

Research Article

Study on Cooling Effect and Pavement Performance of Thermal-Resistant Asphalt Mixture

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To reduce the temperature of asphalt pavement and improve the antirutting performance of asphalt mixture, a thermal-resistant asphalt mixture (TRAM) was produced, in which a certain proportion of mineral aggregate was replaced by ceramic (CE) or floating beads (FB) featuring low thermal conductivity. Firstly, a parallel plate test was developed to test the thermal conductivity of asphalt mixture added with different thermal-resistant materials. Secondly, the illumination test system was designed to study the visual cooling effect of different TRAM by imitating the natural environment. Finally, the effect of different thermal-resistant materials on asphalt pavement performance was evaluated. The results show that the addition of thermal-resistant materials can reduce the thermal conductivity and the temperature of asphalt mixture. The cooling effect of CE75 and CE100 (coarse aggregate substituted by 75% and 100% CE, respectively) is superior to other aggregates. The temperature reduction rates of CE75 and CE100 reached 6.6°C and 6.8°C, respectively. For FB50 and FB75 (fine aggregate substituted with 50 and 75% FB, respectively), the cooling effect of them reached 3.9°C and 4.5°C, respectively. In addition, the CE and FB can improve the antirutting performance of asphalt mixture by reducing the temperature inside the pavement. The high-temperature performance of CE75 and FB75 is the best. With the increase of thermal resistance materials, the low-temperature cracking resistance of asphalt mixture decreases gradually. The failure strain of mixture added with 100% thermal resistance materials is close to the lower limit of Chinese specification. The water stability of different TRAM changes with various test methods. Taking into account the results of pavement performance and the cooling effect, the substitution proportion of CE and FB for TRAM is proposed as 50%~75%, respectively.

1. Introduction

Asphalt mixture is a kind of black material, which highly absorbs solar radiation [1]. The temperature of asphalt pavement is higher than atmospheric temperature, leading to the occurrence of high-temperature deformation. In addition, the absorption of heat energy in asphalt pavement not only leads to the raising of pavement temperature but also releases a lot of heat to the surrounding environment, which results in rutting disease of pavement and “urban heat island effect” [2–10]. Therefore, improving the temperature field of asphalt pavement structure is of great advantage for pavement rutting resistance and mitigation of “heat island effect.” Due to the low thermal conductivity,

the thermal-resistant materials used in asphalt mixture have drawn more and more attention. The heat absorption and storage of asphalt pavement can be decreased, and thus, the pavement temperature is reduced.

Heat-reflective layer and thermal resistance technology have been used to lower the pavement temperature [11]. A heat-reflective layer improves the reflectivity and radiation efficiency of pavement surface and then lowers the pavement temperature by preventing external heat from transferring into pavement structure [12–19]. But, the application of coating has been limited due to the defects in cost, technology, and durability. The thermal resistance technology for reducing the pavement temperature is adding thermal resistance material, which could reduce the temperature of

pavement effectively. The thermal resistance materials include ceramic, pottery sand, diatomite, bauxite, and refractory stone [20–24].

Feng and Yi [25] made a kind of thermal-resistant seal layer by adding ceramic or diatomite; the two seal layers showed obvious cooling effect after strong light exposure for 3 h. The results showed that the ceramic seal layer specimen can reduce the temperature by 2~3°C. Zhang [26] added the ceramic into the asphalt wear layer, and the results showed that, as the aggregates whose diameter varies from 9.5 mm to 4.75 mm are replaced by the equal volume of 20% ceramic, the thermal conductivity of mixture decreases by 31.8% and the specific heat capacity increases by 212.9%. Khan and Mrawira [27] found that the thermal conductivity of asphalt pavement could be improved by adding lightweight aggregate ceramic. Ren [28] studied the thin wear layer of ceramic asphalt mixture with different contents of ceramic waste. The study showed that when the wear layer is 5 cm thick, the cooling effect can reach more than 10°C. The water stability and high-temperature stability of the mixture decrease rapidly when the proportion of ceramic waste is more than 60%; it was found that the optimal content of ceramic waste is 40%~60%.

Li [29] used calcined bauxite to replace the coarse aggregate of AC-13C mixture. The results showed that the incorporation of calcined bauxite would decrease the temperature of asphalt mixture effectively. The optimum content of calcined bauxite for asphalt mixture was proposed as 80%. Cong et al. [30] studied the pavement surface temperature and the relationship between pavement permeability coefficient and mixture porosity. The results showed that the pavement temperature is related to the porosity and connectivity of the mixture. The pavement with 10% porosity can reduce the temperature by 5°C.

Although there have been considerable researches related to the cooling effect of asphalt mixture added with different materials, at present, many studies just describe the cooling effect of thermal resistance materials on pavement, and the test methods cannot simulate the actual working environment of asphalt pavement. Only some studies relate the influence of cooling effect of different thermal resistance materials on pavement performance. In this paper, the test method, imitating the real temperature environment of asphalt pavement, was designed to evaluate the thermal conductivity and antirutting performance of two kinds of TRAM. Firstly, the thermal conductivity was measured by a parallel plate test. Secondly, the indoor and outdoor illumination tests were developed to evaluate the cooling effect of TRAM by imitating the natural environment. Finally, the effect of different thermal-resistant materials on asphalt mixture pavement performance was also studied.

