Research Article

Study on Road Performance and Electrothermal Performance of Poured Conductive Asphalt Concrete

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Received 20 November 2021; Revised 7 March 2022; Accepted 6 April 2022; Published 26 April 2022

Academic Editor: Candido Fabrizio Pirri

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In order to realize the active melting of ice and snow of poured asphalt concrete on steel bridge deck pavement in winter, graphite and carbon fiber were selected as conductive materials to prepare poured conductive asphalt concrete CGA-10. The influence of the content of conductive phase material on the electrical resistivity variation of poured conductive asphalt concrete was studied. The influence of conductive materials and their content on pavement performance of poured conductive asphalt concrete was analyzed. The heating effect of poured conductive asphalt concrete was studied. And the ice melting efficiency of poured conductive asphalt concrete was evaluated by indoor deicing test. Finally, the microstructure characteristics were analyzed by SEM. Experimental results showed: 0.4% carbon fiber + 30% graphite can form a good conductive network in poured conductive asphalt concrete. Carbon fiber can make up for the interruption of graphite particle conductive chain, on the other hand, it plays a reinforcing role.

1. Introduction

Asphalt mixture is widely used in China and abroad due to its excellent performance such as low noise and driving comfort [1–4]. There are many types of asphalt mixture, among which poured asphalt concrete is widely used in steel bridge deck pavement structure due to its good impermeability, low temperature crack resistance and good follow-up with steel bridge deck. However, the completed projects show that the bridge superstructure of the poured asphalt concrete steel bridge deck pavement was easily affected by the external environment temperature in winter, and the ice and snow phenomenon in the bridge area was serious, the vehicles were prone to slip, offset and extend the braking distance, resulting in serious traffic accidents [5, 6]. Researchers have proposed many ways to remove ice and snow, such as spreading chlorine salt, artificial ice and snow removal, spreading chemical agents to melt ice and snow, mechanical ice and snow removal and so on, these methods not only caused pollution to the environment and damaged road structure, but also the efficiency of ice and snow removal was not ideal [7–9]. Conductive asphalt concrete overcomes the shortcomings of the traditional passive methods of melting ice and snow, and has the advantages of maintaining the integrity of pavement structure, improving energy efficiency, clearing ice and snow more thoroughly and energy saving and environmental protection [10].
In order to make asphalt concrete have certain conductive ability, conductive materials are added into asphalt concrete to melt ice and snow through electro-thermal conversion effect under specified external voltage conditions [11, 12]. In addition, conductive asphalt concrete has obvious pressure sensitivity and temperature sensitivity, which can realize the structure of self-diagnosis, traffic monitoring and self-healing, and improve the fatigue resistance of asphalt mixture [13–15]. The main factor affecting the electro-thermal performance and input power of asphalt mixture is the content of conductive materials [16–18]. The content of conductive materials can be determined by the percolation threshold [19], when conductive materials reach the penetration threshold, the resistivity of asphalt mixture decreases significantly, when the content exceeds the penetration threshold, the effect of the content on reducing the resistivity of asphalt mixture is weakened, and then the pavement performance of asphalt mixture is affected.

Selecting suitable conductive materials is an significant problem for conductive asphalt concrete. Powder conductive materials can replace a certain number of fillers to change the volume performance of asphalt mixture and meet the requirements of electrical conductivity without affecting the skeleton structure of asphalt mixture [20]. Graphite can gradually reduce the resistivity of asphalt concrete to achieve the heating rate needed to melt ice and snow [21, 22]. The difference in particle size and shape of graphite leads to the difference of resistivity of asphalt concrete. Flake graphite is more effective in reducing the resistivity of asphalt concrete than amorphous graphite and synthetic graphite, larger flake particles are more conductive than smaller flake particles [23]. Steel slag is easy to oxidize in cement concrete, resulting in the increase of resistivity with time, while the resistivity of steel slag in asphalt concrete can maintain a stable state with time, but its heating and snow melting efficiency is not very ideal [24, 25]. With the increase of the content of steel wool, the resistivity of asphalt concrete decreases rapidly, but when the content of steel wool exceeds a certain value, the indirect tensile strength decreases [26].

Carbon fiber has the characteristics of low density, long diameter ratio and large surface area, which plays a role in adsorption and stability of asphalt. The greater the mass fraction of carbon fiber, the higher the temperature of conductive asphalt concrete, and the power of 24V has a good snow melting effect, snow melting efficiency with the extension of power time multiplied [27]. In theory, the longer the length of carbon fiber is, the easier it is to form a conductive path in the asphalt mixture, and the resistivity of the asphalt mixture is low. However, when a large amount of carbon fiber is added, on the one hand, the optimal asphalt-aggregate ratio of conductive asphalt concrete will increase, which increases the resistivity of conductive asphalt concrete [28]. On the other hand, the dispersion of carbon fiber in the conductive asphalt concrete is poor, and it is easy to form a broken circuit, resulting in increased resistivity [29], and high content of carbon fiber may also lead to conductive asphalt concrete stress concentration phenomenon. The resistivity of asphalt mixture shows a concave trend with the length of carbon fiber, and the minimum value of resistivity is within 8–10 mm [30].

