGFCs with OAC increase, as shown in Table 3, that is, 9.6%/3.8% increment for OGFCs containing the lignin/mineral fiber. Fibers can improve the bonding strength of bitumen and even the adhesion between bitumen and fillers. Due to the improvement of adhesion of the bitumen film, the adhesion between aggregates in OGFCs increases. From the view of mechanical properties, the Marshall residual stability of OGFCs is improved in performance.

Table 3 shows the results of the Marshall experiment for stability of OGFCs, and the results demonstrate that the Marshall residual stabilities of these OGFCs meet the requirements of OGFC-13 specification. With the addition of the lignin/mineral fiber, the Marshall residual stabilities of OGFCs increase, demonstrating the reinforcement effect of fibers on the moisture damage resistance. Furthermore, the water stabilities of OGFCs are also significantly enhanced with the addition of the lignin/mineral fiber. The reason lies in the adsorption of the fiber that increases the thickness of the asphalt film over the aggregate surface and greatly lowers the erosion damage of water to asphalt mortar. Hence, it enhances the resistance of the asphalt mortar to the natural environment. In addition, the adhesion between the fiber and asphalt is stronger than that between the filler and asphalt, which also cuts down the opportunity of moisture damage to asphalt pavement. Since the fraction of structural asphalt in OGFCs increases with the incorporation of the lignin/mineral fiber, the interfacial effect between structural asphalt and the aggregate increases, which enhances the water stability.

Freeze–thaw splitting evaluations of OGFCs containing different fibers were performed, and Table 4 presents the results. The tensile strength increased with the addition of fibers, and the lignin fiber showed the best improvement effect (0.64, 0.50 Mpa) on OGFCs followed by the mineral fiber (0.58, 0.43 Mpa), compared to the OGFC without fibers (0.51, 0.34 Mpa). After the freeze–thaw cycling evaluation, the tensile strength of OGFCs drastically decreased. For OGFCs containing no fiber, mineral fiber, and lignin fiber, the tensile strength reduced by 33.3, 25.9, and 21.9%, respectively. Hence, fibers significantly retard the reduction of tensile strength of freeze–thawed OGFCs. Compared to the mineral fiber, the lignin fiber presents a higher hinder effect. During the splitting evaluation, OGFCs are mainly subjected to tensile stress, and the splitting tensile strength of OGFCs is mainly defined by the bond of asphalt and the friction between mineral aggregates. Fibers can improve the cohesion between aggregates and even that between asphalt and the aggregate, therefore leading to the improvement of antisplitting of OGFCs. Water is filled in the pores of OGFCs, and it will

| OGFCs         | test       | tensile strength/MPa | TSR/% |
|---------------|------------|-----------------------|-------|
| no fiber      | unfreeze–thaw | 0.51                 | 66.7  |
|               | freeze–thaw  | 0.34                 |       |
| lignin fiber  | unfreeze–thaw | 0.64                 | 78.1  |
|               | freeze–thaw  | 0.50                 |       |
| mineral fiber | unfreeze–thaw | 0.58                 | 74.1  |
|               | freeze–thaw  | 0.43                 |       |

Table 3. Marshall Experiment Results for Stability of Different OGFCs

Table 4. Freeze–Thaw Splitting Test Results of Different OGFCs

Figure 4. AVs of OGFCs containing different fibers.

Figure 5. VMAs of OGFCs containing different fibers.

Figure 6. VFAs of OGFCs containing different fibers.
freeze and produce a great volume expansion at $-18^\circ$C. The expansion brings about a frozen-heave stress to the pores in OGFCs and even the formation of original cracks. With the temperature increase, the ice melts and it reduces the adhesion between asphalt and the aggregate. Consequently, after freeze−thaw cycles, the tensile strength is weakened. The freeze−thaw tensile strength ratio (TSR) is the ratio of the tensile strength of water-conditioned OGFCs to that of unconditioned OGFCs, and it is an indicator of water stability for OGFCs. A higher TSR means more difficulty of the asphalt to strip from the OGFCs when it is exposed to water, in other words, a higher water stability. As listed in Table 4, the addition of fibers increases the TSR of OGFCs by 7.4 and 11.4%, suggesting the improvement of the water stability of OGFCs. Moreover, the improvement of the lignin fiber is higher than that of the mineral fiber on water stability.

