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Study of Pavement Performance and Temperature Regulation Capacity of Asphalt Binders Modified with Dual-Phase-Change Materials

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Abstract: Due to the temperature changes caused by seasonal changes and extreme weather, asphalt pavement suffers from rutting, cracking, and other damage. With commonly used pavement additives, the high-temperature performance and the low-temperature performance of asphalt pavement show opposite trends, with related research endeavoring to find a balance between the two. In this study, a dual-phase-change material (DPCM) with both high- and low-temperature effects was prepared. The chemical stability and rheological properties of modified asphalt binders were characterized using Fourier transform infrared spectroscopy (FTIR) and a dynamic shear rheometer (DSR). Temperature control tests of the DPCM-modified asphalt binders were carried out with an indoor simulation device. The results show that the DPCMs could improve the rutting resistance of the asphalt binders at a high temperature, but the fatigue performance of the modified asphalt binder with different DPCM contents was reduced. The FTIR results showed that no chemical reaction occurred in the mixing of the asphalt binder and the DPCM. In the indoor simulation temperature control test, the 40% DPCM-content-modified asphalt binder reduced the high-temperature extreme value by 4.2 °C and increased the low-temperature extreme value by 2.5 °C, showing a good temperature control effect and practical application value.

Keywords: phase-change materials; rheology; modified asphalt; rutting resistance

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1. Introduction

Asphalt binder is a viscoelastic material with high-temperature sensitivity, and it is negatively affected by temperature changes in practical engineering applications. Asphalt pavement is prone to rutting when subjected to vehicle loads in high-temperature environments [1,2]. In winter, it cracks easily in low-temperature environments [3,4]. Meanwhile, cyclic temperature stress also hardens asphalt binder and accelerates the aging of asphalt pavement, thus reducing its service life [5].

In recent years, researchers have developed many effective technologies to alleviate the damage to asphalt pavement caused by temperature changes. These include heat-reflective technology [6], water retention and cooling technology [7], thermal resistance technology [8], and energy conversion technology [9,10]. However, these temperature control technologies can only achieve either high- or low-temperature control; they cannot achieve both a delay in the road temperature rise in high-temperature environments and a delay in the road temperature drop in low-temperature environments. Obviously, this limited temperature regulation is not applicable to monsoon climate areas with distinct seasons and a large temperature range. As an energy storage, temperature regulation technology that has been widely used in recent years, phase-change materials (PCMs) have the potential to delay the temperature rise of road surfaces in high-temperature environments and delay the temperature drop of road surfaces in low-temperature environments [11–13].

At present, there are many types of phase-change materials, and, according to their different phase-change forms, PCMs can be divided into four categories: solid–solid, solid–liquid, solid–gas, and liquid–gas [14]. Among these, researchers consider solid–liquid organic phase-change materials to be the most effective heat storage materials because of their large phase-change enthalpy values and small volume changes before and after phase change [15,16].

Paraffin compounds are one of the most popular PCMs for asphalt pavement. Ryms et al. analyzed the temperature variation rule of asphalt mixtures containing paraffin in the aggregate. They found that the temperature of an asphalt mixture made of aggregate containing 20% paraffin was 7~8 K lower than that of a common asphalt mixture [17]. However, it has been found that the thermal conductivity of paraffin compounds is low and that the temperature regulation efficiency is limited. Adding materials with a high thermal conductivity can improve the temperature regulation efficiency of paraffin compounds [18]. Using a differential scanning calorimeter (DSC), Chen et al. measured the melting temperature of lauric acid, finding that it ranged from 43 to 44 °C and that the latent heat of phase transition was about 160 kJ/kg, showing that it could be used for the temperature control of asphalt pavement [19]. Through scanning electron microscopy (SEM) and DSC tests, Kong et al. found that lauric acid has good compatibility with asphalt binders. A lauric acid-modified asphalt binder showed good heat absorption and release performance [20]. Polyethylene glycol (PEG) is an organic polymer whose phase-transition temperature, enthalpy of melting, and enthalpy of crystallization depend on its molecular weight. At present, PEGs with molecular weights of 2000 [21] and 4000 [22] are widely used to reduce the rutting of asphalt pavement at high temperatures, while PEG with a molecular weight of 400 is used to alleviate icing and snow on asphalt pavement in winter [23].

Many researchers have investigated the phase transition mechanism of PCMs. Studies have shown that most organic PCMs control the temperature by melting and by absorbing heat during temperature rise [24]. In the cooling stage, Anupam et al. believe that the solidification process of PCMs mainly includes three stages: sensible heat release, latent heat release, and sensible heat release. The solidification process of PCMs begins with the formation of initial crystals or initial nuclei, which is called nucleation [14]. Kuznik's research found that some PCMs undergo the phenomenon of overcooling. Due to the low nucleation rate, PCMs remain in the liquid state below the melting temperature, which is not conducive to the PCM's role in regulating temperature within a certain range [25]. Fan et al. found that paraffin and alcohol can effectively promote the formation of PCM crystals, thereby reducing the overcooling of PCMs [26].

In conclusion, solid–liquid organic PCMs, such as paraffin wax, fatty acids, and PEG, can be applied to asphalt pavement. However, the low thermal conductivity of solid–liquid organic PCMs in the application process affects the thermal response speed in asphalt pavement, thus affecting its temperature regulation efficiency.

