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Effects of Thermo-Chromic materials (TCMs) on the performance of asphalt pavement with phase change materials (PCMs)

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ABSTRACT

Temperature regulation is crucial for the longevity of pavements. Thermo-Chromic Materials (TCMs) is proposed for effective temperature regression in pavements with Phase Change Materials (PCMs). In this paper, the performance of asphalt pavements in a typical year is investigated with Abaqus, including the peak temperature, the variation of surface temperature and the properties of PCMs before and after the adoption of TCMs. The incorporation of PCMs resulted in a reduction of peak pavement temperatures by 1.3 °C, while the addition of TCMs further decreased temperatures by 38.5 °C. By comparison with the results with and without PCMs as well as with and without TCMs, it is concluded that both PCMs and TCMs may reduce the peak temperature of asphalt pavements. However, TCMs may further regress the peak temperature but does not result in the time delay of peak temperature, as PCMs does. The peak temperature positively correlates with the variation of surface temperature. Nevertheless, although only four types of correlation between the temperature property of TCMs and that of PCMs are involved, the profile or status of PCMs is much more complicatedly influenced after the adoption of TCMs, indicating the interaction between TCMs and PCMs. More time of PCMs is in the phase of solid, due to the modulation of solar radiation. As far as the peak temperature is considered, it is also possible to reduce the amount of PCMs applied in pavements, with the adoption of TCMs. According to the results in this paper, the application of TCMs in an asphalt pavement with PCMs may be an effective way to reduce the peak temperature, to regress the daily variation degree as well as to improve the performance of PCMs.

1. Introduction

Merited with durability, cost-effectiveness and long lifespan, asphalt pavement is widely accepted as a solution for road construction with heavy loads and harsh weather conditions [1,2]. However, asphalt pavement expands and contracts with temperature change, leading to rutting, thermal cracking and aging issues [3–5], especially in hot summer and cold winter [6]. Correspondingly, to mitigate or minimize the impacts of temperature is crucial for the longevity and performance of asphalt pavements [7,8].

The addition of Phase Change Materials (PCMs) to asphalt is an approach that can help improve the performance of pavement [9,10]. The melting and solidification process of PCMs shows strong ability to store and release thermal energy, respectively [11–13]. Thus, PCMs can positively impact the behavior of asphalt and regulate the temperature of pavement under different environmental conditions [14–16]. Moreover, the application of PCMs in asphalt is able to enhance conductive heat transfer, as the thermal conductivity of PCMs may be larger than that of asphalt [17–19]. Therefore, the temperature gradient and the potential crack in pavements can be regressed by PCMs. Sha et al. [20,21] developed a solid–solid phase change material using polyurethane to enhance the cooling properties of asphalt pavement. The effectiveness of this innovation was validated through road performance tests conducted on asphalt mixtures. Ma et al. [22] employed the latent heat storage capacity testing method to examine how the performance of asphalt pavement is influenced by the heat transfer characteristics and heat capacity of micro-phase change materials. Proper properties of PCMs, such as the phase-change temperature and the heat storage amount, are significant to the performance of asphalt pavements, especially in a long-term operation. Moreover, the adoption of PCMs in asphalt is constrained by several factors, such as the compatibility and stability of materials [23], as well as the leakage [24] and cost, etc. The direct incorporation of PCMs in asphalt results in the

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Nomenclature

C	Thermal capacity, $J \cdot kg^{-1} \cdot K^{-1}$
h	Convective heat transfer coefficient, $W \cdot m^{-2} \cdot ℃^{-1}$
I	Indirect solar radiation, $J \cdot m^{-2}$
k	Thermal conductivity, $J \cdot m^{-1} \cdot h^{-1} \cdot ℃^{-1}$
m	Mass, g
T	Temperature, ℃
u	Speed of wind, $m \cdot s^{-1}$
x	Melting degree

Subscripts

a	Asphalt
am	Ambient
ap	Composite of asphalt and PCMs
b	Bottom
i	The i-th layer
j	The j-th layer
l	Liquid-phase
m	Melting-phase
m1	Onset of melting
m2	Onset of solidification
p	PCMs
s	Solid-phase
s1	Lower value
s2	Upper value
S	Surface
Sm	Hourly maximum value
Sp	Peak value
Sv	Valley value
t	Time, s, h, d
Z	Absolute zero

Greek

α	Absorptivity of solar radiation
ρ	Density, $kg \cdot m^{-3}$
ΔH	Enthalpy change of PCMs, $J \cdot kg^{-1}$
ΔT	Variation of temperature, ℃
Δx	Difference of melting degree
ε	Emissivity of asphalt, 0.81
ξ	Mass fraction of PCMs, %
σ	Stefan-Boltzmann constant, 2.041×10^{-4} $J \cdot h^{-1} \cdot m^{-2} \cdot K^{-4}$

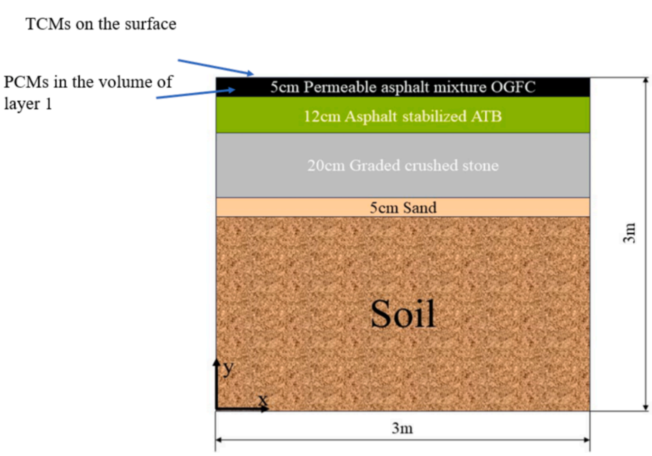

Fig. 1. Sketch of asphalt pavement structure.

Table 1
Parameters of the asphalt pavement.