In summary, although some scientific research achievements and engineering applications have been made in the study of conductive asphalt concrete, there are few studies on the steel bridge deck pavement of poured conductive asphalt concrete and the ice-snow melting effect of steel bridge deck. Due to its high asphalt content and high mineral powder filler, the influence of adding a certain amount of conductive materials on the electrical conductivity and pavement performance of poured conductive asphalt concrete is rarely reported. In addition, in the previous study of conductive asphalt concrete, most of the tests on its electrical conductivity were prepared into cylindrical specimens, ignoring the influence of pavement construction. Therefore, graphite and carbon fiber were selected as conductive additives to prepare poured conductive asphalt concrete. By changing the content of graphite and carbon fiber, the influence of the content on the electrical resistivity, pavement performance, electrothermal performance and deicing effect was explored. In the pavement performance test, the influence of conductive materials on pavement performance was analyzed by range analysis, and the electrothermal performance test adopted rutting plate specimen to simulate the actual working state of pavement. Heating effect and deicing effect were quantified to evaluate heating efficiency and ice melting efficiency of poured conductive asphalt concrete. The combination and dispersion of conductive materials in asphalt mixture were observed by SEM, and the conductive mechanism of poured conductive asphalt concrete was revealed from the micro perspective.

2. Materials

2.1. Raw Materials

2.1.1. Asphalt and Mineral Aggregates. SBS modified asphalt with penetration of 33.1 (0.1 mm at 25°C, 100 g and 5 s), softening point of 83.6°C and ductility of 31 cm (5 cm/min at 10°C) was provided by Zhengzhou Zhengfa Municipal Construction Co., Ltd. The coarse aggregate and fine aggregate are basalt rolled crushed stone, and the filler is limestone powder. Asphalt and mineral aggregates meet specification requirements [31].

2.1.2. Sasobit. Sasobit can significantly improve the workability and high temperature stability of poured asphalt concrete. The main performance indexes of Sasobit modified particles in Henan Lupeng Transportation Technology Co., Ltd. are shown in Table 1.

2.1.3. Conductive Materials. High carbon content scalamous graphite and short-cut carbon fiber of about 9 mm are produced by Qingdao Huatai. The main performance indicators are shown in Tables 2~3, and the micromorphology is shown in Figures 1~2.
2.2. Determination of Conductive Material Content. In order to avoid the simultaneous change of graphite and carbon fiber, the quality of carbon fiber is calculated according to the percentage of quality of mineral aggregates. Taking into account the close particle size of 150 μm graphite and mineral powder, graphite is used to partially replace mineral powder. The proportion of mineral powder in mineral material is 25%. Since the density of mineral powder is 2.69 g/cm³ and the density of graphite is 2.15 g/cm³, the density difference between the two is large. If added according to the same quality, the volume fraction cannot be the same. Therefore, when graphite is used to replace mineral powder with equal volume, the quality of mineral powder should be converted according to equation (1). The quality of mineral powder minus the quality of mineral powder replaced by graphite is the final quality of mineral powder to be added.

\[
B_m = \frac{B_c \times R_m}{R_b},
\]

where, \(B_m\) is the quality of graphite replacing mineral powder, \(B_c\) is the quality of graphite, \(R_b\) is the density of graphite, and \(R_m\) is the density of mineral powder.

2.3. Preparation Process. The mix proportion design of poured conductive asphalt concrete CGA-10 refers to poured asphalt concrete GA-10, the median value of grading is used for design, the proportions of coarse aggregate, fine aggregate and mineral powder in the mixture are determined by the sieve passing rate of each particle size in Table 4.

GA-10 adopts the mix proportion design method of penetration test and luer fluidity test, the specification [32] stipulates that the flowability at 240°C is less than 20 s, the penetration at 60°C is 1~4 mm, and the penetration increment is less than 0.4 mm. The optimal asphalt content is 8.1%, Sasobit is expressed as 3% by the mass percentage of asphalt content. The determination of the optimum asphalt-aggregate ratio of CGA-10 asphalt mixture is based on the method of poured asphalt concrete. Due to the incorporation of conductive materials with large oil absorption, the optimum asphalt-aggregate ratio needs to be appropriately increased. The optimum asphalt-aggregate ratio is calculated by floating 0.3% up and down according to the predicted median asphalt-aggregate ratio.

The mixing time and sequence of conductive materials will affect the oil absorption of conductive materials. If the mixing sequence is not appropriate, the wrapping of asphalt on aggregate is seriously affected, resulting in insufficient adhesive force of the mixture, which will cause the aggregate to be exposed outside the asphalt. Therefore, asphalt is first fully mixed with coarse and fine aggregates, conductive materials are added to the mixing pot after aggregates adsorb large amounts of asphalt. The preparation process is shown in Figure 3.

3. Test Scheme and Methods

3.1. Test Scheme. In order to achieve the purpose of active ice-snow melting of steel bridge deck pavement and improve its ice-snow melting efficiency, nine groups of poured conductive asphalt concrete with different contents of conductive materials are proposed in this paper for electrical resistivity test and pavement performance test, as shown in Table 5. According to the results of resistivity test and pavement performance test, three groups of schemes were selected for electrical and thermal performance test to verify the heating effect, and the simulated deicing test was carried out to evaluate the heating efficiency and deicing efficiency.

3.2. Test Methods

3.2.1. Electrical Resistivity Test. The electrical resistivity is generally used to represent the conductivity of the material, and the resistivity formula is shown in equation (2).
Table 4: CGA-10 matching requirements.

| Sieve aperture/mm | 13.2 | 9.45 | 4.75 | 2.36 | 1.18 | 0.6  | 0.3  | 0.15 | 0.075 |
|-------------------|------|------|------|------|------|------|------|------|-------|
| Passing rate/%    | 100  | 80–100 | 63–80 | 48–63 | 38–52 | 32–46 | 27–40 | 24–36 | 20–30 |
| Gradation median  | 100  | 90   | 71.5 | 55.5 | 45   | 39   | 33.5 | 30   | 25    |

Figure 1: Graphite morphology. (a) Overall morphology at 50 times. (b) Local morphology at 5000 times.