The objectives of this study were to (1) prepare a dual-phase-change material with both high- and low-temperature regulation abilities and to test the pavement performance of modified asphalt, and to (2) clarify the optimal dosage of dual-phase-change materials through an indoor simulation temperature control test to verify their practical application value.

2. Materials and Methods

2.1. Experimental Materials

2.1.1. Asphalt Binder

A modified asphalt binder specific for an ultra-thin surface was selected and tested according to the American Society of Testing Materials (ASTM) standard. The results are shown in Table 1.

Table 1. Basic performance index of asphalt binder.

Index	Unit	Result	Specification Requirement	Standard
Penetration (25 °C)	0.1 mm	57	≥50	ASTM D5 [27]
Softening point	°C	84	≥65	ASTM D36 [28]
Rotary viscosity (135 °C)	Pa·s	2.725	≤3.0	ASTM D4402 [29]
Ductility (5 °C)	cm	27	≥20	ASTM D113 [30]

2.1.2. Dual-Phase-Change Material (DPCM)

Beijing has a typical temperate continental monsoon climate. Its monthly temperature trend throughout the year is shown in Figure 1. It can be seen in Figure 1 that the temperature in Beijing is below 0 °C for five months in a year. Similarly, there are five months in which the temperature is above 25 °C. In such months, the daytime temperature of the road surface can reach more than 45 °C [31]. In order to solve the problems of the low thermal conductivity and low thermal storage efficiency of PEG, in this study, externally expanded graphite (EG) was chosen as a carrier matrix to adsorb PEG with different molecular weights. A PEG/EG composite phase-change material was prepared, which encapsulated PEG and improved its thermal storage efficiency. A PEG400/EG composite phase-change material was prepared for paving at 0 °C. A PEG1500/EG composite phase-change material was used for pavements at 45 °C and above. Finally, the two composite phase-change materials were mixed at a ratio of 1:1 to obtain a dual-phase-change material, as shown in Figure 2. The dual-phase-change material was a black granular solid with good dispersion, and its apparent density was 1.07 g/cm^3.

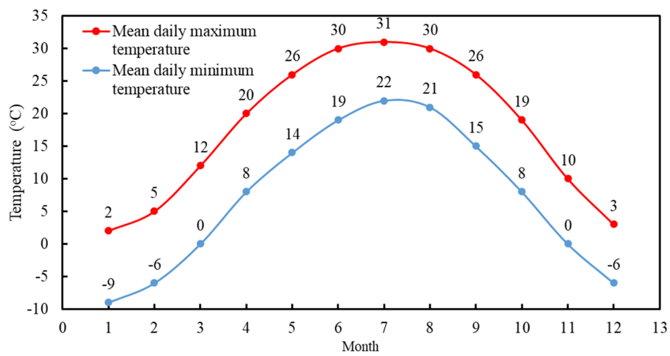


Figure 1. Monthly temperature trend of Beijing throughout the year.

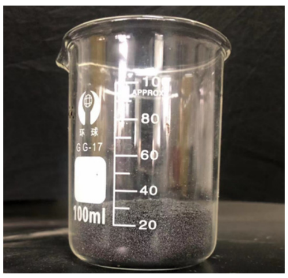


Figure 2. Dual-phase-change material.

2.1.3. DPCM-Modified Asphalt

The DPCMs were directly mixed with asphalt binders according to the mass ratios of 10%, 20%, 30%, and 40% to prepare DPCM-modified asphalt binders. The specific processes were as follows: The asphalt binder was heated in an oven at 165 °C to reach the flowing state and then transferred to a constant temperature oil bath at 170 °C. The DPCMs were slowly poured into the asphalt binders during the oil bath and stirred with a glass rod at a speed of 60 r/min. After that, a high-torque electric mixer was used to stir at a speed of 500 r/min for 20 min. Finally, a glass rod was used to manually stir at a speed of about 60 r/min for 10 min to remove the bubbles in the DPCM-modified asphalt binders.

2.2. Test Methods

2.2.1. Temperature Scanning Test

A DHR-1 instrument produced by TA Company in the USA was used to conduct a temperature scanning test on the various asphalt binders modified with dual-phase-change materials. Parallel plates with a diameter of 25 mm and a thickness of 1000 μm were selected to test the rutting factor. Plates with a diameter of 8 mm and a thickness of 2000 μm were selected to test the fatigue factor. Plates with a diameter of 4 mm and a thickness of 2200 μm were selected to test the low-temperature performance. The test parameters were as follows:

- Temperature range: 30~70 °C (high-temperature performance), 10~40 °C (fatigue performance), and −20~10 °C (low-temperature performance).
- Strain: 0.01% (for −20~−5 °C) and 1% (for −5~70 °C).
- Scanning frequency: 10 rad/s.

The complex modulus frequency curve and phase angle frequency curve at each temperature were adapted according to the time–temperature superposition principle (TTSP).

2.2.2. Scanning Electron Microscope (SEM) Test

The microstructures of the EG and PEG/EG composite PCMs were studied via scanning electron microscopy (SEM). The electron microscope model was SU9000. The test parameters were as follows:

- Acceleration voltage: 15,000 V.
- Magnification: 1500 times.