Parameters	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	PCM (l/s)
Density, ρ / $kg \cdot m^{-3}$	2100*	2380	1900	1700	1800	773/ 900
Thermal conductivity, k / $J \cdot m^{-1} \cdot h^{-1} \cdot ℃^{-1}$	3015*	4493	4867	2090	5616	504/ 1008
Specific heat, C / $J \cdot kg^{-1} \cdot ℃^{-1}$	1099*	815	810	920	1040	2950/ 2464

Note: * refers to the value of asphalt.

performance deterioration of pavement, due to the alteration of mechanical properties [25]. To some extent, it is desired to reduce the amount of PCMs incorporated, as long as the performance of pavement is promised.

Reflective and Absorptive materials are also adopted to reflect and absorb solar radiation to keep pavement cool in summer and warm in winter, respectively. If temperature modification both in summer and in winter is demanded, thermochromic pavements are designed to alter color and reflection automatically [26–28]. Thermo-Chromic Materials (TCMs) exposed to a variation of temperature undergoes reversible chemical or physical changes, resulting in a change of colors, e.g. colorless at high temperature and colored at low temperature [29–31].

Table 2
Properties of PCMs.

Case No.	Amount of PCMs applied in layer 1, ξ/ %	Temperature range of phase-change	
		Onset temperature of melting, T_{m1} / ℃	Onset temperature of solidification, T_{m2} / ℃
A1B1	5	22	27
A1B2		27	32
A1B3		32	37
A1B4		37	42
A2B1	10	22	27
A2B2		27	32
A2B3		32	37
A2B4		37	42
A3B1	15	22	27
A3B2		27	32
A3B3		32	37
A3B4		37	42
A4B1	20	22	27
A4B2		27	32
A4B3		32	37
A4B4		37	42

Note: The property of PCMs is categorized into two groups, i.e. the amount of PCMs applied in layer 1 of asphalt pavement (Group A) and the temperature range of phase-change process (Group B). Both Group A and Group B include four sub-Groups, naming from 1 to 4. The range of temperature in phase-change process is designated at 5 ℃.

Table 3
Properties of TCMs.

Temperature range of thermo-chromic		Absorptivity of solar radiation	
Lower temperature, T_{s1} / ℃	Upper temperature, T_{s2} / ℃	Absorptivity at T_{s1}, α_1	Absorptivity at T_{s2}, α_2
30	35	0.9	0.4

Note: The variation of absorptivity from 0.9 to 0.4 is corresponding to the change of reflection from 0.1 to 0.6[44].

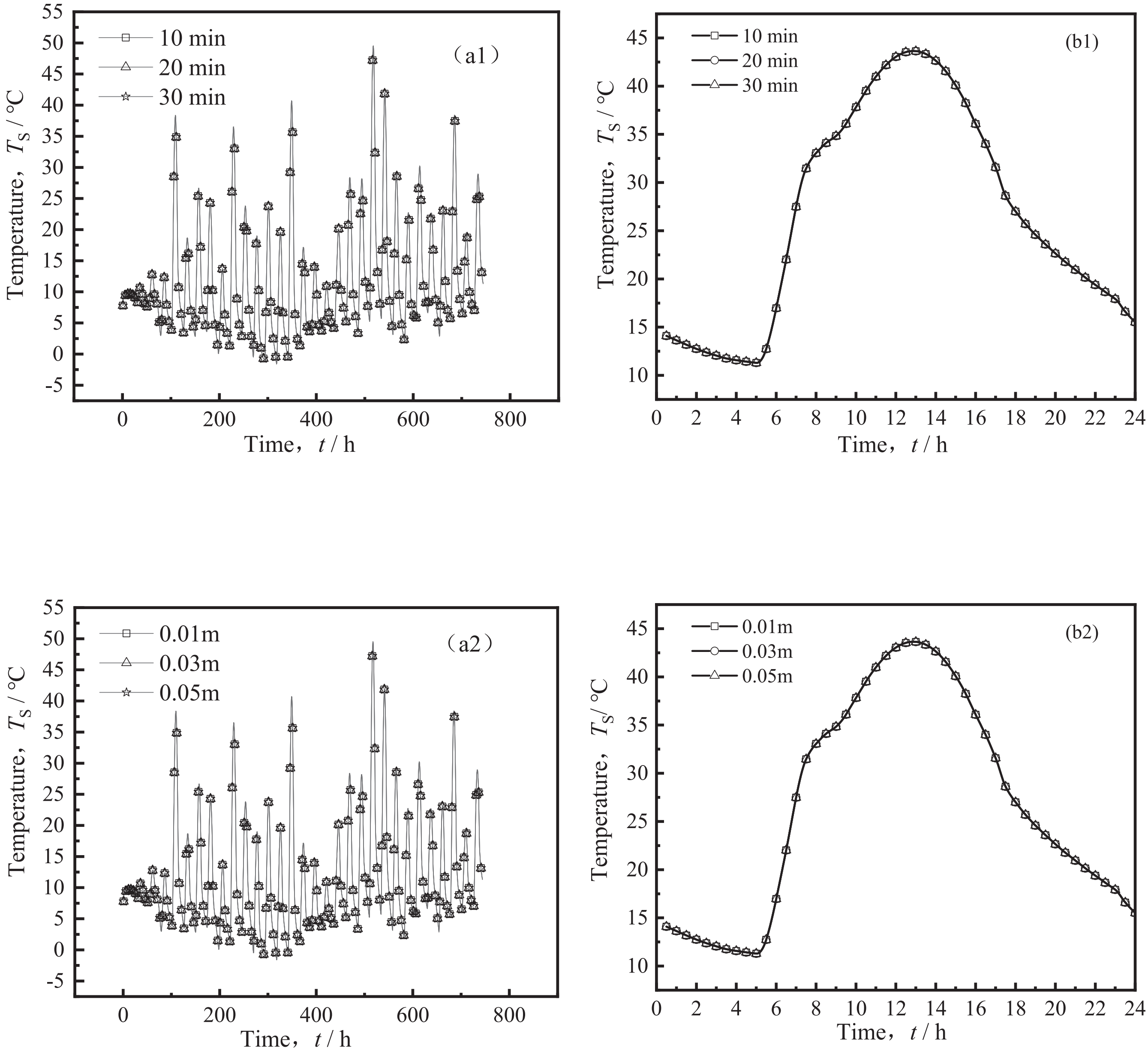

Fig. 2. Results of T_S for sensitivity analysis. (a1) and (a2) Results in April; (b1) and (b2) Results on April 1st; (a1) and (b1) Impact of time step; (a2) and (b2) Impact of node size.