Figure 2: Form of carbon fiber. (a) Overall morphology at 100 times. (b) Local morphology at 5000 times.

Figure 3: Preparation process of conductive gussasphalt mixture.
Conductive asphalt mixture was about 240°C. If the temperature is lower than 240°C, it shall be stirred again or replaced. If the temperature is cold, the asphalt concrete begins to shrink and is prone to generate cracks, when its shrinkage tensile stress is greater than the ultimate tensile stress, cracks will appear and affect the pavement performance of asphalt concrete. Low temperature performance of poured conductive asphalt concrete was evaluated by limit strain of low temperature bending test. The equipment was a multifunctional dynamic test system for asphalt mixture produced by Nanjing Luda Measurement and Control Technology Co., Ltd. The beam size of CGA-10 asphalt mixture is 300 mm × 100 mm × 50 mm, and the bending limit strain is not less than 7 × 10³. The low-temperature bending test method is the same as that of the ordinary asphalt mixture, and the three-point loading is damaged. The specimen was placed on both ends of the mold, and the single point loading was carried out in the middle, and the test temperature was −10°C, loading rate was 50 mm/min, as shown in Figure 5.

| Scheme | Carbon fiber/ % | Graphite/ % | Optimal asphalt content/ % |
|--------|-----------------|-------------|----------------------------|
| N1     | 0.3             | 20          | 11.3                       |
| N2     | 0.3             | 30          | 11.9                       |
| N3     | 0.3             | 40          | 12.9                       |
| N4     | 0.4             | 20          | 11.5                       |
| N5     | 0.4             | 30          | 12.1                       |
| N6     | 0.4             | 40          | 13.2                       |
| N7     | 0.5             | 20          | 11.6                       |
| N8     | 0.5             | 30          | 12.6                       |
| N9     | 0.5             | 40          | 13.3                       |

\[ \rho = \frac{RS}{L} \]  

(2) Cracking Test at Low Temperature. When the temperature is cold, the asphalt concrete begins to shrink and is prone to generate cracks, when its shrinkage tensile stress is greater than the ultimate tensile stress, cracks will appear and affect the pavement performance of asphalt concrete. Low temperature performance of poured conductive asphalt concrete was evaluated by limit strain of low temperature bending test. The equipment was a multifunctional dynamic test system for asphalt mixture produced by Nanjing Luda Measurement and Control Technology Co., Ltd. The beam size of CGA-10 asphalt mixture is 300 mm × 100 mm × 50 mm, and the bending limit strain is not less than 7 × 10³. The low-temperature bending test method is the same as that of the ordinary asphalt mixture, and the three-point loading is damaged. The specimen was placed on both ends of the mold, and the single point loading was carried out in the middle, and the test temperature was −10°C, loading rate was 50 mm/min, as shown in Figure 5.

(3) Water Stability Test. Water damage is easy to occur when asphalt pavement and pavement structures accumulate water. Rain water penetrates into the mixture through the cracks, resulting in the pit slot phenomenon, and finally penetrates into the steel bridge deck plate, resulting in corrosion of the steel bridge deck and seriously affecting the mechanical properties of the steel bridge deck. The water stability of poured conductive asphalt mixture was evaluated by immersion Marshall test and freeze-thaw splitting test, and the test was carried out according to the regulations [33].

3.2.2. Pavement Performance Test

(1) High Temperature Stability Test. The dynamic stability of rutting test was used to evaluate the high temperature stability of poured conductive asphalt concrete. The test equipment was the YLDCZ-8S two-way scientific research rutting test machine produced by Xi’an Yaxing Civil Instrument Co., Ltd. Poured asphalt concrete is more likely to be unstable under high temperature environment. At present, there is no explicit requirement for dynamic stability index of poured asphalt concrete in China. Referring to Japanese requirements for dynamic stability, Japanese specification requires dynamic stability not less than 300 times/mm for wheel load test at 60°C and 0.64 MPa. Lubricants were smeared around the rutting plate mold in advance, and the asphalt mixture was stirred in a stirring pot at 240°C for 45 min. Then the poured asphalt mixture was poured into the rutting plate mold. The pouring process needs to be completed quickly to ensure that the asphalt mixture is about 240°C. Otherwise, its fluidity is weakened, and it is difficult to form self-compacting. The steel bars were inserted around it, and the surface was scraped flat. Finally, it was cooled naturally in the room without rolling the molding machine.

3.2.3. Electothermal Performance Test. According to the results of resistivity test and pavement performance test, three groups of schemes with better conductivity were selected for heating test, and the internal temperature and the surface temperature were tested respectively. In the temperature measurement, most of the temperature sensors were embedded in the asphalt concrete for testing, which was easy to damage the temperature sensor probe and wire. Moreover, the temperature required for the poured
conductive asphalt concrete molding specimen is very high, which is more likely to damage the temperature sensor. The hand-held impact drill was used to drill holes in the middle and surface of the rutting plate specimen. The diameter of the drilling hole is not too large, which should be similar to the diameter of the sensor probe, and then the temperature sensor probe was inserted into the hole drilled in advance. Because the heat transfer effect of mineral powder is the same as that of poured conductive asphalt concrete, the borehole is filled with mineral powder to reduce heat loss.