2. Materials and Methods

2.1. Materials

2.1.1. Raw Materials. SK-70# asphalt was used in the TRAM. The coarse basalt aggregate, fine limestone aggregate, and limestone powder were selected. Thermal-resistant materials

were shale ceramic (CE) and fly ash floating beads (FE). CE is a mineral material which is produced through the process of burning up and foaming. It is a spherical material with smooth surface and honeycomb porous. In this paper, CE was used to replace the coarse aggregate to produce a thermal-resistant asphalt mixture due to its larger particle size. The shale ceramic was adopted in this paper, and the particle size was between 5 and 15 mm [31]. The physical properties of CE are shown in Table 1.

Floating beads (FB) [32] is a fly ash material, derived from power plant fly ash. It is a material with following features such as lightweight, heat insulation, sound insulation, high-temperature resistance, high wear resistance, low thermal conductivity, and good mobility. The use of FB in asphalt mixture can reduce pavement temperature. In addition, its application is helpful in the resources recycling [33]. The physical properties of FB are shown in Table 2.

2.1.2. Design of TRAM. In this paper, AC-13C which was widely used in the upper layer of asphalt pavement was used to analyze the thermal resistance effect of CE and FB. The gradation composition is detailed in Table 3.

(1) Optimal Asphalt Content of CE. The aggregate was replaced by CE with an equal volume proportion in the asphalt mixture. CE was used to replace three sizes of coarse aggregate (13.2 m, 9.5 mm, and 4.75 mm) in AC-13C asphalt mixture. The substitution proportions were 0, 25, 50, 75, and 100% respectively, and the five ratios were represented by CE0, CE25, CE50, CE75, and CE100. The replacement mass can be calculated using the following formula [34]:

$$M_{R,i} = \frac{M_{A,i} \cdot P_i \cdot \rho_{R,i}}{\rho_{A,i}}, \quad (1)$$

where $M_{R,i}$ is the quantity of the thermal-resistant material that replaces the aggregate in size i , g; $M_{A,i}$ is the quantity of the aggregate in size i of the specimen, g; P_i is the proportion of the thermal-resistant material of aggregate in size i , %; and $\rho_{A,i}$ and $\rho_{R,i}$ are, respectively, the apparent density of the aggregate in size i and the thermal-resistant material, g/cm³.

According to the Marshall test, the optimal asphalt content of CE (CE0, CE25, CE50, CE75, and CE100) can be determined. The results are shown in Table 4.

(2) Optimal Asphalt Content of FB. FB was used to replace the fine aggregate due to its small particle size. Appropriate particle size of FB was chosen to replace the fine aggregate (0.6 mm, 0.3 mm, 0.15 mm, and 0.07 mm), and the substitution proportions were 0, 25, 50, 75, and 100%, respectively. The five substitution ratios were represented by FB0, FB25, FB50, FB75, and FB100. Formula (1) is also used in the calculation of the replacement mass of FB. According to the Marshall test, the optimal asphalt content and volume parameters of the mixture with different proportion FB were determined as shown in Table 5.

TABLE 1: The physical properties of CE.

Technical index	Unit	Measured value	Norms requirement
Crushing value	%	30.1	≤26
Los Angeles wear rate	%	26	≤28
Polished value	PSV	50	≥42
Average particle size coefficient	%	0.9	≤1.6
Adhesion	—	4 grade	≥4 grade
Water absorption	%	5.3	≤3

TABLE 2: Major performance indexes of FB used in the test.

Technical index	Unit	Floating beads	Fly ash
Refractory temperature	°C	1500	1400
True density	g/cm ³	0.721	1.95
Specific surface area	cm ² /g	2516	3120
SiO ₂ content	%	55–59	1.3–65
Particle-size distribution	μm	0–600	0–300
Thermal conductivity	W/(m·K)	0.058	0.110

TABLE 3: Aggregate gradation used for AC-13C mixture.

Mineral aggregate gradation	Passing ratio (by mass) (%)									
	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
AC-13C	100	96.5	80.0	53.7	37.0	25.2	17.5	11.8	9.0	5.4

TABLE 4: Results of the mixture with different CE proportions.

Mixture type	Optimal asphalt content (%)	Gross volume density (g/cm ³)	Maximum theoretical relative density	VV (%)	VMA (%)	VFA (%)	MS (kN)	FL (0.1 mm)
CE0	4.7	2.384	2.493	4.4	16.1	73.00	11.58	3.24
CE25	4.8	2.214	2.320	4.6	17.0	73.12	11.44	3.37
CE50	4.8	2.059	2.156	4.5	16.8	71.10	10.77	3.17
CE75	5.2	1.956	2.052	4.7	21.7	78.44	10.43	2.96
CE100	5.5	1.817	1.902	4.5	26.9	83.30	10.31	3.52

TABLE 5: Results of the mixture with different FB proportions.

Mixture type	Optimal asphalt content (%)	Gross volume density (g/cm ³)	Maximum theoretical relative density	VV (%)	VMA (%)	VFA (%)	MS (kN)	FL (0.1 mm)
FB0	4.7	2.384	2.493	4.4	16.1	73.00	11.58	3.24
FB25	4.8	2.331	2.425	3.9	16.7	76.79	10.32	2.46
FB50	4.6	2.320	2.415	3.9	12.6	68.74	9.73	2.33
FB75	4.4	2.273	2.368	4.0	10.8	62.99	9.39	2.05
FB100	4.3	2.225	2.326	4.1	8.2	51.24	9.28	1.44

2.2. Test Methods

2.2.1. Thermal Conductivity Test. The thermal resistance material was applied to reduce pavement temperature due to its low thermal conductivity. To verify the thermal conductivity of thermal resistance materials, the parallel plate test was developed. The schematic diagram is shown in Figure 1.