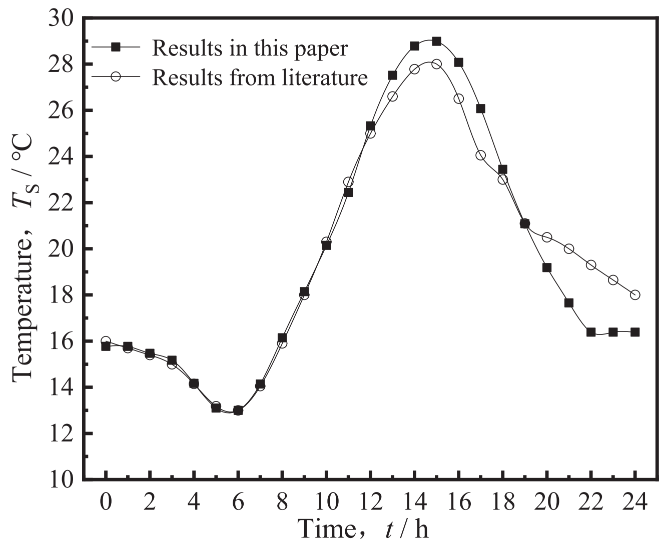

Fig. 3. Comparison with reference for a pavement in Wuhan.

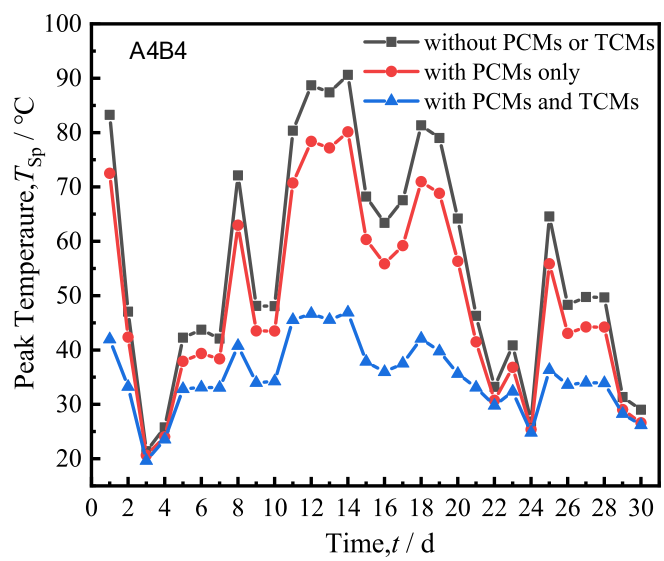

Fig. 4. Peak temperature of asphalt pavement in April.

Therefore, the solar radiation on the surface of pavements is modulated by TCMs [32,33]. As a result, the boundary heat flux and pavement temperatures are regulated. Hu et al. [34] observed enhancements not only in solar radiation reflectivity but also in the resistance to rutting and moisture prevention, indicating the comprehensive performance of these innovative asphalt mixtures. Nevertheless, the performance of TCMs pavements depends strongly on the property of solar radiation, as the major effects on heat transfer in pavements can be attributed to the modulation of boundary heat flux due to solar radiation. Correspondingly, the thermochromic process works periodically. It does not work at night and does not work well on cloudy or rainy days. Moreover, it is reported that TCMs may suffer from the aging issue, due to its exposure to the solar radiation [35]. Thus, frequent thermochromic process should not be expected for the long-term operation.

Recently, composite of PCMs with TCMs is applied [36,37], mainly in the field of medical, optical fiber and buildings, for the improvement of thermal comfort in the whole year. Zhang et al. [38] prepared a recyclable thermochromic elastic phase change oleogel for cold compress therapy. Zhang et al. [39] prepared reversible thermochromic microencapsulated phase change materials for enhancing the functionality of silicone rubber materials. Niu et al. [40] present a wet-spinning-based core-sheath strategy to fabricate smart thermochromic phase change fibers (TPCFs) by directly encapsulating PCMs into flexible fibers. Jin et al. [41] uncovered that during summer, on both sunny and cloudy days, the performance of the PCM-integrated thermochromic triple-glazing units surpassed that of conventional double-glazing units. This superiority was evident in a remarkable reduction of total heat absorption, up to 32 % and 40 %, respectively. Nevertheless, in winter, these units demonstrated a tendency to impede the ingress of beneficial solar radiation, resulting in comparatively lower insulation efficacy compared to standard double-glazing units. Miao et al. [42] designed and synthesized a waterborne polyurethane (WPU) resin with phase-change functionality as a binder in asphalt pavement reflective coatings to enhance cooling performance. The research findings indicate that WPU can significantly improve the cooling efficiency of reflective coatings. Synergistic cooling effects are verified with the composite of PCMs and thermal reflection materials in asphalt pavements. However, in most references, the estimation is conducted, according to the effects of PC or/and TC properties on the comprehensive performance in applications. Instead, the interaction between PC and TC processes, especially the effects of TC properties on PC process, has not been well discussed to the most of our knowledge.