The low temperature test box was adjusted to $-8.0^\circ$C 1h before the test. Three temperature sensors were utilized to test the internal temperature, surface temperature and internal temperature of the low temperature test box. The specimen needs to be placed in advance in the low temperature test box at $-5^\circ$C for 4 h. Alternating current has the advantages of convenient acquisition and high heat transfer efficiency compared with direct current [34], so AC was selected in this paper. The porosity of poured asphalt concrete is very small, and it has excellent waterproof performance for steel bridge surface, which can be laid on the upper layer or the middle layer. In this paper, it was applied to the middle layer for research. Considering the traffic safety, the voltage of this test was set to 50 V. The test time was 90 min, and the internal temperature, surface temperature and the internal temperature of the low temperature test chamber were recorded every 10 min. The simulated environment of the low temperature test chamber is shown in Figure 6.

3.2.4. Simulated Deicing Test. In order to evaluate the ice melting effect of poured conductive asphalt concrete more truly and quantify its ice melting efficiency, the simulated deicing test of the optimal scheme in Section 3.2.3 was carried out. Low temperature test box was used to simulate outdoor temperature environments. The temperature of the low temperature test box was adjusted to $-8.0^\circ$C, and then the rutting plate specimen was put into the low temperature test box, and 300 ml water was poured into the surface of the rutting plate. After waiting for 4 hours, 4 mm ice layer was formed on the surface of the rutting plate, and then the rutting plate specimen was heated. The heating process was the same as that in Section 3.2.3, and the changes of internal temperature, surface temperature and internal temperature of low temperature test box during the surface ice melting of rutting plate specimen were recorded. The simulated deicing test is shown in Figure 7.

3.2.5. SEM. The distribution of conductive materials in poured conductive asphalt concrete was studied by JEOL-JSM-7500F scanning electron microscope to reveal the conductive mechanism of different conductive materials. According to the results of pavement performance test and electrothermal performance test, the optimal scheme was selected for SEM test. The sample was processed into a small sample with a thickness of less than 5 mm $\times$ 5 mm. The sample was uniformly adhered to the sample plate with a conductive tape, and vacuum gold plating was carried out in the coating instrument. Finally, the sample was moved to the scanning electron microscope for morphology observation.

4. Results and Discussion

4.1. Effect of Conductive Material Content on Electrical Resistivity. According to the electrical resistivity test scheme in 3.2.1, the test results are shown in Table 6 and Figure 8.

Table 6 and Figure 8 show that when the carbon fiber content is 0.3%, the electrical resistivity of the specimen decreases rapidly with the increase of graphite content. When the graphite content is 30%, the electrical resistivity decreases more. When the graphite content is 40%, the electrical resistivity does not change very much. The electrical resistivity at 0.4% carbon fiber content decreased by 44.6%, 89.1%, 16.9% lower than that at 0.3% carbon fiber content, respectively. The electrical resistivity decreases at 30% graphite content, but the electrical resistivity decreases.
less at 40% graphite content. This is because the poured conductive asphalt concrete with 0.4% carbon fiber content and 30% graphite content has formed a good conductive network. At this time, the conductive materials have reached the "percolation threshold". If the graphite content is further increased, the electrical resistivity is not significantly reduced. The resistivity at 0.5% carbon fiber content does not decrease significantly with the increase of graphite content, indicating that it has exceeded the "percolation threshold" of conductive materials at this time, and the resistivity decreases slowly with the increase of conductive materials.

4.2. Pavement Performance of Poured Conductive Asphalt Concrete

4.2.1. High Temperature Stability. According to the high temperature stability test scheme in Section 3.2.2, the test results are shown in Table 7 and Figure 9, and the range analysis of the test results is shown in Table 8, where, $K$ represents the total value of each factor at each level, $k$ represents the average value of the total value, indicating the influence of this factor on the test parameters.

It can be seen from Tables 7~8 and Figure 9 that the dynamic stability of nine groups of poured conductive

**Table 6: Resistance test results of rutting plate specimen.**

| Scheme   | Specimen height/mm | Electrical resistance/Ω | Electrical resistivity/Ω·m |
|----------|--------------------|-------------------------|---------------------------|
| N1(0.3 + 20) | 50.3               | 21780                   | 1089                      |
| N2(0.3 + 30) | 50.2               | 3104                    | 155.2                     |
| N3(0.3 + 40) | 50.4               | 341                     | 17.05                     |
| N4(0.4 + 20) | 50.4               | 12042                   | 602.1                     |
| N5(0.4 + 30) | 50.4               | 336                     | 16.8                      |
| N6(0.4 + 40) | 50.2               | 284                     | 14.2                      |
| N7(0.5 + 20) | 50.1               | 3670                    | 183.5                     |
| N8(0.5 + 30) | 50.3               | 263                     | 13.2                      |
| N9(0.5 + 40) | 50.2               | 249                     | 12.5                      |