2.2.3. Fourier Transform Infrared Spectrometer (FTIR)

A spectrum II infrared spectrometer produced by PE Company of the United States was selected for the test. The spectrum had a resolution of 0.5 cm^{-1} and a test range of 4000–500 cm^{-1} [32]. A heated spatula was dipped into the asphalt binder sample and then used to evenly apply the sample to a diamond crystal for scanning. The result was analyzed using OMNIC.

2.2.4. Temperature Detection and Recording Device

A PT100 platinum resistance sensor and temperature recorder (as shown in Figure 3) were selected to record and analyze the temperature control effect of the dual-phase-change materials on the asphalt binders.

(**a**) PT100 platinum resistance sensor (**b**) Temperature recorder

Figure 3. Temperature detection and recording device for temperature regulation test.

- Recording frequency: once per minute.
- Temperature deviation: ±0.1 °C.

2.2.5. Indoor Simulated Temperature Regulation Test

An indoor simulated temperature regulation test was carried out by using an environment chamber. The steps were as follows: (1) 300 mL of the DPCM-modified asphalt binders with different DPCM contents was divided into 5 beakers, and then the beakers were heated to reach a flowing state. The metal probe of the PT100 platinum resistance sensor was inserted into the asphalt binder of each beaker and kept in the middle position. (2) All the beakers were put into the environmental chamber. The initial temperature of the high-temperature regulation test was 25 °C, and it was 20 °C in the low-temperature regulation test. (3) In the high-temperature regulation test, the DPCM-modified asphalt binders with a stable temperature were heated from 25 °C to 65 °C. When one sample reached 65 °C, all samples were cooled from 65 °C to 25 °C. In the low-temperature regulation test, the DPCM-modified asphalt binders with a stable temperature were cooled from 20 °C to −20 °C. When one sample reached −20 °C, all samples were heated from −20 °C to 20 °C. The temperature changes in the DPCM-modified asphalt binders were recorded per minute using a temperature recorder. The main process of the indoor simulation temperature regulation test is shown in Figures 4 and 5.

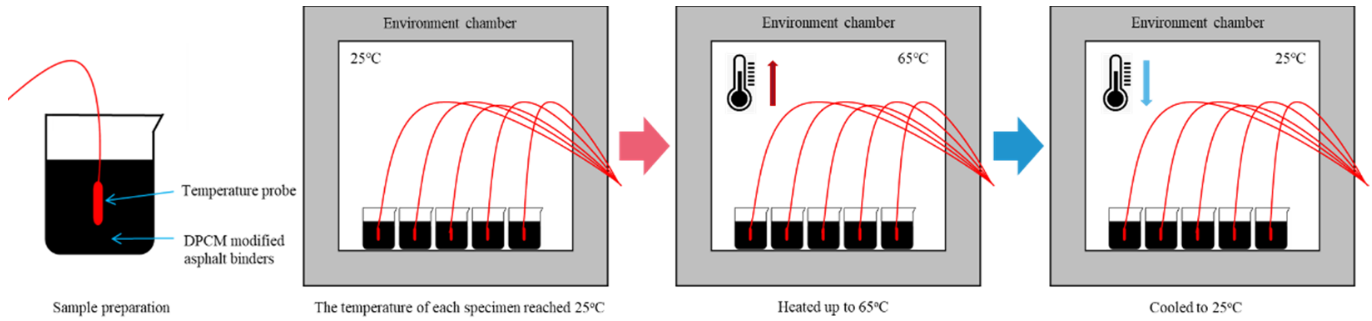


Figure 4. Flowchart of indoor simulated high-temperature regulation test.

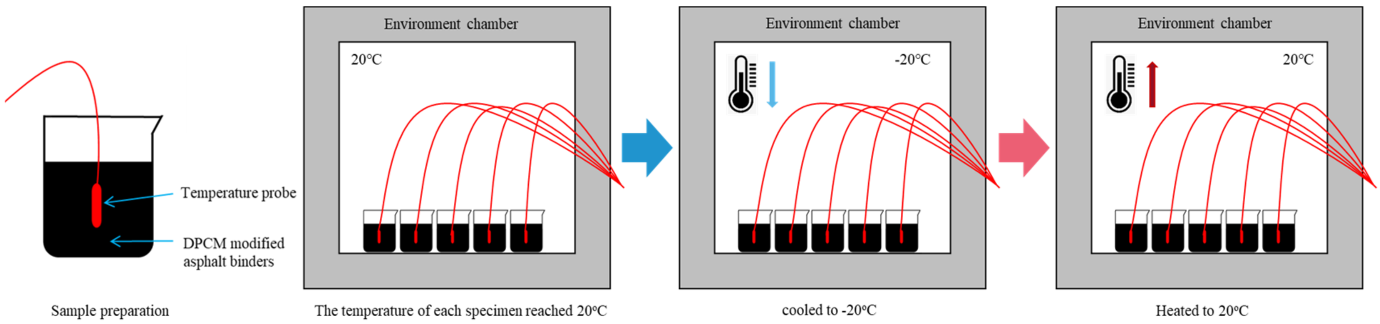
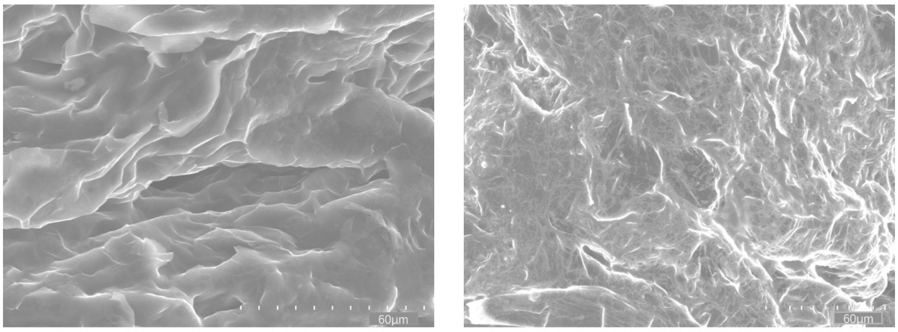