2.6. High-Temperature Performance. The results suggest that with the addition of the lignin/mineral fiber, the dynamic stabilities of all OGFCs with OAC increase, as illustrated in Figure 7, that is, 17.5%/5.8% increment for OGFCs containing the lignin/mineral fiber, and the following results were obtained.

![Graph showing dynamic stability of OGFCs containing different fibers.](image)

OGFCs containing the lignin/mineral fiber. In addition, with the introduction of fibers, the rate of deformation of OGFCs with OAC decreases, as illustrated in Figure 8, that is, 14.5%/7.3% decrease for OGFCs containing the lignin/mineral fiber. The reason is that the fiber has a large surface area to absorb the light component in asphalt; hence, the alkali active substances in the asphalt increase, and asphaltene also increases. As a result, the viscosity of the OGFCs is increased, and the adhesion becomes stronger. At the same time, due to the physical and chemical interactions between asphalt and the fiber, such as adsorption, diffusion, and chemical bonding, asphalt is distributed over the surface of the fiber as a single molecule layer, forming a “fiber−asphalt” interfacial layer with strong bonding strength. Therefore, in terms of high-temperature stability, the OGFCs containing the lignin/mineral fiber are much stronger than that without the fiber.

![Graph showing deformation rate of OGFCs containing different fibers.](image)

Figures 7 and 8 show the results of the rut experiment for OGFCs, and it can be seen that the Marshall dynamic stabilities of these OGFCs meet the requirements of the OGFC-13 specification. With the addition of the lignin/mineral fiber, the Marshall dynamic stabilities of OGFCs increase, indicating that fibers improve the high-temperature rutting resistance. As presented in Figures 7 and 8, the Marshall dynamic stabilities of OGFCs increase steeply with the addition of the lignin/mineral fiber whereas their deformation rates decrease. A better enhancement of lignin fiber is found compared to the mineral fiber. It can be seen that the addition of fibers enhances the pavement’s resistance to rutting at high temperatures. When the OGFCs are loaded, the pressure acts on the aggregate initially, and then it is transferred to the fiber through the interface between the fiber and OGFCs. Since the fiber has a higher tensile strength and stronger bonding strength with asphalt, it prevents the damage of asphalt under tension and shear. The fiber can evenly disperse the load into the mineral aggregate and asphalt mortar, acting as a reinforcing and bridging agent. Hence, the rutting resistance of OGFCs is significantly enhanced.

3. CONCLUSIONS

A comprehensive laboratory experiment was carried out to study the mechanical and volumetric properties of OGFCs containing the lignin/mineral fiber, and the following results were obtained.

1. With the introduction of the lignin/mineral fiber to OGFCs, the OAC can increase to 4.4 and 4.5 wt %, respectively. The result indicates that fibers require more asphalt to wrap the surface because of the high surface area and their absorption of light fractions in bitumen. Draindown experiment results suggested that OGFCs containing the lignin/mineral fiber efficiently retard the draindown of the mineral filler and binder.

2. A higher OAC can result in a lower $G_{mb}$ with the same compaction effect. Simultaneously, the $G_{mb}$ value of OGFCs containing fibers with OAC is slightly higher than that using a bitumen content of 4.3 wt %.

3. For the OGFCs without fibers, the AVs vary between 16.2 and 20.5%, while AVs can reach 21.5%/22.0% for OGFCs containing the lignin/mineral fiber, respectively. These results indicate that the fiber can bring higher AVs to the OGFC, and the different specific gravities of fibers may primarily account for the result.

4. The voids in the mineral aggregate of OGFCs increase. By contrast, the bulk specific gravity decreases. Meanwhile, both the lignin and mineral fiber can result in much more asphalts to be filled in the voids of mineral aggregates in OGFCs because of their higher absorption of asphalt.

5. With the addition of the lignin/mineral fiber, the Marshall residual stability and TSR of OGFCs increase, indicating that fibers can enhance the moisture damage resistance. The Marshall dynamic stabilities of OGFCs
increase sharply, whereas the deformation rates decrease, and the improvement of the lignin fiber is better than that of the mineral fiber. It is noted that the introduction of the lignin/mineral fiber can improve the pavement resistance to rutting at high temperatures.

4. EXPERIMENTAL SECTION

4.1. Experimental Materials. 4.1.1. Asphalt. The styrene–butadiene–styrene (SBS)-modified bitumen investigated in the study was produced by Sino Petroleum Corp, and Table 5 lists the basic properties of the SBS-modified bitumen.