In this paper, we conducted an investigation on the performance of asphalt pavement with PCMs and TCMs. The effects of thermochromic property on the temperature regulation as well as the phase change process, with the consideration of the interaction between TC and PC process, are discussed in details. In Section 2, the physical models with and without PCMs and TCMs are introduced. The results of temperature profile in seasons as well as typical days are compared and the phase change properties with PCMs and TCMs are discussed in Section 3. The results indicate that composition of TC and PC properties is effective for temperature regression. The peak temperature is significantly regressed. The adoption of TCMs results in less demand of PCMs application in asphalt pavements. The results concluded in this paper are valid for the feasible design, avoiding the side effects of PCMs adoption in pavements.

2. Physical model

A horizontal asphalt pavement located in Shanghai (31.14 N 121.29E) with 5-layer structure, as depicted in Fig. 1 is taken as the physical model. The width of the pavement is designated as 3 m, to keep the hypothesis of two adiabatic side boundaries valid. From the surface to the bottom, the pavement with a thickness of 3 m is divided into layer 1 (Permeable asphalt mixture OGFC; 5 cm), layer 2 (Asphalt stabilized ATB; 12 cm), layer 3 (Graded crushed stone; 20 cm), layer 4 (Sand; 5 cm) and layer 5 (soil). When thermo-chromic property is adopted, the surface of layer 1 is coated with TCMs. When phase change property is applied, the volume of layer 1 is filled with PCMs.

The bottom of layer 5 (Soil) is assumed adiabatic. Correspondingly, the heat transfer in asphalt pavement is composed of the conduction within and among the layers, the convection with the ambient on the surface of layer 1, the radiation between the surface of layer 1 and the ambient, as well as the indirect solar radiation on the surface of layer 1.

The temperature T_i in i-th layer is determined by Eq. (1).

$$\rho \times C \times \frac{\partial T_i}{\partial t} = k \times \left(\frac{\partial^2 T_i}{\partial x^2} + \frac{\partial^2 T_i}{\partial y^2}\right) \tag{1a}$$

and the boundary condition at the interface (i-j) between i-th layer and j-th layer is expressed as:

$$\begin{cases} T_i|_{i-j} = T_j|_{i-j} \\ \frac{\partial T_i}{\partial y}|_{i-j} = \frac{\partial T_j}{\partial y}|_{i-j} \end{cases} \tag{1b}$$

The temperature at the bottom of layer 5 is adiabatic and expressed as:

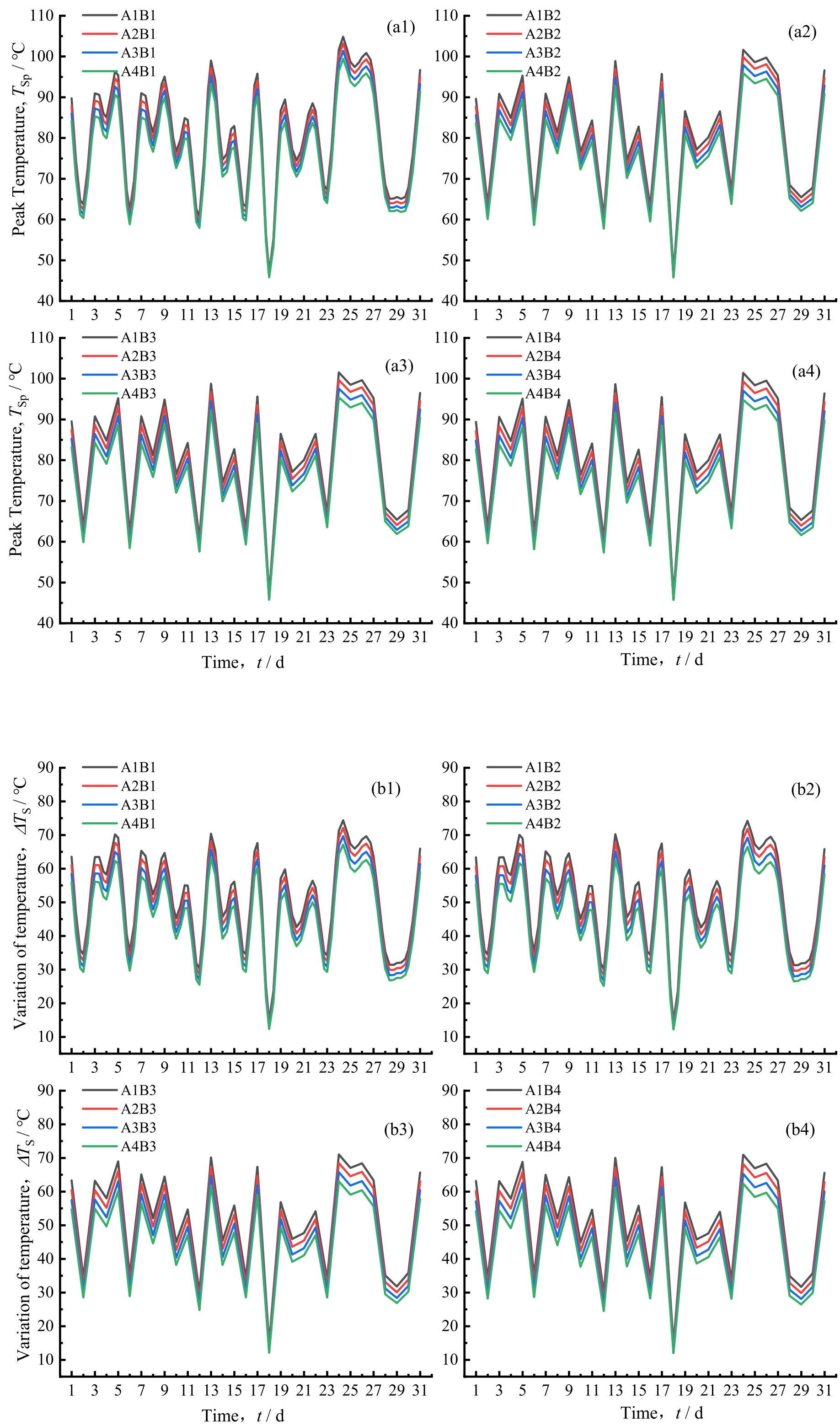

Fig. 5. Temperature of pavement with PCMs. (a1 ~ a4) Peak temperature in July; (b1 ~ b4) Variation of surface temperature and (c1 ~ c4) Surface temperature on July 24th.