The test device is mainly composed of three parts: heating and temperature control system, temperature acquisition system, and insulation system. The test specimens were 300 mm × 300 mm × 50 mm in dimensions. In order to accurately control and measure the heat passing through

the specimen, the electric heating plate was sandwiched between two slab specimens; the constant-temperature water tank was controlled by a thermostatic circulation system which was arranged on the outside of the two specimens so that the heat passes through the specimens from the inside to the outside and gradually forms a stable gradient temperature field through which the thermal conductivity state can be reached. The probes of the temperature collector were arranged on both sides of the specimen. Thus, the collector can accurately measure the surface temperature on both sides, and then, the data were imported and stored in a multichannel temperature data acquisition instrument.

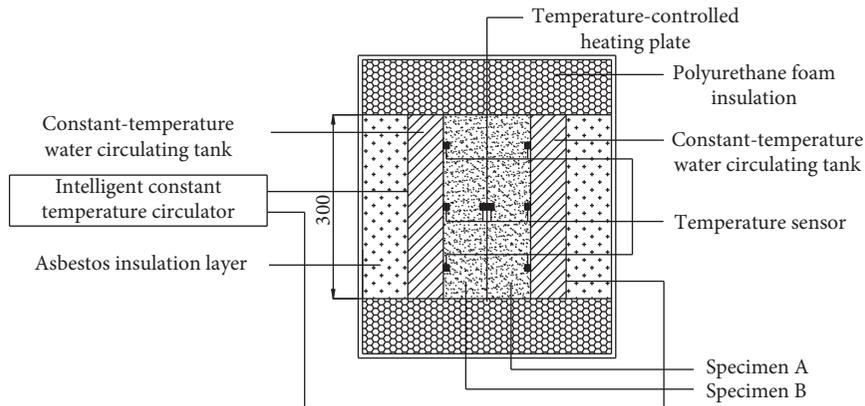


FIGURE 1: Schematic diagram of the test system.

2.2.2. Cooling Effect Test

(1) *Indoor Illumination Test.* The cooling effect of asphalt mixture was evaluated by the indoor illumination system developed by Chang'an University. The slab specimen with the dimension of $30\text{ cm} \times 30\text{ cm} \times 5\text{ cm}$ was formed with rolling wheel compaction and placed in the testing apparatus, as shown in Figure 2. To prevent heat from getting out and improve the measurement accuracy, a test board around was sealed by using a 5 cm thick foam plate. The testing apparatus consists of a lighting system (xenon lamps, wire, and bracket), a temperature acquisition system (a temperature sensor, a temperature recorder, and a computer), and a transparent glass box with top opening. The illumination intensity of 788 W/m^2 of the illumination system was adopted according to the equivalent conversion for the total solar illumination intensity of the pavement.

The temperature sensors were installed in the middle of top and bottom surface of the slab specimen, respectively. The temperature of the specimens was measured by using the multichannel automatic temperature recorder at the intervals of 30 min. In the procedure, the specimen was exposed to the lighting system at least 5 hours in the test.

(2) *Outdoor Illumination Test.* To verify the accuracy of the indoor illumination test, the outdoor illumination test was also designed. The test was conducted using the same specimen that was used in the indoor test. The test system is the same as of the indoor test as described, as shown in Figure 3. To reduce environment disturbance, the specimen around was insulated by clay.

2.2.3. *Pavement Performance Test.* To evaluate the influence of asphalt mixture with different thermal-resistant materials on pavement performance, the asphalt mixture with different contents of CE and FB was subjected to the illumination rutting test, the little beam bending test, the freeze-thaw splitting test, and the Hamburg wheel tracking device (HWTDD) test.

At present, the rutting test is a widely used method for evaluating the high-temperature performance of mixture. In the rutting test, the specimen is conditioned at 60°C for 5

hours in the environment box. By this insulated condition process, the top and bottom of the specimen reaches a thermal equilibrium; the cooling effect of the thermal-resistant material cannot work in the rutting test. Therefore, the test method of illumination rutting was developed to evaluate the high-temperature performance of different thermal resistance asphalt mixtures. In the environment box, the temperature change of the asphalt mixture is close to its regularity under natural illumination during actual use so that the rutting resistance of the thermal resistance asphalt mixture was evaluated more objectively. The illumination rutting test system operates as shown in Figure 4.

(1) *Illumination Rutting Test System.* In the illumination rutting test system, the illumination heating was used instead of the traditional air bath heating. The system consists of three parts: a rolling system, an illumination system, and temperature acquisition system. The kilowatts iodine tungsten lamp was used as the illumination source. The lamp heating equipment was fixed above the slab specimen, and the illumination intensity was set to 788 W/m^2 . One four-channel temperature recorder was used for temperature acquisition with the recording frequency of 15 min/times. Two temperature sensor probes were set on the top and bottom of the slab specimen parallel to the rolling direction, and the probes were positioned at the two sides for 3 cm from the wheel track.

(2) *Test Process.* The rolling times were counted as the illumination system turned on, and at that time, the room temperature was measured; then, as the temperature at the top of the specimen was 60°C , the rutting test was ended and the rolling times were recorded.