4.1.2. Aggregates and Filler. Both the mineral powder and coarse aggregate originate from the crushed limestone, and the fine aggregate is sand. The basic properties of these materials are listed in Tables 6–7, respectively. Obviously, these materials can reach the technical requirements proposed by the Chinese specification JTG F40-2004, demonstrating that they can be applied to the experiment in this study.

4.1.3. Fibers. Fibers were primarily used to prevent bitumen from draindown during mixing, transportation, and pavement. In this study, two different fibers including the lignin fiber and mineral fiber were chosen to act as a stabilizer, and the basic properties and images of the lignin/mineral fiber are shown in Table 2 and Figure 1.

The suitable thermal stability of the fiber is necessary, which requires no physical or chemical changes at the mixing temperature. Moreover, the fiber’s performance cannot change during transportation, high-temperature mixing, and pavement. The poor thermal stability can make the fiber curl or agglomerate when heated, which limits the mixing temperature and time. Therefore, prior to the application, the thermal stability of the fiber should be tested. In this experiment, the two fibers were put in an oven at 163 °C for 5 h, and then the color, mass, and shape changes were recorded. The results showed that no obvious change was found for the two fibers, indicating the good thermal stability, which can meet the construction requirement of OGFCs.

4.2. Experimental Methods. 4.2.1. Mesh-Basket Draindown Test. The test was performed to check the fiber’s absorption and stabilization of the bitumen binder. About 0.3 wt % fiber by weight of OGFCs based on the pavement practice was used. Consequently, 40 g of a fiber–asphalt binder was put into a mesh-basket uniformly at room temperature for 120 min. Then, the basket was heated at 130, 140, and 170 °C successively, and the drained asphalt was weighed. The weight ratio of the drained asphalt to the original specimen is the draindown.

4.2.2. SEM. SEM is an important tool to study the surface morphology of the lignin and mineral fiber, which can produce an important effect on the asphalt binder. SEM images of the fibers were obtained using a Hitachi S-4800 microscope. During the preparation of the sample, fibers were sprayed with gold to increase their conductivity. Several fields were examined at different magnifications to find more information about the surface morphology difference between the two fibers.

4.2.3. Specimen Preparation. In the experiment, the aggregate gradation for OGFC-13, the most common mixture in the wet and rainy South China, was chosen and designed according to the Chinese specification JTGF40-2004. At the stage of design, aggregate gradation selection, the mixing of the aggregate, asphalt with fiber or not were included. The aggregate gradation selected in this study is listed in Table 9. The mineral/lignin fiber was introduced to the OGFCs with a fraction of 0.35 and 0.3 wt %, respectively.

The mineral/lignin fiber was blended with the aggregate thoroughly and subsequently heated at 175 °C. Then, the liquid asphalt at a temperature of 165 °C was added to the aggregate–fiber mixture and blended thoroughly to form well-coated aggregate particles. The hot mixture was put into a steel frame and blew 50 times to obtain cylindrical Marshall samples according to the Chinese specification JTG F40-2004. Ultimately, the mechanical properties of the samples were checked as follows.

4.3. Mechanical Testing. Marshall stiffness test was conducted to evaluate the stability and the flow of the mixture. The test was performed according to the Chinese specification JTGF40-2004. At the stage of design, aggregate gradation selection, the mixing of the aggregate, asphalt with fiber or not were included. The aggregate gradation selected in this study is listed in Table 9. The mineral/lignin fiber was introduced to the OGFCs with a fraction of 0.35 and 0.3 wt %, respectively.

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Table 9. Aggregate Gradations of OGFCs

| sieve size (mm)      | 16  | 13.2 | 9.5  | 4.75 | 2.36 | 1.18 | 0.6  | 0.3  | 0.15 | 0.075 |
|----------------------|-----|------|------|------|------|------|------|------|------|-------|
| specified passing   | 100 | 90–100 | 60–80 | 12–30 | 10–22 | 6–18 | 4–15 | 3–12 | 3–8  | 2–6   |
| weight passing      | 100 | 93.3 | 66.1 | 21.5 | 11.4 | 7.0  | 6.0  | 5.0  | 4.6  | 4.1   |
4.2.4. Volumetric Properties. The AVs and $G_{nb}$ of the OGFC were calculated according to the Chinese specification JTGF40-2004. Therefore, eq 1 was employed to calculate the VMA, where $G_{nn}$ is the theoretical maximal specific gravity of OGFCs and $P_i$ is the aggregate proportion calculated using the weight of OGFCs.