**Figure 6: Simulated temperature rise test of track board in low temperature test chamber.**

**Figure 7: The simulated deicing test.**
asphalt concrete is greater than 300 times/mm, which meets the design requisition. Under the dosage of 0.3% + 20%, 0.3% + 30% and 0.3% + 40%, the DS values of the latter are 12.4% and 16.9% lower than those of the former respectively, and the DS values of 0.4% + 20%, 0.4% + 30% and 0.4% + 40% are 5.7%, 8.2% and 13.2% higher than those of 0.3% + 20%, 0.3% + 30% and 0.3% + 40% respectively. The range $R$ of graphite is 370.7, which is much higher than that of carbon fiber, indicating that graphite has a greater influence on the dynamic stability of cast conductive asphalt concrete than carbon fiber. From the range results, it can be also found that 0.4% carbon fiber has the best improvement effect on the dynamic stability. From the microscopic morphology in Section 4.6, it can be found that the carbon fiber is equivalent to the steel bar in the concrete, which enhances the strength of the mixture. The carbon fiber tightly connects the asphalt and the aggregates, and adsorbs a large number of “free asphalt.” The “free asphalt” is reduced, and the shear resistance of CGA-10 is enhanced. Therefore, the dynamic stability of CGA-10 concrete is improved and the high temperature stability is enhanced. When 0.5% carbon fiber is added, the dispersion of carbon fiber is poor, and the carbon fiber is locally agglomerated in the mixture, which reduces its shear resistance.

4.2.2. Low Temperature Crack Resistance. According to the low temperature crack resistance test scheme in Section 3.2.2, the test results are shown in Table 9 and Figure 10, and the range analysis of the test results is shown in Table 10, where, $K$ represents the total value of each factor at each level, $k$ represents the average value of the total value, indicating the influence of this factor on the test parameters.

Table 9 and Figure 10 illustrate that the low temperature bending limit strain of the nine groups of schemes meets the bending limit strain specified in the pavement design guide, which is not less than $7 \times 10^{-4}$. Under the same graphite content, the maximum bending strain of 0.4% carbon fiber was 1.2% higher than that of 0.3%, and the maximum bending strain of 0.5% carbon fiber was 1.6% higher than that of 0.4%. Under the same carbon fiber content, with the increase of graphite content, the maximum bending strain showed a downward trend. It can be seen from Table 10 that the carbon fiber range $R$ is 0.24 and graphite range $R$ is 0.39, indicating that graphite has a more obvious negative impact on low temperature crack resistance. With the increase of carbon fiber content, the maximum flexural strain of asphalt mixture is significantly improved, it can be observed from the microstructure of CGA-10 that fiber forms a three-dimensional network structure in asphalt mixture, which restrains the crack of matrix, and carbon fiber can play a similar role as steel bars in poured conductive asphalt concrete, which is to bear and disperse the load on the matrix, so as to make up for the defects of graphite.

4.2.3. Water Stability. The test was carried out according to the water stability test scheme in Section 3.2.2, the test results are shown in Tables 11 and 12, and Figures 11 and 12.
range analysis of the test results is shown in Tables 13 and 14, where, \( K \) represents the total value of each factor at each level, \( k \) represents the average value of the total value, indicating the influence of this factor on the test parameters.

Tables 11, 13 and Figure 11 present the test results of the nine groups meet the design requisition of more than 85%. The addition of graphite reduced the stability of 0.5h and 48h, with the maximum reduction of 8.2% and 14.3%, respectively, while the residual stability increased with the increase of graphite content, with the maximum increase of 8.1%. The range \( R \) of graphite is 5.03, which is far greater than that of carbon fiber. The residual stability of 40% graphite content is the highest, indicating that increasing the graphite content can significantly improve the residual stability of the asphalt mixture. This stems from the fact that the graphite powder is uniformly dispersed in the asphalt mortar, reducing its porosity, and forming a hydrophobic asphalt film between the mineral aggregates, erecting a water barrier.

According to Table 12, 14 and Figure 12, the test results of the nine groups of schemes meet the design requisition. Under the same graphite content, the splitting intensity ratio of 0.5% carbon fiber is higher than that of 0.3% carbon fiber and 0.4% carbon fiber. Under the same carbon fiber content, with the increase of graphite content, the freeze-thaw splitting intensity ratio decreases. This shows that 0.5% carbon fiber content than 0.3% and 0.4% carbon fiber content is better to improve the freeze-thaw splitting strength of asphalt mixture, 20% graphite content than 30% and 40% graphite content is more helpful to enhance the freeze-thaw splitting strength of asphalt mixture. This is because carbon fiber adsorbs asphalt and reduces the porosity of asphalt mixture. At the same time, its connection between mineral materials plays the effect of reinforcement. Although graphite can reduce the porosity of asphalt mixture and reduce the water content of specimens, its lubrication effect still leads to the decrease of freeze-thaw splitting strength ratio of the specimen.

| Scheme | N1 | N2 | N3 | N4 | N5 | N6 | N7 | N8 | N9 |
|--------|----|----|----|----|----|----|----|----|----|
| Limit flexural tensile strength/MPa | 12.07 | 11.24 | 10.15 | 12.86 | 11.72 | 10.93 | 13.42 | 12.55 | 11.84 |
| Maximum bending tensile strain/με (1 × 10^3) | 9.83 | 9.62 | 9.44 | 9.91 | 9.74 | 9.52 | 10.06 | 9.88 | 9.67 |