The addition of thermal-resistant material causes the change of the temperature field in pavement structure under the illumination and ultimately affects the antirutting ability of the pavement.

3. Results and Discussion

3.1. *Results of Thermal Conductivity Test.* It can be seen from Figure 5 that the thermal conductivity of asphalt mixture decreases as the content of thermal resistance materials

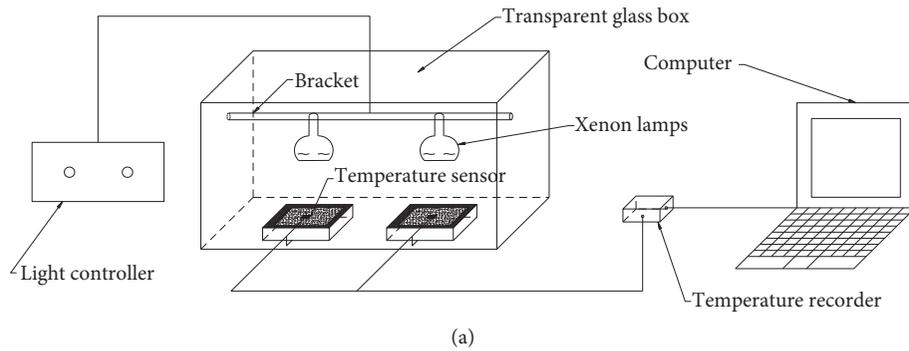


FIGURE 2: Test system of indoor illumination. (a) Schematic diagram of the illumination test and (b) light testing apparatus.



FIGURE 3: Test system of outdoor illumination.

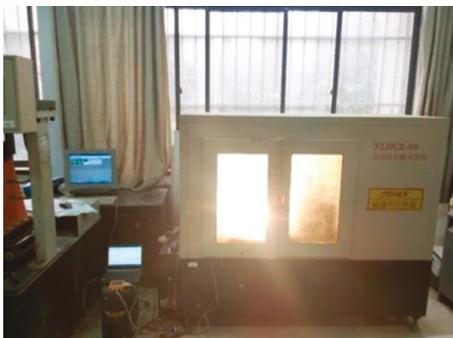


FIGURE 4: Illumination rutting test system.

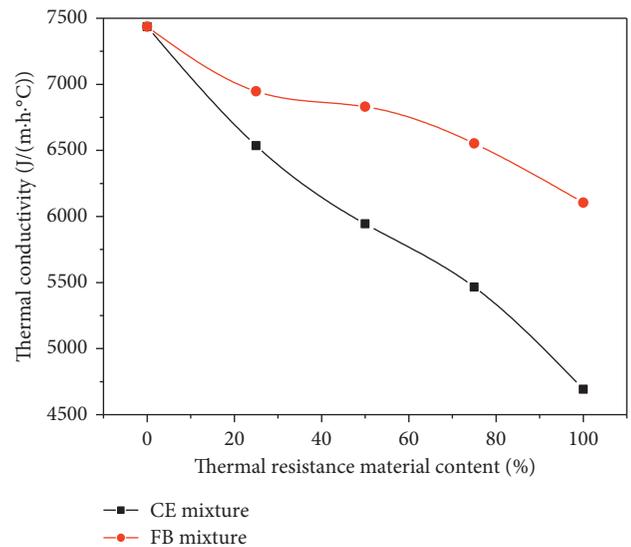


FIGURE 5: Results of the thermal conductivity test.

more thermal-resistant materials, the decreasing amplitude becomes larger gradually; it is because more and more thermal-resistant materials connect the heat transfer path in the mixture, so the effect of thermal resistance is superimposed and enhanced [35, 36]. By comparison, it can be seen that thermal conductivity of CE mixture is smaller than that of FB mixture under the same amount of admixture.

increases; the reason may be that the thermal conductivity of CE and FB is much smaller than that of mineral aggregate. Adding thermal resistance materials into aggregate will decrease thermal conductivity of the mixture. And with

3.2. Results of Cooling Effect

3.2.1. *Indoor Illumination Test.* The slab specimens of CE and FB mixtures were subjected to the indoor illumination

test, and the results are shown in Figure 6 and Table 6. It can be seen from Figure 6 that the test results of CE mixture and FB mixture show similar trends, where the temperatures at the top and bottom of the slab specimens gradually increase with the illumination time during 5 hours lighting; it accords the change law of temperature of asphalt pavement in the natural environment. But, with the addition of more CE and FB, the maximum temperature of top surface increases and that of bottom surface decreases. This is due to that the increasing of thermal resistance materials lead to the decrease of thermal conductivity of mixture, and it can effectively impede heat transfer downward, resulting in more accumulation of heat near the top surface and the temperature of lower layer in pavement to reduce. Table 6 shows that when the substitution proportion of CE is 25, 50, 75, and 100%, the effect of cooling is 2.6, 4.2, 6.6, and 6.8°C, respectively. This shows that the cooling effect increases with more addition of CE, but the rate of increase slows down because the increase rate of top surface temperature also increases with more CE, which weakens the cooling effect of the whole pavement structure. With the more addition of FB, the effect of cooling is 3.1, 3.9, 4.5, and 2.2°C respectively. FB can reduce the temperature of the pavement, but the cooling effect of FB does not correspond with the proportion strictly, which does not mean that the more the FB, the better the cooling effect. When the substitution proportion is more than 75%, its cooling effect is relatively poor. That may be caused by the less asphalt content which results in inadequate compaction of asphalt mixture. The heat insulation effect of asphalt mixture gets poorer when the aggravate structure is loose, so the proportion of FB should not be too large.