Figure 5. Flowchart of indoor simulated low-temperature regulation test.

3. Results and Discussion

3.1. Microstructures of EG and PEG

Figure 6 shows that, during the melt blending and vacuum adsorption, a large amount of liquid PEG entered the pore structure of EG under the actions of capillary force and vacuum negative pressure. EG was connected closely to a network of structures, which were conducive to improving the thermal conductivity efficiency of PEG/EG, thus improving the temperature regulation effect of the DPCM.



(**a**) PEG400/EG (**b**) PEG1500/EG

Figure 6. Microstructures of EG and PEG.

3.2. Rheological Properties of DPCM-Modified Asphalt Binders

DSR was used to study the influence of the DPCM content on the viscoelastic properties of the asphalt binders. The road performance of the modified asphalt binders at different temperatures was evaluated.

3.2.1. High-Temperature Performance of DPCM-Modified Asphalt Binders

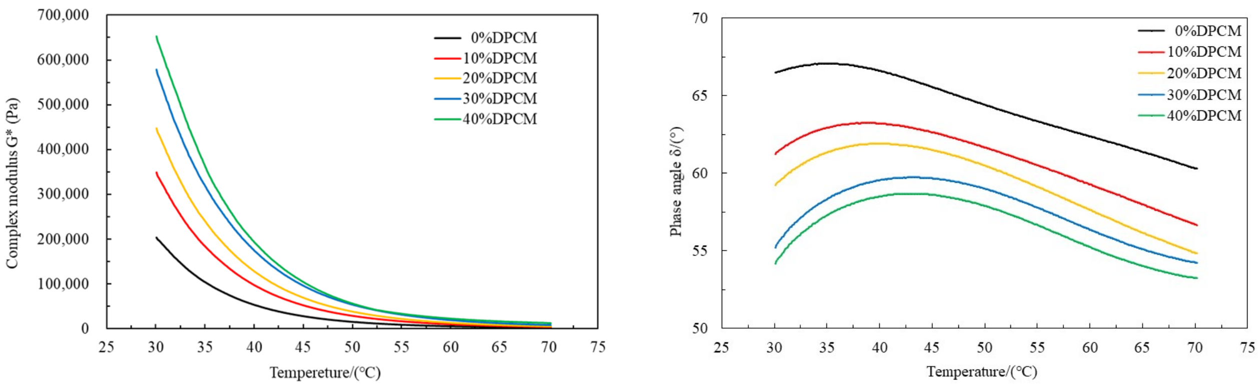
$$\text{Rutting factor} = G^*/\sin\delta$$

$$\text{Fatigue factor} = G^* \times \sin\delta$$

In the Superpave specification, the rutting factor can effectively characterize the high-temperature stability of asphalt binders. An asphalt binder with a larger rutting factor has a better rutting resistance.

The fatigue factor represents the energy lost by asphalt samples under repeated loading. An asphalt binder with a smaller fatigue factor has a better fatigue resistance under repeated loading.

The changes in the complex modulus, phase angle, and rutting factor of the DPCM-modified asphalt binders with different DPCM contents in the temperature range of 30~70 °C were studied using a temperature scanning test. The test results are shown in Figures 7 and 8.



(**a**) Complex modulus (**b**) Phase angle

Figure 7. Effect of DPCM content on complex modulus and phase angle of DPCM-modified asphalt binders at high temperatures.

As shown in Figures 7 and 8, in the temperature range of 30~70 °C, the difference in the complex modulus of each DPCM-modified asphalt binder gradually decreased with the increase in the temperature. Meanwhile, the phase angle first increased and then decreased with the increase in the temperature, which was mainly related to the viscoelastic properties of the original asphalt [33]. At the same temperature, the complex modulus of the modified asphalt increased, and the phase angle decreased with the increase in the DPCM content, which led to an increase in the rutting factor. The physical property of the DPCM was similar to that of the mineral powder, which improved the viscosity performance of the modified asphalt binders. This is one of the reasons for the improvement of the rutting resistance of the DPCM-modified asphalt. In addition, no effect of the phase change on the rheological properties of the asphalt binders was found during the heating process, which was due to the greater function of the DPCM than the mineral powder in the asphalt binders. Compared with the function of the mineral powder, the effect of the phase transformation on the rheological properties at high temperatures was too slight to be observed.