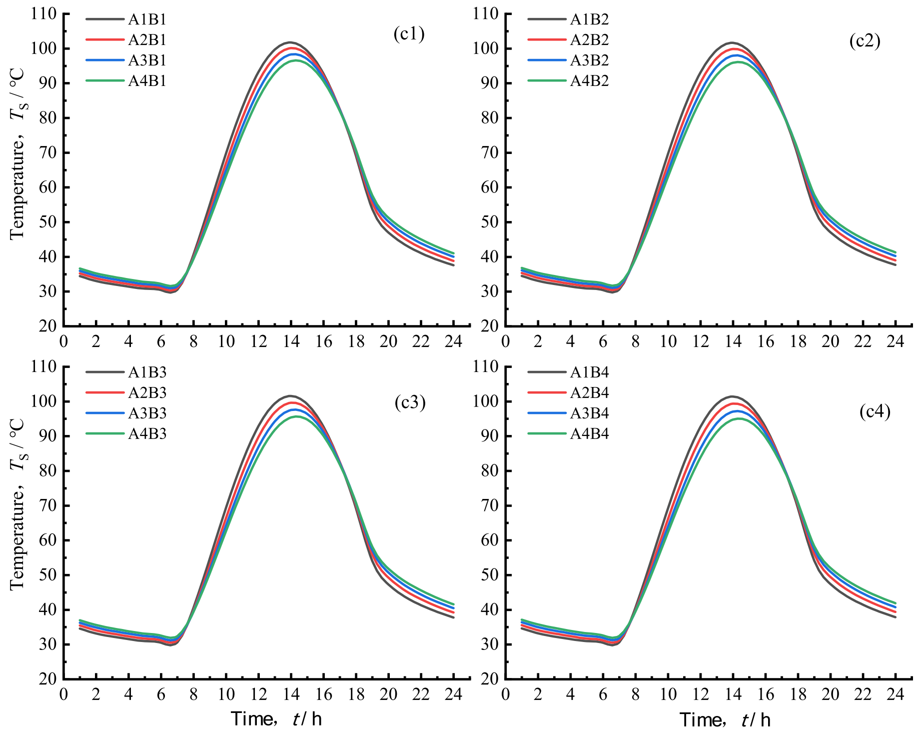

Fig. 5. (*continued*).

$$\frac{\partial T_5|_b}{\partial y} = 0 \tag{1c}$$

The temperature at the surface of layer 1 is determined by:

$$k \times \frac{\partial T_1}{\partial y}|_s = h \times (T_{am} - T_1|_s) + \alpha \times I - \varepsilon \times \sigma \times \left((T - T_Z)^4 - (T_{am} - T_Z)^4\right) \tag{1d}$$

where ε and σ are the emissivity of asphalt in layer 1, i.e. 0.81 and Stefan-Boltzmann constant, i.e. 2.041×10^{-4} $J \cdot h^{-1} \cdot m^{-2} \cdot K^{-4}$, respectively. The absolute temperature T_Z is −273.15 ℃. The convective heat transfer coefficient h is determined by:

$$h = 3.7 \times u + 9.4 \tag{1e}$$

The annual meteorological information of Shanghai is cited from reference [43], including the ambient temperature T_{am}, the indirect solar radiation I and the speed of wind u. Using the UMAT subroutine in ABAQUS, hourly weather data is interpolated to time interval and adopted in boundary condition definitions. The thermal physical parameters of the pavement are listed in Table 1.

2.1. Asphalt pavement with PCMs

The application of PCMs in pavement is considered as a measure of thermal capacity augment, since the latent heat storage capacity during the melting and solidification process is much larger than the sensible heat storage capability of PCMs and asphalt. PCMs is distributed uniformly in layer 1. As a result, the thermal capacity of layer 1 in the asphalt pavement composed with PCMs is determined by Eq. 2.

$$C_{ap} = \frac{\sum_i (m_i \times C_i)}{\sum_i m_i} = \frac{m_a \times C_a + m_p \times C_p}{m_a + m_p} \tag{2a}$$

where m_a and m_p are the mass of asphalt and PCMs in layer 1, respectively. With the definition of the mass fraction of PCMs ξ, Eq. (2a) is re-expressed as:

$$C_{ap} = (1 - \xi) \times C_a + \xi \times C_p \tag{2b}$$

C_a, C_p and C_{ap} represent the thermal capacity of asphalt, PCMs and the composite of asphalt and PCMs, respectively. C_a is listed in Table 1. Since phase change process is involved, the thermal capacity of PCMs is related with temperature, and is determined by Eq. (2c).

$$C_p = \begin{cases} C_l & T < T_{m1} \\ \dfrac{\Delta H}{T_{m2} - T_{m1}} = C_m & T_{m1} \le T \le T_{m2} \\ C_s & T > T_{m2} \end{cases} \tag{2c}$$

where C_l, C_s and C_m refer to the thermal capacity of liquid-phase, solid-phase and melting-phase of PCMs, respectively. ΔH is the enthalpy change of PCMs during phase change process, and is designated as 112.8 J/g. T_{m1} and T_{m2} are the onset temperature of melting and solidification, respectively.

Similarly, the density ρ and thermal conductivity k of composite of asphalt and PCMs are expressed as:

$$\rho_{ap} = \frac{\rho_p \times \rho_a}{(1 - \xi) \times \rho_p + \xi \times \rho_a} \tag{3a}$$

and

$$k_{ap} = \frac{(1 - \xi) \times \rho_p \times k_a + \xi \times \rho_a \times k_p}{(1 - \xi) \times \rho_p + \xi \times \rho_a} \tag{3b}$$

The properties of PCMs are listed in Table 2. In summary, 16 cases are under discussion, categorized by the amount of PCMs adopted and the temperature range of phase change process.