For the mixture added with CE, the order of their cooling effect is as follows: 100, 75, 50, 25, and 0%, while for the mixture added with FB, the order is as follows: 75, 50, 25, 100, and 0%; the cooling effect of specimen CE100 and specimen FB75 reaches 6.8°C and 4.5°C, respectively. By comparison, the cooling effect of CE is better than that of FB.

3.2.2. Outdoor Illumination Test. In order to verify the accuracy of the indoor illumination test, the outdoor illumination test of CE was carried out in this study. The results are shown in Figure 7 and Table 7. Figure 7 shows that the maximum temperature at the top surface of specimens changes little. However, the maximum temperature at the bottom reduces gradually with the increase of thermal-resistant materials, which is different from the indoor test. The reason is that the outdoor test was carried out in the air environment in which the air flows freely. This makes the radiant heat dissipate out and results in that the rise of top surface temperature is not obvious. Furthermore, in the outdoor test, the illumination intensity and the incident angle are changing with time. The illumination is weak both in morning and evening, and it is just strong at noon, which inevitably results in that the pavement temperature will not vary greatly. As can be seen in Table 7, the cooling effect of specimen CE is

slightly better than the results from the indoor test. When the substitution proportions of CE are 25, 50, 75, and 100%, the effect of cooling is 4.3, 5.2, 6.7, and 6.8°C, respectively. But, the cooling trend of CE as a thermal resistance material in the asphalt mixture is the same under two different test conditions; that is, the cooling effect increases with the larger proportion of CE. What is more, the mixture added with 100% proportion of CE is exposed to both indoor and outdoor illuminations, which has the same cooling effect of 6.8°C. This indicates that the indoor illumination test has limitation, but it can still be used to evaluate the cooling effect of thermal resistance asphalt mixture.

3.3. Results of Road Performance

3.3.1. Evaluation of High-Temperature Performance. As can be seen from Figure 8 that as the temperature of the top of the specimen reached 60°C, the rutting depth of CE mixture declines first and then increases slightly with the increase of CE. In the rutting depths of CE0, the CE25, CE50, CE75, and CE100, the decrease rates are 17.4%, 30.8%, 36.5%, and 32.9%, respectively. As for the deformation rate, it declines first and then increases. Because the temperature field of the slab specimen changes with the addition of CE, the anti-rutting performance improves. It must be noted that, with the addition of porous materials, the mechanical properties of the mixture may decrease. When the amount of CE is more than 75%, the performance degradation is larger than the performance improvement caused by temperature decrease, so the deformation rate of the specimen will increase. However, the performance of CE mixture is still better than ordinary hot mix in general.

For FB mixture, the change laws of rutting depth and deformation rate are similar to the CE mixture as a whole. With the increasing of FB, compared with FB0, the decrease rates are 8.5% (FB25), 20.1% (FB50), 25.1% (FB75), and 16.5% (FB100). The reason for the change of rutting depth and deformation rate is similar to that of CE mixture.

Under the same proportion of admixture, the anti-rutting performance of FB mixture is worse than that of CE mixture. Moreover, the cooling effect of CE mixture is also better than that of FB mixture, and the same conclusions are achieved in the thermal conductivity test and cooling effect test. The order of CE mixture performance is conducted as follows: 75, 100, 50, 25, and 0%. It can be seen that the high-temperature performance order of mixture with 75% and 100% CE is not consistent with the cooling effect order. The reason is that hollow ceramic makes the strength of mixture to decrease and the content of asphalt will increase due to more porous materials in the mixture. These two factors comprehensively make the high-temperature performance decrease, so the content of CE in the mixture should be controlled. While for the mixture with FB, the order of anti-rutting performance is as follows: 75, 50, 100, 25, and 0%, which is not consistent with the cooling effect order of the mixture with 25% and