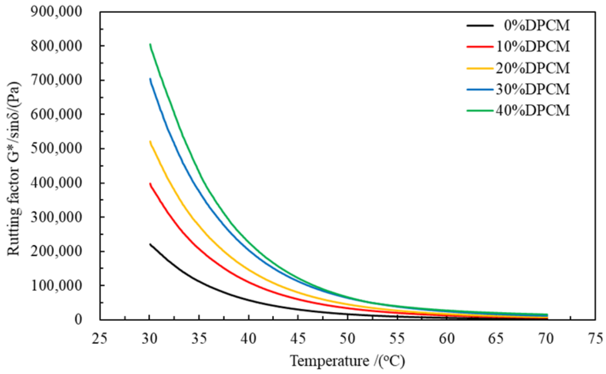
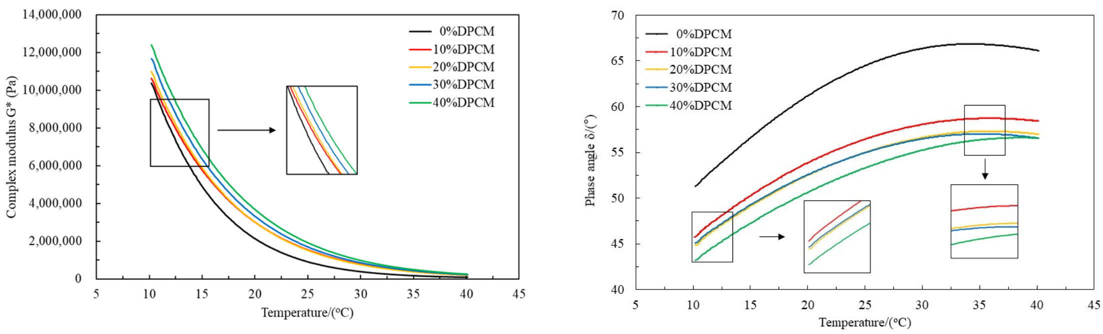


Figure 8. Effect of DPCM content on rutting factor of DPCM-modified asphalt binders at high temperatures.

3.2.2. Fatigue Properties of DPCM-Modified Asphalt Binders

The changes in the complex modulus, phase angle, and fatigue factor of the DPCM-modified asphalt binders with different DPCM contents in the temperature range of 10~40 °C were studied using a temperature scanning test. The results are shown in Figures 9 and 10.



(**a**) Complex modulus (**b**) Phase angle

Figure 9. Effect of DPCM content on complex modulus and phase angle of DPCM-modified asphalt binders at medium temperatures.

As shown in Figures 9 and 10, in the temperature range of 10~40 °C, with the increase in the DPCM content, the complex modulus of the modified asphalt binders increased. The phase angle of the asphalt binder with the DPCM was significantly lower than that of the virgin asphalt binder at each temperature. This is due to the physical morphology of the DPCM being similar to that of the mineral powder. The powder–binder ratio increased with the content of the DPCM. The DPCM itself does not have viscosity, so the viscous component of the asphalt mastic decreased, and the elastic component increased. The fatigue factor was the product of G* and sinδ, which increased with the content of the DPCM. This means that the asphalt mastic is more inclined to crack under repeated loading, and the fatigue life became worse. Therefore, the content of DPCM in asphalt binders should not be too high.

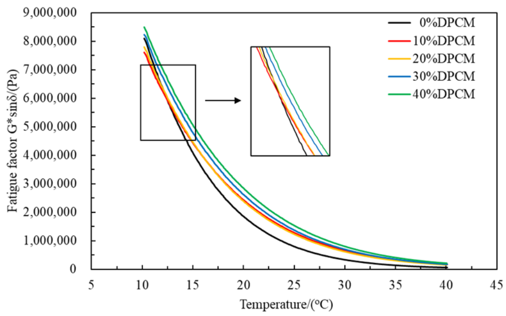
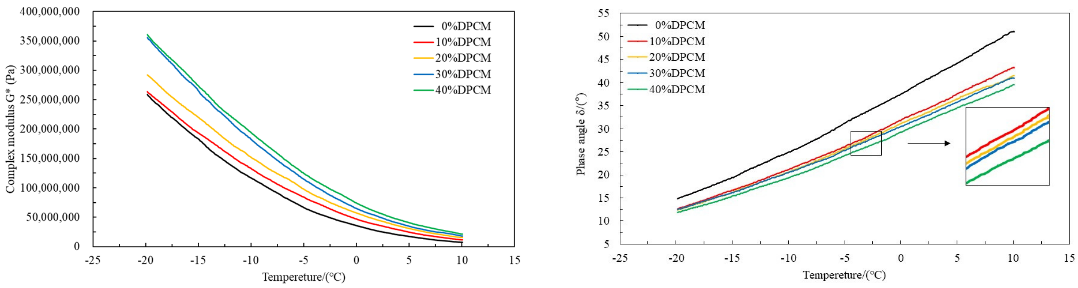


Figure 10. Effect of DPCM content on fatigue factor of DPCM-modified asphalt binders.