2.2. Asphalt pavement with PCMs and TCMs

TCMs is proposed as the thin coating on the surface of layer 1. The influence of TCMs coating on the density ρ, thermal conductivity k and specific heat C of layer 1 is neglected. With the adoption of TCMs, the

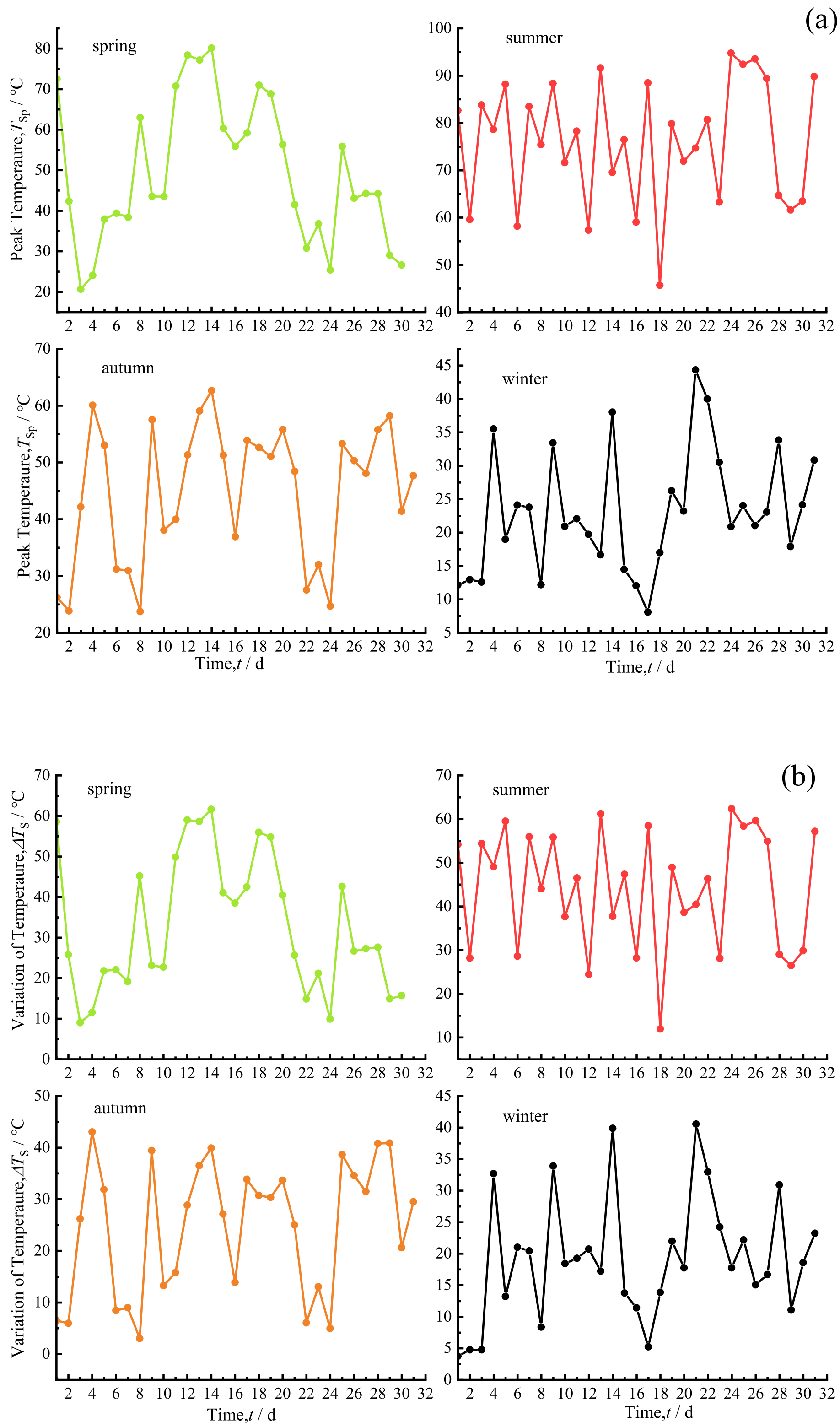

Fig. 6. Results of T_{Sp} and ΔT_S in four seasons. (a) Peak temperature; and (b) Variation of surface temperature.

Table 4
Peak temperature in the typical year (A1B1 ~ A4B4).

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Asphalt*	51.6	65.6	80.5	90.6	90.9	103.1	103.1	99.4	95.0	70.4	59.1	49.8
A1B1	49.2	***63.2***	***78.1***	***88.6***	***88.8***	***101.8***	***101.7***	***97.8***	***93.3***	***68.6***	***57.0***	***47.9***
A1B2	49.2	63.1	78.0	88.5	88.7	101.7	101.6	97.7	93.2	68.5	56.9	47.8
A1B3	49.2	63.0	77.9	88.4	88.6	101.6	101.5	97.6	93.1	68.4	56.8	47.8
A1B4	***49.3***	63.0	77.7	88.2	88.4	101.4	101.40	97.5	92.9	68.3	56.8	***47.9***
A2B1	47.0	***60.6***	***75.4***	***86.3***	***86.5***	***100.2***	***100.1***	***96.0***	***91.4***	***66.7***	***54.8***	46.0
A2B2	47.0	60.4	75.1	86.0	86.2	99.9	99.9	95.8	91.1	66.5	54.7	45.9
A2B3	47.1	60.3	74.9	85.7	85.9	99.7	99.6	95.5	90.8	66.3	54.6	46.0
A2B4	***47.3***	60.3	74.7	85.4	85.6	99.4	99.3	95.2	90.5	66.1	54.6	***46.1***
A3B1	45.2	***58.2***	***72.7***	***83.9***	***84.0***	***98.3***	***98.3***	***94.0***	***89.3***	***64.9***	***53.1***	44.5
A3B2	45.3	58.1	72.3	83.4	83.5	98.0	97.9	93.7	88.9	64.6	52.9	44.5
A3B3	45.4	58.0	72.1	83.0	83.1	97.6	97.5	93.2	88.4	64.4	52.9	44.6
A3B4	***45.7***	58.0	71.9	82.6	82.7	97.1	97.1	92.7	87.9	64.2	53.0	***44.8***
A4B1	43.5	***56.4***	***70.5***	***81.6***	***81.6***	***96.5***	***96.4***	***92.0***	***87.2***	***63.5***	***51.5***	43.2
A4B2	43.7	56.2	70.1	81.1	81.1	96.0	95.9	91.5	86.6	63.2	51.3	43.2
A4B3	44.0	56.2	69.9	80.5	80.6	95.4	95.4	91.0	86.1	62.9	51.3	43.4
A4B4	***44.4***	56.3	69.7	80.1	80.1	94.8	94.8	90.4	85.5	62.6	51.5	***43.6***