$$VMA = 100 \left(1 - \frac{G_{nb}}{G_{nn}} \right)$$

The VFA was calculated using eq 2.

$$VFA = 100 \left(1 - \frac{AV}{VMA} \right)$$

4.2.5. Marshall Stability. The test was performed following the Chinese specification JTGE20 T 0709-2011.30 Before the experiment, the samples were put into a water bath at 60 °C for an hour. Subsequently, they were given a compressive load until being crushed. The maximal load at sample crushing was recorded, that is to say, the Marshall stability.

4.2.6. Moisture Susceptibility. The experiment was performed as follows to evaluate the moisture damage resistance. Six samples in two groups were prepared. The three samples in group I were put into a water bath at 60 °C for half an hour while the others in group II for 48 h. The Marshall stability was determined as described in Section 2.5, and then the residual stability of OGFCs, denoted as MSR, which was used to characterize the moisture susceptibility, was determined using eq 3. MS is the Marshall stability of the sample immersed for 48 h while MS1 is that for 30 min.16

$$MS_R = \frac{MS_2}{MS_1} \times 100\%$$

4.2.7. Freeze–Thaw Split Experiment. The freeze–thaw splitting experiment conditions were set according to the Chinese specification JTGE20 T 0729-2011, as reported by our previous study.15 TSR is the ratio of the tensile strength of water-conditioned OGFCs to that of unconditioned OGFCs, and it can be determined using eq 4. TSR is an indicator of water stability for OGFCs.

$$TSR = \frac{S_2}{S_1} \times 100\%$$

where $S_1$ is the average tensile strength of water-conditioned OGFCs, and $S_2$ is that of unconditioned OGFCs.

4.2.8. Dynamic Stability. The dynamic stability was checked to test the high-temperature performance (rutting resistance) of OGFCs based on the Chinese specification JTGE20-2011, and a higher dynamic stability represents a higher rutting resistance. Prior to the test, a slab specimen of 300 mm × 300 mm × 50 mm was prepared and then heated at 60 °C for 6 h. The rutting test was performed with a solid rubber tire rolling on the slab specimen at a speed of 42 cycles/min under a contact pressure of 0.7 ± 0.05 MPa.

The dynamic stability (cycle/mm) of OGFCs can be calculated using eq 5 in which $d_{60}$ is the rutting depth (mm) at 60 min while $d_{45}$ is that at 45 min.

$$DS = \frac{42 \times 15}{d_{60} - d_{45}}$$

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Notes

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■ REFERENCES

1. Punith, V. S.; Veeraragavan, A. Characterization of OGFC mixtures containing reclaimed polyethylene fibers. J. Mater. Civ. Eng. 2011, 23, 335–341.
2. Tannadeh, R.; Javad, T.; Mehrdad, H. Experimental study on the effect of basalt and glass fibers on behavior of open-graded friction course asphalt modified with nano-silica. Constr. Build. Mater. 2019, 212, 467–475.
3. Zhang, K.; Lim, J.; Nassiri, S; Alshareedah, O.; Li, H.; Englund, K. Field pilot study of porous asphalt pavement reinforced by cured carbon fibre composite materials (CCFCMs). Int. J. Pavement Eng. 2020, 23, 801–810.
4. Zhu, X. Y.; Ye, F. Y.; Cai, Y. S.; Birgisson, B.; Lee, K. Y. Self-healing properties of ferrite-filled open-graded friction course (OGFC) asphalt mixture after moisture damage. J. Cleaner Prod. 2019, 232, S18–S30.
(5) Hu, M. J.; Li, L. H.; Peng, F. G. Laboratory investigation of OGFC-5 porous asphalt ultra-thin wearing course. Constr. Build. Mater. 2019, 219, 101−110.

(6) Chen, J.; Yao, C.; Wang, H.; Ding, Y. M.; Xu, T. Expansion and contraction of clogged open graded friction course exposed to freeze–thaw cycles and degradation of mechanical performance. Constr. Build. Mater. 2018, 182, 167−177.

(7) Morea, F.; Zrebinio, R. Improvement of asphalt mixture performance with glass macro-fibers. Constr. Build. Mater. 2018, 164, 113−120.