3.2.3. Low-Temperature Properties of DPCM-Modified Asphalt Binders

The changes in the complex modulus and phase angle of the DPCM-modified asphalt binders with different DPCM contents in the temperature range of −20~10 °C were studied using a temperature scanning test. The result is shown in Figure 11.

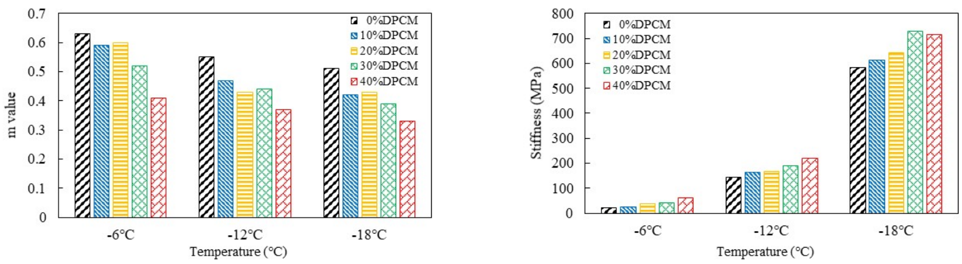


(**a**) Complex modulus (**b**) Phase angle

Figure 11. Effect of DPCM content on complex modulus and phase angle of DPCM-modified asphalt binders at low temperatures.

As shown in Figure 11, in the temperature range of −20~10 °C, the complex modulus of the DPCM asphalt increased, and the phase angle decreased with the increase in the content of the DPCM. This shows that the influence of the amount of DPCM on the complex modulus and phase angle in this temperature range is consistent with that in the high-temperature and medium-temperature ranges. At low temperatures, the DPCM still mainly assumed the role of mineral powder, and its thermodynamic properties had little influence on the rheological properties of the asphalt binders.

Sui et al. proposed a test method using DSR to test the low-temperature performance of asphalt binders. There was a strong linear correlation between the test data and BBR test data [34]. On the basis of the existing data, the m values and stiffness at −6 °C, −12 °C, and −18 °C were calculated. The results are shown in Figure 12.



(**a**) m value (**b**) Stiffness

Figure 12. The m values and stiffness obtained via temperature scanning test.

The increase in the m value means that the tensile stress in the material reduced at low temperatures, and the possibility of cracking also decreased. As can be seen in Figure 12a, with the increase in the DPCM content, the m value of the asphalt binder decreased at all temperatures, making it more prone to cracking. The DPCM improved the stiffness modulus of the asphalt to different degrees under three different low-temperature conditions. It is worth noting that the stiffness modulus of all samples was already greater than 300 MPa at −18 °C, indicating that these samples are more prone to cracking when serving at low temperatures of −18 °C.

The change in the m value and stiffness modulus proves that, in the case of continuous extremely low temperatures, when the DPCM no longer implemented phase transformation, the asphalt binders tended to crack at low temperatures due to the excessive DPCM content.

3.3. Chemical Stability of DPCM-Modified Asphalt Binders

By comparing the infrared characteristic peaks of the DPCM-modified asphalt binders with those of the original asphalt binders in the FTIR test, the potential chemical reaction in the blending process of the DPCM and asphalt was studied. The test result is shown in Figure 12.

There were obvious infrared characteristic peaks at 3411 cm^{-1}, 2888 cm^{-1}, and 1111 cm^{-1}, corresponding to the stretching vibration peaks of -OH, $-CH_2$, and C-O, respectively [35,36]. In the infrared spectrum of the asphalt binders, 2920 cm^{-1} and 2851 cm^{-1} corresponded to the C-H stretching vibration peaks in alkanes and cycloalkanes. Furthermore, 1454 cm^{-1} and 1375 cm^{-1} corresponded to the stretching vibration peaks in the C-H plane of C-CH3 and $-CH_2$. It can be clearly seen in Figure 13 that the infrared characteristic peaks of the DPCM-modified asphalt binders included the characteristic peaks of the DPCM and the original asphalt binders. There were no new structural characteristic peaks, indicating that there was no chemical reaction in the DPCM modification process. The modification of the DPCM was a physical mixing process.

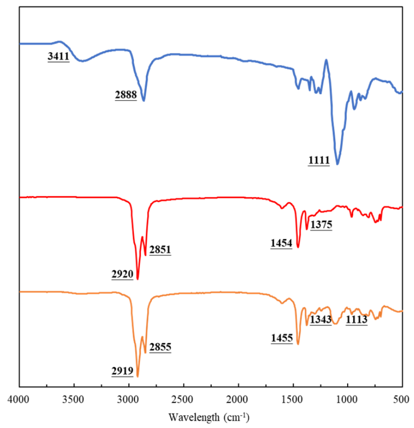


Figure 13. Infrared spectrum of DPCM-modified asphalt binders.

3.4. Temperature Regulation Performance of DPCM-Modified Asphalt Binders

The temperature regulation effect of the DPCM-modified asphalt binders with different DPCM contents was studied by controlling the sample temperature in the environment chamber. The indoor simulated temperature regulation tests of the DPCM-modified asphalt binders were carried out in temperature ranges of 25~65 °C and −20~20 °C.