Note: * The results of pavement without PCMs are listed in the first line.

absorptivity of solar radiation α is modulated, responding to the variation of surface temperature $T_1|_S$ (or expressed as T_S), as shown in Eq. (4).

$$\alpha = \begin{cases} \alpha_1 & T \leq T_{s1} \\ \left(\dfrac{T_S - T_{s1}}{T_{s2} - T_{s1}}\right) \times (\alpha_2 - \alpha_1) + \alpha_1 & T_{s1} \leq T \leq T_{s2} \\ \alpha_2 & T \geq T_{s2} \end{cases} \tag{4}$$

where T_{s1} and T_{s2} determine the temperature range of thermo-chromic process. α_1 and α_2 refer to the absorptivity of layer 1 with TCMs at the temperature of T_{s1} and T_{s2}, respectively.

The properties of TCMs are listed in Table 3.

2.3. Validation of simulation

2.3.1. Sensitivity analysis

Fig. 2 depicts the impact of time step (10 min, 20 min and 30 min) and node size (0.01 m, 0.03 m and 0.05 m) on simulation results of surface temperature T_S in April and on April 1st in Shanghai. The time step and the node size are designated at 30 min and 0.01 m, respectively.

2.3.2. Validity verification

The surface temperature T_S of asphalt pavement in Wuhan in this paper agrees well with the results in the literature [45], as shown in Fig. 3. The deviation may be due to the difference in meteorological information cited. Therefore, the simulation in this paper is valid.

3. Results and discussion

3.1. Temperature of asphalt pavements

The peak temperatures T_{Sp} of asphalt pavement in April in the case of A4B4, i.e. phase change temperature range of PCMs at 37 ℃ ~ 42 ℃ and amount of PCMs in layer 1 at 20 %, with and without PCMs or/and TCMs are shown in Fig. 4.

According to the results, it is concluded that the composite of PCMs and TCMs is favored for the temperature regression of asphalt pavements and is more effective than that with PCMs only, although the peak temperature is also regressed by PCMs.

3.1.1. Pavement with PCMs

PCMs undergo the phase transitions during the change of phase process, a phenomenon accompanied by energy transformations which enable the storage or release of heat, while maintaining a constant temperature in the material itself. This character of PCMs significantly enhances the thermal capacity and buffers the impact of external temperature fluctuations on internal temperatures, therefore decreasing the temperature variations of the pavement. The effects on temperature regression of asphalt pavements are dependent on the properties of PCMs, i.e. the phase-change temperature range and the amount of PCMs, as listed in Table 2.

For cases A1B1 ~ A4B4, the peak temperature T_{Sp} (the highest temperature of pavement in each day) and the variation of surface temperature ΔT_S, i.e. the difference between the peak value T_{Sp} and the valley value T_{Sv} (the lowest temperature of pavement in each day) in July as well as the results on the day with the highest peak temperature, representing the operation of asphalt pavements in a hot summer, are depicted in Fig. 5.

It is found that T_{Sp} is the least on July 18th and the most on July 24th. The more amount of PCMs adopted, the lower the peak temperature of T_{Sp}, because a larger amount and proportion of heat is stored in the melted phase of PCMs. As a result, there is less demand of sensible heat storage in asphalt as well as the materials in the layers below. Therefore, the temperature variation is small and the peak temperature is lower. With the adoption of PCMs, the highest temperature of T_{Sp} in July reduces from approximate 101.7 ℃ to 94.8 ℃ (by 6.9 ℃), when the amount of PCMs applied in the pavements increases from 5 % in the case of A1B1 to 20 % in the case of A4B4.

The valley temperature of T_{Sp} in July is almost the same as 45 ℃ in all the cases, implying not much influenced by the amount of PCMs applied or the melting temperature range. This is due to the fact that the peak temperature is always higher than the temperature range for PCMs, i.e. Groups B1 ~ B4. Stronger heat flux at the boundary, because of convection and solar radiation, leads to larger temperature increase, if the pavement temperature is out of the range for phase change. Therefore, the highest temperature of T_{Sp} on July 24th, identified with strong solar radiation and high temperature, is more influenced by the amount of PCMs, while the lowest temperature of T_{Sp} on July 18th is less influenced.

The daily results of peak temperature T_{Sp} and the variation of surface temperature ΔT_S in four seasons, i.e. April in spring, July in summer, October in autumn and January in winter, are shown in Fig. 6, in the case of A4B4. The annual results are listed in Table 4.

The correlation of peak temperature T_{Sp} and variation of surface temperature ΔT_S in the case of A4B4 are shown in Fig. 7.