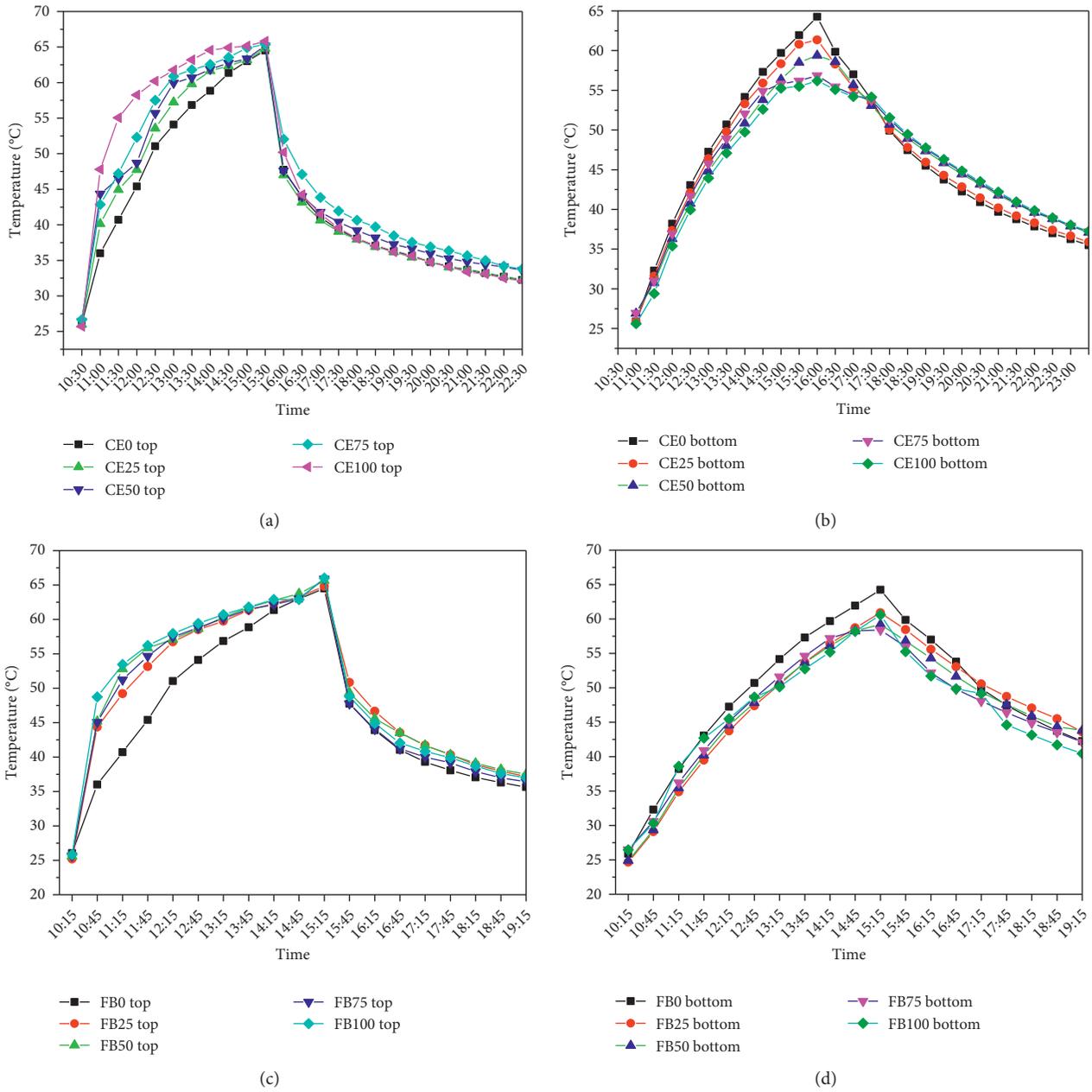


FIGURE 6: Temperature variation of the indoor illumination test (°C). (a) The top surface for CE type, (b) the bottom surface for CE type, (c) the top surface for FB type, and (d) the bottom surface for FB type.

TABLE 6: Results of the indoor cooling effect for TRAM.

Mixture type	Top surface maximum temperature (°C)	Bottom surface maximum temperature (°C)	Temperature difference (°C)	Cooling effect (°C)
CE0	64.5	64.3	0.3	—
CE25	64.8	61.4	3.4	2.6
CE50	65.2	59.4	5.8	4.2
CE75	65.35	56.85	8.5	6.6
CE100	65.8	56.2	9.6	6.8
FB0	64.5	64.3	0.2	—
FB25	64.8	60.9	3.9	3.1
FB50	65.7	59.2	6.5	3.9
FB75	65.9	58.4	7.5	4.5
FB100	66.0	60.6	5.4	2.2

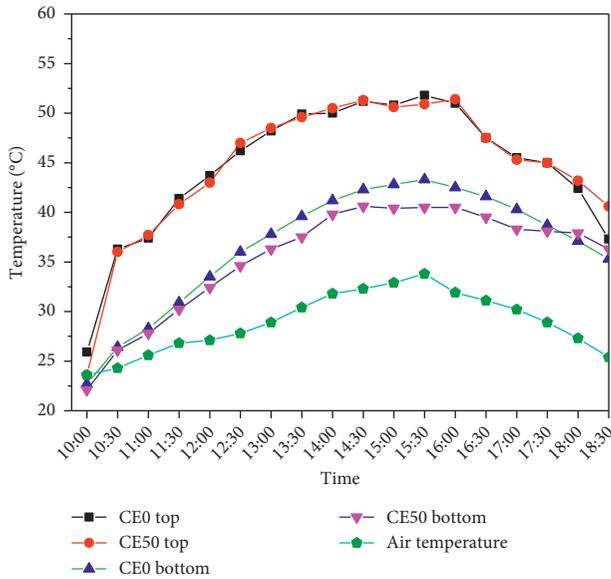


FIGURE 7: Temperature variation of the outdoor illumination test (°C).

TABLE 7: Results of outdoor cooling effect for CE.

Mixture type	Top surface maximum temperature (°C)	Bottom surface maximum temperature (°C)	Temperature difference (°C)	Cooling effect (°C)
CE0	51.8	45.3	6.5	—
CE25	51.6	41.2	10.4	4.3
CE50	51.3	40.6	10.7	5.2
CE75	51.5	38.9	12.6	6.7
CE100	51.8	38.5	13.3	6.8

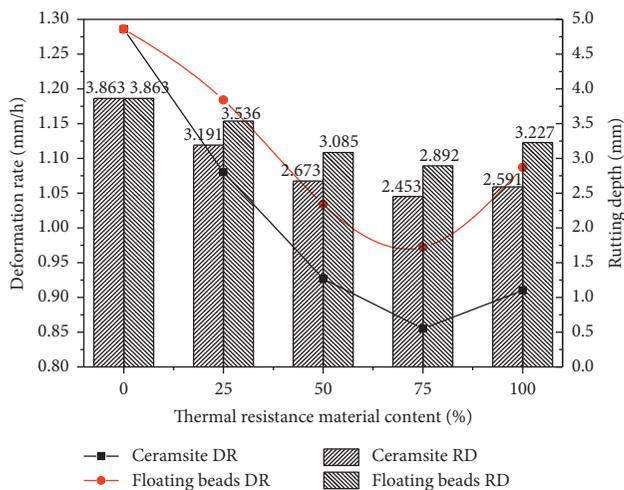


FIGURE 8: Results of the illumination rutting test.