3.4.1. Indoor Simulated High-Temperature Regulation Test

An indoor simulated high-temperature regulation test was carried out on the modified asphalt binders. The temperature range was 25~65 °C. The maximum temperature and heating rate of the DPCM-modified asphalt binders during the heating process were selected to evaluate the effect of the DPCM content on the temperature regulation effect. The heating rate of the DPCM-modified asphalt binders is expressed by Formula (1):

$$Q_1 = \frac{T_1 - T_0}{\Delta t} \quad (1)$$

In the formula, Q_1 is the heating rate of the sample during the heating process, in unit °C/min or °C/h; T_1 is the final temperature of the sample during the heating process, in unit °C; T_0 is the initial temperature of the sample during the heating process, in unit °C; and Δt is the time required for the sample to heat up, in unit min or h.

The cooling rate of the DPCM-modified asphalt binders is expressed by Formula (2):

$$Q_2 = \frac{T_2 - T_3}{\Delta t} \quad (2)$$

In the formula, Q_2 is the cooling rate of the sample during the cooling process, in unit °C/min or °C/h; T_2 is the final temperature of the sample during the cooling process, in unit °C; T_3 is the initial temperature of the sample during the cooling process, in unit °C; and Δt is the time required for the sample to cool down, in unit min or h.

Based on the above evaluation index of the temperature regulation effect, the influences of the different contents of the DPCM on the temperature regulation effect in the modified asphalt binders at high temperatures are shown in Table 2 and Figure 14.

Table 2. Influence of the content of DPCMs on the temperature regulation effect of DPCM-modified asphalt binders at high temperatures.

Content (%)	High-Temperature Extreme (°C)	Heating Rate Q_1 (°C/min)	Cooling Rate Q_2 (°C/min)
0	64.7	1.588	0.167
10	63.3	1.532	0.158
20	61.7	1.468	0.151
30	61.1	1.444	0.150
40	60.5	1.420	0.146

As can be seen in Table 2 and Figure 14, with the increase in the DPCM content, the high-temperature extreme value in the heating and cooling stages decreased. Meanwhile, the heating rate also decreased significantly. During the 25 min heating process, with the addition of the DPCM, the temperature rise rate decreased from 1.588 °C/min in the original asphalt binders to 1.420 °C/min in the asphalt binders with 40% DPCM. The temperature rise rate decreased by 10.6%. The temperature of the asphalt without the addition of DPCM rose to the highest value of 64.7 °C during heating, while the extreme value of the high temperature decreased with the increase in the DPCM content. The cooling range of the asphalt binders with 40% DPCM content was the highest, up to 4.2 °C. In the cooling stage, the cooling rate of the modified asphalt binders also decreased with the increase in the DPCM content. The cooling rate of the asphalt binders with 40% DPCM was 12.6% lower than that of the asphalt binders without DPCM. In the heating process, the DPCM melted and absorbed heat through the phase change when the external temperature rose to about 40~50 °C. The DPCMs stored part of heat, thus delaying the temperature rise rate of the asphalt binders and reducing their high-temperature extreme value. In the cooling process, when the temperature reached a certain range, the DPCM solidified and released the stored heat through the reverse phase change, thus delaying the cooling rate of the asphalt binders. With the increase in the DPCM content, the temperature regulation effects at 25~65 °C gradually improved. The effects of peak cutting and valley filling displayed in Figure 14 were more intuitive and obvious.

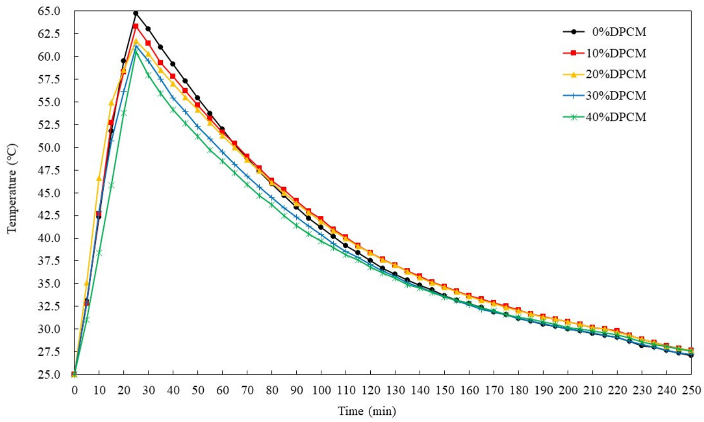


Figure 14. Influence of the content of DPCMs on the temperature regulating effect of DPCM-modified asphalt binders at high temperatures.

3.4.2. Indoor Simulated Low-Temperature Regulation Test

The temperature range was −20~20 °C. In the same way, the minimum temperature and cooling rate of each DPCM-modified asphalt binder were selected to evaluate the influence of the DPCM content on the temperature regulation effect. The heating and cooling rates were still calculated according to Formulas (1) and (2). The results of the low-temperature regulation effect test are shown in Table 3 and Figure 15.

Table 3. Influence of the content of DPCMs on the temperature regulation effect of DPCM-modified asphalt binders at low temperatures.