(8) Putman, B. J.; Amirkhanian, S. N. Utilization of waste fibers in stone matrix asphalt mixtures. Resour. Conserv. Rec. 2004, 42, 265−274.

(9) Zhang, X. Y.; Gu, X. Y.; Lv, J. X.; Zhu, Z. K.; Ni, F. J. Mechanism and behavior of fiber-reinforced asphalt mastic at high temperature. Int. J. Pavement Eng. 2018, 19, 407−415.

(10) Wu, M. M.; Li, R.; Zhang, Z. Y.; Fan, L.; Wei, J. M.; Lv, Y. C. Stabilizing and reinforcing effects of different fiber on asphalt mortar’s performance. Pet. Sci. 2015, 12, 189−196.

(11) Wu, M. M.; Li, R.; Zhang, Z. Y.; Wei, J. M.; Lv, Y. C.; Ding, X. Reinforcement effect of fiber and deoiled asphalt on high viscosity rubber/SBS modified asphalt mortar. Pet. Sci. 2014, 11, 454−459.

(12) Szabó, L.; Imanishi, S.; Hirose, D.; Tsukegi, T.; Wada, N.; Takahashi, K. Mussel-Inspired Design of a Carbon Fiber-Cellulotic Polymer Interface toward Engineered Biobased Carbon Fiber-Reinforced Composites. ACS Omega 2020, 5, 27072.

(13) Wu, M. M.; Liang, J. L.; Cai, H. M.; Chen, H. L.; He, Q. M.; Zhang, Y. Z. Effect of Fibers on the Performance of a Porous Friction Course. ACS Omega 2022, 7, 28324−28333.

(14) Hu, J. Y.; Ma, T.; Ma, K.; Xu, J. Three-dimensional discrete element simulation on degradation of air voids in double-layer porous asphalt pavement under traffic loading. Constr. Build. Mater. 2021, 313, No. 125570.

(15) Kusumawardani, D. M.; Wong, Y. D. Evaluation of aggregate gradation on aggregate packing in porous asphalt mixture (PAM) by 3D numerical modelling and laboratory measurements. Constr. Build. Mater. 2020, 246, No. 118414.

(16) JTG F40-2004, Standard Specification for Construction and Acceptance of Highway Asphalt Pavements; Ministry of Communication: Beijing, China, 2004.

(17) Chen, J. S.; Lin, K. Y. Mechanism and behavior of bitumen strength reinforcement using fibers. J. Mater. Sci. 2005, 40, 87−95.

(18) Dong, F. Q.; Xin, Y.; Wang, T. Y. Influence of base asphalt aging levels on the characteristics and rheological properties of foamed asphalt. Constr. Build. Mater. 2018, 177, 43−50.

(19) Wu, S. P.; Chen, Z.; Ye, Q. S.; Liao, W. D. Effects of fiber additive on the high temperature property of asphalt binder. J. Wuhan Univ. Technol. 2006, 21, 118−120.

(20) Luo, D.; Khater, A.; Yue, Y. C.; Abdelsalam, M.; Zhang, Z.; Li, Y.; Li, J.; Isley, D. T. The performance of asphalt mixtures modified with lignin fiber and glass fiber: A review. Constr. Build. Mater. 2019, 209, 377−387.

(21) Hinrichsen, J. A.; Heggen, J. Minimum voids in mineral aggregate in hot-mix asphalt based on gradation and volumetric properties. Transp. Res. Rec. 1996, 1545, 75−79.

(22) Li, R.; Leng, Z.; Wang, Y. L.; Zou, F. Characterization and correlation analysis of mechanical properties and electrical resistance of asphalt emulsion cold-mix asphalt. Constr. Build. Mater. 2020, 263, No. 119974.

(23) Jiang, Y. J.; Xue, J. S.; Chen, Z. J. Influence of volumetric property on mechanical properties of vertical vibration compacted asphalt mixture. Constr. Build. Mater. 2017, 135, 612−621.

(24) Liang, M.; Xin, X.; Fan, W. Y.; Wang, H.; Jiang, H.; Zhang, J.; Yao, Z. Phase behavior and hot storage characteristics of asphalt modified with various polyethylene: experimental and numerical characterizations. Constr. Build. Mater. 2019, 203, 608−620.

(25) Mo, L.; Huurman, M.; Wu, S.; Molenaar, A. A. Raveling investigation of porous asphalt concrete based on fatigue characteristics. Mater. Des. 2009, 30, 170−179.