100% FB. This is because when the substitution proportion of FB reaches 100%, the spherical shape of FB makes the asphalt mixture easily to be compacted and less optimum

asphalt content, which improves the high-temperature performance to some extent.

3.3.2. Evaluation of Low-Temperature Anticracking Performance. The low-temperature anticracking performance of mixture added with different contents of CE and FB was evaluated by the beam bending test, respectively. The results are shown in Figure 9.

As shown in Figure 9, with the increase of thermal resistance materials, the ultimate flexural strength and failure strain of the mixture decrease gradually, and the stiffness modulus increases. The results show that the addition of thermal resistance materials reduces the low-temperature cracking resistance of the mixture, the failure strain of CE100 and FB100 reaches 2938.6 $\mu\epsilon$ and 2812.3 $\mu\epsilon$, respectively. Obviously, when the proportion of thermal resistance materials reaches 100%, the failure strain of the mixture is close to the lower limit of Chinese specification. So, the replacement of two thermal resistance materials in the mixture should be less than 100%.

3.3.3. Evaluation of Water Stability Performance. As can be seen from Figure 10 and Table 8, the results of freeze-thaw splitting test for CE mixture are similar to those of HWTD. That is, a small amount of CE reduces the water stability of the mixture. But, with the increase of CE, the water stability performance increases first and then decreases. The reason is that the addition of low crushing value of CE reduces the overall strength of asphalt mixture. As CE dosage continues to increase, the porous structure of CE forms connected void in the mixture, and the space is reserved for the frost heave of water. Furthermore, CE can absorb light oil. CE plays the role of wedging and anchoring in the mixture. So, with the increase of CE, the water stability performance has a small increase. When the content of CE is more than 75%, its low mechanical strength is the main factor affecting the decline of water stability, thus causing the TSR of CE100 near the lower limit of specification. But, the water stability of CE mixture can still meet the requirements of Chinese standard JTG F40-2004.

For the mixture with FB, the TSR of asphalt mixture gradually drops as the proportion of FB increases. When the substitution proportion of FB reaches 100%, water stability of asphalt mixture cannot meet the requirements of specification. In the HWTD test, the order of water stability performance is as follows: 75, 50, 25, 0, and 100%. This means that the conclusions about the water stability evaluation of the mixture with FB are concerned with different test methods. The reason is that the freeze-thaw splitting test is used to evaluate short-term water stability, and the test loading mode of asphalt mixture is different from reality, causing the relatively low result reliability. In comparison, the dynamic loading is used in the HWTD test to simulate real load action which can imitate the effect of dynamic water on adhesion between asphalt and aggregate, so the result is more credible.

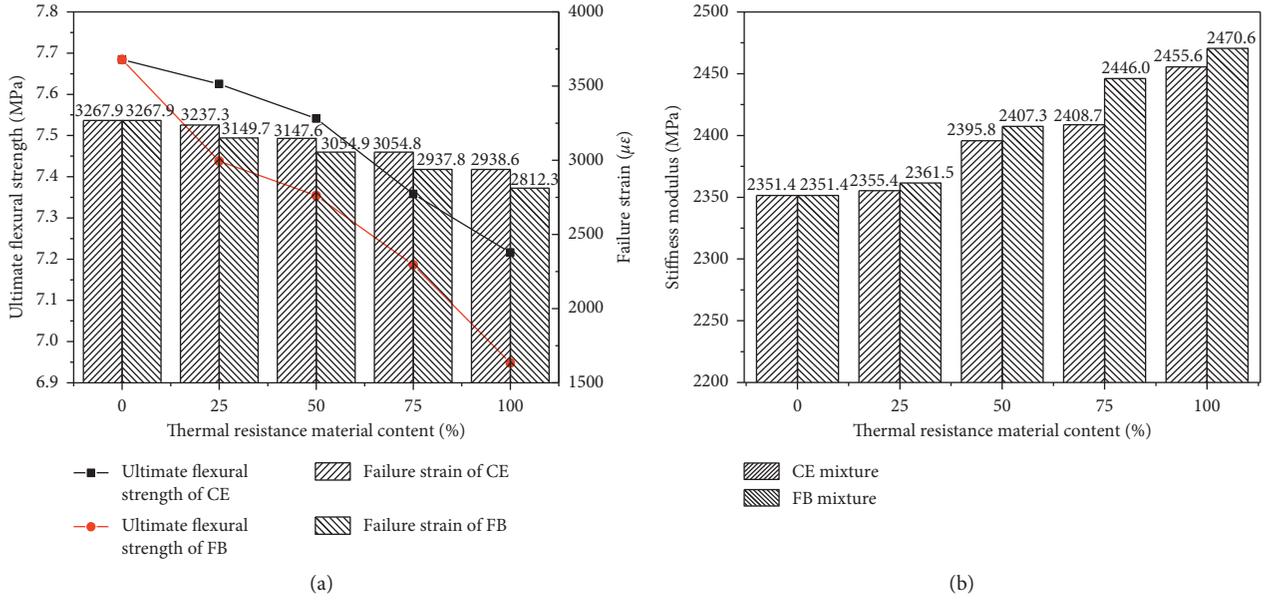


FIGURE 9: Results of the little beam bending test. (a) Ultimate flexural strength and failure strain and (b) stiffness modulus.