Content (%)	Low-Temperature Extreme (°C)	Cooling Rate Q_2 (°C/min)	Heating Rate Q_1 (°C/min)
0	−19.9	0.363	0.304
10	−19.5	0.359	0.288
20	−18.7	0.352	0.282
30	−17.9	0.345	0.279
40	−17.4	0.340	0.274

As can be seen in the table and figure above, with the increase in the content of DPCMs, the low-temperature extreme value of the DPCM-modified asphalt binders gradually increased during the rising and cooling process from −20 °C to 20 °C. The cooling rate also significantly decreased. In the cooling process, when the temperature of the DPCM-modified asphalt binders was reduced to −19.9 °C, the cooling amplitudes of the DPCM-modified asphalt binders with 10%, 20%, 30%, and 40% DPCM contents were 0.4 °C, 1.2 °C, 2.0 °C, and 2.5 °C, respectively. The cooling rate decreased from 0.363 °C/min in the original asphalt binders to 0.340 °C/min in the modified asphalt binders with 40% DPCM. The cooling rate was decreased by 6.3%. In the heating process, the heating rate of the DPCM-modified asphalt binders also decreased with the increase in the DPCM content. Obviously, in the cooling process, the DPCM in the modified asphalt binders released the stored heat through endothermic and exothermic phase changes when the external temperature reduced to about −10~0 °C, thus delaying the cooling rate of the asphalt binders and increasing their low-temperature extreme value. In the heating stage, the DPCM melted and absorbed heat through phase change when the temperature reached a certain range. It stored part of the heat for the next exothermic phase-change process. With the increase in the DPCM content, the temperature regulation effects of the DPCM-modified asphalt binders at −20~20 °C also gradually improved.

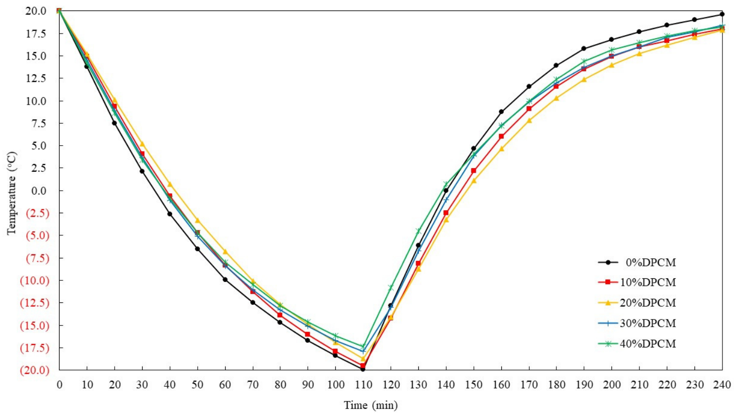


Figure 15. Influence of the content of DPCMs on the temperature regulation effect of DPCM-modified asphalt binders at low temperatures.

4. Conclusions

PEG400/EG and PEG1500/EG composite phase-change materials were used as the raw materials of dual-phase-change materials. DPCM-modified asphalt binders were prepared. The thermal storage properties, rheological properties, chemical stability, and temperature regulation properties of the DPCM-modified asphalt binders were studied. The main conclusions are as follows:

(1) The effect of the DPCM on the rheological properties of the asphalt mastic is due to the increase in the powder–binder ratio. In the research on the pavement performance of the modified asphalt binders based on rheological parameters, the influence of the DPCMs on the rheological properties of the asphalt binders was mostly similar to influence of the mineral powder. The addition of the DPCMs increased the high-temperature rutting resistance of the asphalt binders, but a high DPCM content showed a negative influence on the fatigue performance of the modified asphalt binders.

(2) PEG could be adsorbed by the pores of EG to form a stable microstructure. In the SEM test, continuous and stable network structures of PEG400/EG and PEG1500/EG were observed, which were conducive to improving the thermal conductivity efficiency and temperature regulation effect.

(3) The modification of asphalt by DPCM is only a physical mixing process. In the FTIR test, the results showed that the infrared characteristic peaks of the DPCM-modified asphalt binders included the characteristic peaks of the DPCM and the original asphalt binders. No new structural characteristic peaks appeared, indicating that there was no chemical reaction in the DPCM modification process. The chemical properties of both the DPCM and the original asphalt binders were not changed.

(4) Increasing the content of DPCM can improve the temperature change rate and temperature extremum of DPCM-modified asphalt. In the indoor simulated temperature regulation test, the DPCM-modified asphalt binders showed a good temperature regulation effect in the two temperature domains of −20~20 °C and 25~65 °C. Their temperature regulation effect increased with the increase in the DPCM content. The modified asphalt binders with a 40% DPCM content reduced the high-temperature extremum by 4.2 °C during the heating process. The asphalt heating rate was reduced by 10.6%. In the cooling process, the low-temperature extreme value of the asphalt was increased by 2.5 °C, while the cooling rate of the asphalt was reduced by 6.3%.

(5) The use of these DPCM-modified asphalt binders in pavement in monsoon climate areas will reduce the occurrence of pavement defects and prolong its service life.

In future studies, the effects of DPCMs in asphalt mixtures should be further confirmed, including but not limited to the cycle stability, durability, and heat storage capacity. In addition, more application scenarios suitable for DPCMs can be explored, such as bridge paving and airport roads, to improve the durability of road surfaces in key areas.

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