**Table 10: Range analysis of trabecular bending test.**

| Indicator                  | Carbon fiber | Graphite |
|----------------------------|--------------|----------|
| K1                         | 28.89        | 29.8     |
| K2                         | 29.17        | 29.24    |
| K3                         | 29.61        | 28.63    |
| k1                         | 9.63         | 9.93     |
| k2                         | 9.72         | 9.75     |
| k3                         | 9.87         | 9.54     |
| Range                      | 0.24         | 0.39     |
| Optimization scheme        | 0.5          | 20       |
4.3. Electrothermal Performance of Poured Conductive Asphalt Concrete. The heating effect is shown in Figures 13–15 according to the test scheme of 3.2.3. Figures 13–15 show that the temperature of the three groups of rutting plates decreased in the first 10 min, mainly because the temperature of specimens after freezing was lower than that of the low temperature test box, and the heating rate was relatively slow at the beginning, so the temperature decreased in the first few minutes. The internal temperature of 0.3% + 40% plate specimen increased by 3.7°C, and the internal rise rate was 2.47°C/h. The internal temperature of 0.4% + 30% plate specimen increased by 5.3°C, and the internal rise rate was 3.53°C/h. The internal temperature of 0.5% + 30% plate specimen increased by 6.0°C, and the internal rise rate was 4.0°C/h. It can be found that the increase of temperature is related to the content of conductive materials. Within a certain range, the higher the content of conductive materials, the smaller the electrical resistivity and the greater the increase of temperature. On the contrary, the temperature rise of the specimen is smaller.

4.4. Deicing Effect of Poured Conductive Asphalt Concrete. The deicing effect is shown in Figures 16–18 according to the simulated snow melting test scheme in Section 3.2.4.
It can be seen from Figures 16∼18 that in the environment where the temperature of the low temperature test box is basically unchanged, the temperature of the rutting plate specimen with 0.5%+30% increases the fastest, and the surface and internal temperatures of the specimen increase by 7.1°C and 9.2°C, respectively. The ice melting time is 390 min.

4.5. Heating Efficiency and Ice Melting Efficiency. The heating efficiency of poured conductive asphalt concrete is evaluated according to the heating test results of rutting plate in Section 4.3, as shown in Table 15. The ice melting efficiency is quantified according to the deicing effect of rutting plate in Section 4.4, as shown in Table 16.
where $c_{ca}, P_{ca},$ and $v_{ca}$ are the specific heat, density and volume fraction of carbon fiber (J/(kg·K), kg/cm³, %), $c_{cb}, P_{cb},$ and $v_{cb}$ are the specific heat, density and volume fraction of graphite (J/(kg·K), kg/cm³, %), $c_{co},$ and $P_{co}$ are the specific heat and density of asphalt concrete (J/(kg·K), kg/cm³, %), $c_a,$ and $P_a$ are the specific heat and density of conductive asphalt concrete (J/(kg·K), kg/cm³, %).

According to the law of conservation of energy, the total heat generated is calculated according to equation (4).

$$P\Delta t = \frac{U^2}{R} \times \Delta t = m \cdot C_p \cdot \Delta T + m \cdot C_p \cdot \Delta T \cdot \mu + Q_s \cdot m \cdot \mu + Q_s,$$  \tag{4}

where $m, C_p,$ and $\Delta T$ are the mass, specific heat and elevated temperature of asphalt concrete (kg, J/(kg·K)), $m \cdot C_p,$ and $T_s$ are the mass, specific heat and elevated temperature of ice (kg, J/(kg·K), °C)), $P$ is the input power (W); $\Delta t$ is the voltaic time (s), $Q_s$ is the solution heat of ice (J/kg), $Q_s$ is the heat loss of melting ice (J), $R,$ and $U$ are the resistance and applied voltage of asphalt concrete (Ω). $V$.

Referring to the research results of ice melting of poured conductive concrete [35], the following parameters are obtained: $C_{Pa} = 2050 J/(kg \cdot K)$, $P_{ca} = 917 kg/cm^3$, $Q_s = 3.35 \times 10^3 J/kg$, $c_{ca} = 939.5 J/(kg \cdot K)$, $P_{SBS asphalt mixture} = 2339 kg/cm^3$, $c_{cb} = 710 J/(kg \cdot K)$, $P_{graphite} = 2150 kg/cm^3$, $c_{ca} = 720 J/(kg \cdot K)$, $P_{carbon fiber} = 1820 kg/cm^3$.

The following can be seen from Tables 15 ~ 16 that:

1. The energy consumption of the three groups of rutting plates is small, which is 0.064 degrees, 0.056 degrees and 0.060 degrees respectively, the input power is 7.33 W, 7.44 W and 9.16 W. Due to the small input power and lesser energy consumption of the specimen, the heating process is slow. In practical engineering applications, the appropriate voltage should be selected to improve the input power and reduce the time required for melting ice and snow.

2. The heating efficiencies of 0.3% + 40%, 0.4% + 30% and 0.5% + 30% are 55.82%, 78.85% and 67.49%, respectively. The ice efficiencies of 0.3% + 40%, 0.4% + 30% and 0.5% + 30% are 43.94%, 50.03% and 46.90%, respectively. Among them, the heating efficiency and ice melting efficiency of 0.4% + 30% are higher, indicating that under this condition, the efficiency of poured conductive asphalt concrete to convert electric energy into heat energy is better, and the heat energy loss is less.

4.6 Microstructure Analysis of Poured Conductive Asphalt Concrete. Scheme N5 (0.4% carbon fiber + 30% graphite) was selected for SEM, which has the best economy, pavement performance and electrothermal performance. Figure 19 shows that the layered graphite powder particles are filled in the gaps of asphalt concrete and wrapped closely with asphalt mortar, which reduces the porosity of asphalt mixture. When the content of conductive particles is very small, the conductive particles cannot transition in the mixture. Layered graphite particles will be blocked by aggregates and asphalt. At this time, the electrical resistivity of
the mixture is still large, and it is determined by the electrical resistivity of aggregates and asphalt. When the mixing amount reaches the percolation threshold, the conductive molecules are blocked by a small amount of aggregates and asphalt mortar, and they are still unable to contact directly. When the blocking situation slows down, the spacing between conductive molecules is small and the transition is fast. One noticeable feature is that the electrical resistivity drops sharply. Through the electrical resistivity test, it can also be seen that with the addition of the same carbon fiber, the resistance drops from tens of thousands or thousands ohms to hundreds ohms with the increase of graphite content. When the content is higher than the percolation threshold, the spacing of conductive molecules is smaller and can even be directly contacted, and the conductive network formed by graphite particles in the mixture is gradually stable.