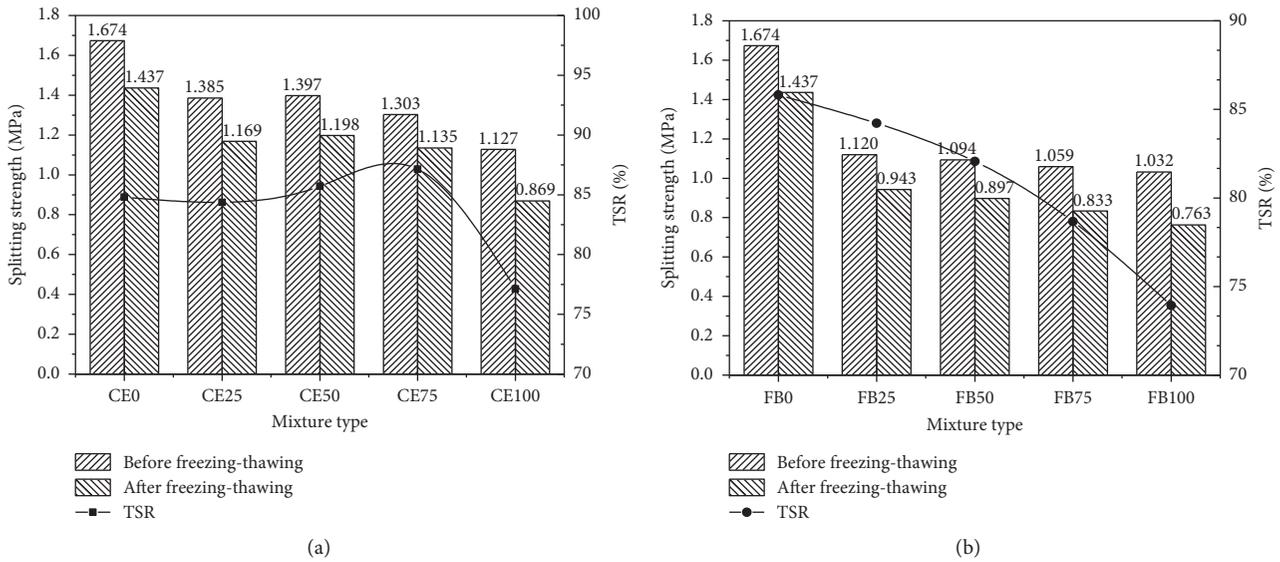


FIGURE 10: Results of the freeze-thaw splitting test. (a) CE type. (b) FB type.

TABLE 8: Results of HWTD.

Mixture type	Loading times (times)	Rut depth (mm)	Sip (times)	Strip slope
HMA	20000	19.4	11800	450.3
CE25	20000	18.9	9800	576.4
CE50	20000	17.3	12160	858.5
CE75	20000	15.6	12710	999.7
CE100	20000	18.0	7360	835.9
FB25	20000	15.6	12920	995.5
FB50	20000	16.4	13250	910.2
FB75	20000	16.5	13900	751.7
FB100	20000	19.2	8130	703.3

4. Conclusions

In this study, the cooling effect of two kinds of thermal resistance materials was studied through indoor and outdoor illumination tests. The road properties of the mixture, such as high-temperature performance, low-temperature performance, and water stability performance, added with thermal resistance materials were investigated. The main conclusions are summarized as follows:

- (1) The thermal conductivity of asphalt mixture decreases as the proportion of thermal resistance material increases. The thermal conductivity of CE mixture is smaller than that of FB mixture under the same proportion of admixture.
- (2) For CE mixture, the cooling effect increases gradually with the increase of CE content. The temperature of the mixture added with 75% and 100% CE drops to 6.6 and 6.8°C, respectively. And, for FB mixture, the cooling effect increases first and then decreases as the proportion of FB increases. The temperature drops to 3.9°C and 4.5°C, respectively, for the mixture added with 50% and 75% FB. The cooling effect of CE is better than that of FB.
- (3) The high-temperature performance of the mixture added with CE and FB increases first and then decreases. When the proportion of CE and FB is 75%, the mixture obtains the best high-temperature performance. The antirutting performance of FB mixture is worse than that of CE mixture. With the increase of two thermal resistance materials, the low-temperature cracking resistance of cooling mixture decreases. The failure strain of CE100 and FB100 is close to the lower limit of Chinese specifications, so the replacement of two thermal resistance materials in the mixture should be less than 100%. The water stability of different TRAM varies with the test methods.
- (4) Based on the results of pavement performance and the cooling effect, the substitution proportion of CE and FB for the TRAM is proposed as 50%~75%.

Data Availability

We confirm that the data submitted in this manuscript are available. All the data provided in the manuscript were obtained from the experiments performed at the Key Laboratory for Special Area Highway Engineering of Ministry of Education of Chang'an University.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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