Although graphite particles are easy to disperse and have good electrical conductivity, it is necessary to control graphite content and balance the relationship between electrical conductivity and mechanical properties. In addition to the same conductive mechanism of graphite, the size

| Mixing amount/% | Resistance/Ω | Input power/W | Total heat/kJ | Specific heat capacity of specimen/(kg·K) | Increasing temperature/°C | Heat storage energy of specimen/kJ | Heat generation efficiency/% |
|-----------------|-------------|---------------|--------------|------------------------------------------|--------------------------|-----------------------------------|-------------------------------|
| 0.3% carbon fiber +40% graphite | 341 | 7.33 | 39.58 | 819.1 | 3.7 | 22.09 | 55.82 |
| 0.4% carbon fiber +30% graphite | 336 | 7.44 | 40.18 | 871.24 | 5.3 | 31.68 | 78.85 |
| 0.5% carbon fiber +30% graphite | 263 | 9.16 | 49.46 | 850.1 | 6.0 | 33.38 | 67.49 |

![Figure 19: 0.4% carbon fiber +30% graphite CGA-10 micrograph. (a) Asphalt mixture morphology at 200 times. (b) Asphalt mixture morphology at 500 times.](image-url)
of carbon fiber is much larger than that of graphite, and aggregates have less blocking effect on carbon fiber. On the one hand, carbon fiber can make up for the interruption of the conductive chain of graphite particles, and connect the separated conductive particles in the poured asphalt concrete. The conductive region is connected by a bunch of carbon fiber wires to enhance its conductive stability. On the other hand, high-strength chopped carbon fiber can play a role in reinforcing the poured asphalt concrete, which is able to inhibit the development of cracks and improve the strength of the poured asphalt concrete.

5. Conclusion

(1) The poured conductive asphalt concrete mixed with graphite and carbon fiber is successfully prepared, and 0.4% carbon fiber + 30% graphite has reached the “percolation threshold” of pouring conductive asphalt concrete, which can form a good conductive network.

(2) The pavement performance of the prepared nine groups of poured conductive asphalt concrete meets the requirements. Compared with carbon fiber, graphite has a great influence on the high temperature performance, low temperature performance and water stability of poured conductive asphalt concrete. Adding a certain amount of carbon fiber can balance the adverse effect of graphite on the pavement performance of poured conductive asphalt concrete.

(3) The higher the content of conductive materials, the faster the heating rate, and the better the heating effect. The heating efficiency of 0.4% carbon fiber + 30% graphite poured conductive asphalt concrete is 78.85%, and the ice melting efficiency is 50.03%.

(4) Layered graphite powder particles are tightly wrapped with asphalt mortar, which reduces the porosity and resistivity of asphalt mixture. On the one hand, bundled carbon fiber can make up for the interruption of graphite particle conductive chain, on the other hand, it can play a role in reinforcing.

Data Availability

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors do not have any conflict of interest with other entities or researchers.

Acknowledgments

Original draft preparation was done by Li, Z. X., and Y. Lu.; reviewing and editing were performed by Guo, T. T., Y. Z. Chen, and X. J. Niu.; investigation performed by Yang, X., and L. H. Jin.; discussion was done by Y Guo, T. T., Y. Z. Chen, and X. J. Niu. All authors have read and agreed to the published version of the manuscript. This work was supported by Key R&D and Promotion of Special Scientific and Technological Research Projects of Henan Province [Grant nos. 182102210061 and 212102310089] and Key Scientific Research Projects of Colleges and Universities in Henan Province in 2021: Study on pavement performance of cotton straw cellulose modified asphalt [Grant no. 21A580004].

References

[1] J. Man, K. Yan, Y. Miao et al., “3D Spectral element model with a space-decoupling technique for the response of transversely isotropic pavements to moving vehicular loading,” Road Materials and Pavement Design, pp. 1–25, 2021.
[2] J. Zhao and H. Wang, “Dynamic pavement response analysis under moving truck loads with random amplitudes,” Journal of Transportation Engineering, Part B: Pave ments, vol. 146, no. 2, Article ID 04020020, 2020.
[3] L. You, K. Yan, J. Man, and T. Shi, “3D spectral element solution of multilayered half-space medium with harmonic moving load: effect of Layer, Interlayer, and loading properties on dynamic response of medium,” International Journal of Geomechanics, vol. 20, no. 12, Article ID 04020227, 2020.
[4] H. Yu, T. Ma, and D. Wang, “Summary of academic research on pavement engineering in China-2020,” China Journal of Highway and Transport, vol. 33, no. 10, pp. 1–66, 2020.
[5] Q. Chen, C. Wang, and Z. Fan, “Prediction model for heat conduction effect of cast conductive asphalt concrete composite structure,” Materials Reports, vol. 33, no. 10, pp. 1659–1665, 2019.
[6] C. Wang, Q. Chen, and Z. Gao, “Present situation and development of cast asphalt concrete,” Materials Reports, vol. 31, no. 5, pp. 135–145, 2017.
[7] Y. Chen, Z. Li, C. Zhao et al., “Research on environmental protection slow-release active snowmelt coating materials,” China Journal of Highway and Transport, vol. 33, no. 09, pp. 155–167, 2020.
[8] H. Chen, Y. Wu, H. Xia, B. Jing, and Q. Zhang, “Review of ice-pavement adhesion study and development of hydrophobic surface in pavement deicing,” Journal of Traffic and Transportation Engineering, vol. 5, no. 03, pp. 224–238, 2018.
[9] M. A. Notani, A. Arbabzadeh, H. Ceylan, S. Kim, and K. Gopalakrishnan, “Effect of carbon-fiber properties on volumetrics and ohmic heating of electrically conductive asphalt concrete,” Journal of Materials in Civil Engineering, vol. 31, no. 9, 2019.
[10] Y. Tan, C. Zhang, H. Xu, and T. Dong, “Review on snow melting and ice melting characteristics and road performance of active deicing pavement,” China Journal of Highway and Transport, vol. 32, no. 04, pp. 1–17, 2019.
[11] Y. Tan, K. Liu, and Y. Wang, “Nonlinear volt-ampere characteristics of carbon fiber/graphene conductive asphalt concrete,” Journal of Building Materials, vol. 22, no. 02, pp. 278–283, 2019.
[12] P. Pan, “Conductive asphalt concrete: a review on structure design, performance, and practical applications,” Journal of Intelligent Material Systems and Structures, vol. 26, no. 7, pp. 755–769, 2015.
[13] X. Liu, W. Liu, S. Wu, and C. Wang, “Effect of carbon fillers on electrical and road properties of conductive asphalt materials,” Construction and Building Materials, vol. 68, pp. 301–306, 2014.
[14] P. Apostolidis, X. Liu, A. Scarpas, C. Kasbergen, and M. F. C. van de Ven, "Advanced evaluation of asphalt mortar for induction healing purposes," *Construction and Building Materials*, vol. 126, pp. 9–25, 2016.

[15] A. O. Monteiro, A. Loredo, P. M. F. J. Costa, M. Oeser, and P. B. Cachim, "A pressure-sensitive carbon black cement composite for traffic monitoring," *Construction and Building Materials*, vol. 154, pp. 1079–1086, 2017.

[16] M. Shu, *Finite Element Simulation of Conductive Asphalt Concrete Melting Snow and Ice*, Nanchang University, Nanchang, China, 2011.

[17] K. Liu, *Study on Conductive Mechanism and Road Performance of Conductive Asphalt concrete*, Nanchang University, Nanchang, China, 2013.

[18] U. Shafi, C. Yang, L. Cao et al., "Material design and performance improvement of conductive asphalt concrete incorporating carbon fiber and iron tailings," *Construction and Building Materials*, vol. 303, 2021.

[19] J. Jiang, X. Zhang, X. Liu, Y. Deng, and L. Dong, "Grey correlation analysis of influencing factors of conductive asphalt concrete pavement performance," *Railway Science and Engineering Journal*, vol. 12, no. 04, pp. 784–789, 2015.

[20] Y. Rew, X. Shi, K. Choi, and P. Park, "Structural design and lifecycle assessment of heated pavement using conductive asphalt," *Journal of Infrastructure Systems*, vol. 24, no. 3, 2018.

[21] Z. Liu, S. Wu, P. Liu, and G. Hu, "Research progress on conductive asphalt concrete and its functional properties," *Materials Reports*, vol. 31, no. S1, pp. 374–378+387, 2017.

[22] Y. Rew, A. Baranikumar, A. V. Tamashausky, S. El-Tawil, and P. Park, "Electrical and mechanical properties of asphaltic composites containing carbon based fillers," *Construction and Building Materials*, vol. 135, pp. 394–404, 2017.

[23] F. Chen, S. Wu, and Y. Zhang, "Electrical properties of steel slag conductive asphalt concrete," *Road Construction Machinery and Construction Mechanization*, vol. 27, no. 11, pp. 51–54, 2010.

[24] Y. He, Z. Ao, L. Lv, Q. Ding, and S. Hu, "Resistance stability of steel slag conductive asphalt concrete for ice melting," *Journal of Beijing University of Technology*, vol. 37, no. 01, pp. 80–84, 2011.

[25] B. Li, Y. Li, and X. Liang, "Research on induction healing performance of porous asphalt concrete with steel wool," *Journal of China and Foreign Highway*, vol. 35, no. 4, pp. 239–243, 2015.

[26] Y. Yuan, H. Xu, and Y. Zhang, "Experimental study on thermal performance of conductive asphalt concrete," *Journal of Huazhong University of Science and Technology (Natural Science Edition)*, no. 10, pp. 128–132, 2014.

[27] X. Wang and Y. Gao, "Preparation and electrical conductivity of carbon fiber graphite conductive asphalt concrete," *Highway*, no. 1, pp. 139–142, 2012.

[28] H. Zhang, L. Wang, S. Zhao, and H. Liu, "Conductive mechanism of PANI/PP composite conductive fiber asphalt concrete," *Journal of Dalian University of Technology*, vol. 50, no. 04, pp. 564–569, 2010.

[29] X. Feng, X. Cha, and J. Cheng, "Preparation and performance of PAN-based carbon fiber conductive asphalt concrete," *China Journal of Highway and Transport*, vol. 25, no. 02, pp. 27–32, 2012.