It is concluded from Figs. 6, 7 and Table 4 that the adoption of PCMs leads to the regression of peak temperature all the year around. With the increase of melting temperature of PCMs, i.e. from B1 to B4, the peak temperature increases slightly in the cold seasons, such as January and December, and the increment is a bit more for the pavement with large amount of PCMs, i.e. the Group of A4. In January, the peak temperature

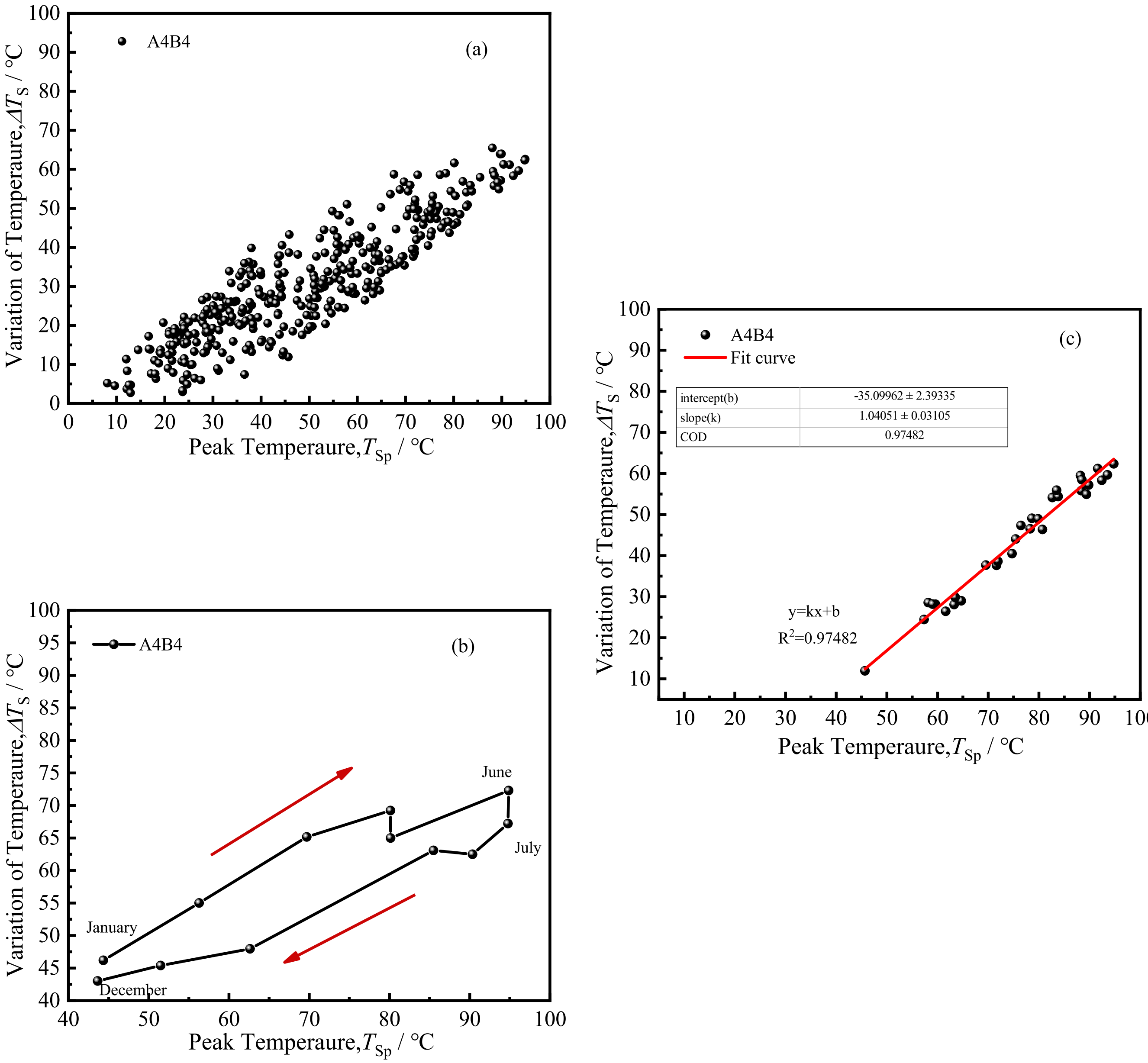

Fig. 7. Correlation of peak temperature and variation of temperature. (a) Annual results; (b) Monthly results and (c) Daily results in July.

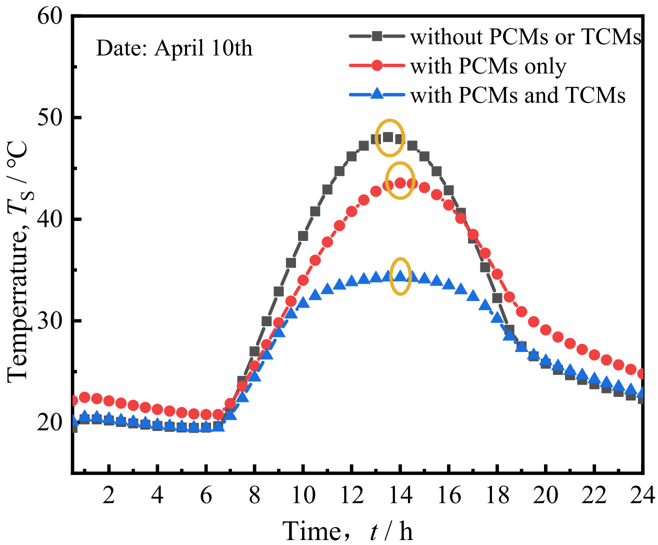

Fig. 8. Comparison of surface temperature T_S on April 10th (A4B4).

is increased by 0.1 ℃, if PCMs in a pavement varies from the case A1B1 to A1B4, while the increment degree is 0.9 ℃, if PCMs varies from A4B1 to A4B4. Similar results are found in December. However, in the hot seasons, such as June, July and August, the peak temperature decreases with the melting temperature as well as the amount of PCMs applied. For example, the peak temperature is reduced from 96.5 ℃ in the case of A4B1 to 94.8 ℃ in the case of A4B4, by 1.7 ℃.

Moreover, according to Fig. 7, it is found that the correlation between the peak temperature and the variation degree of temperature exists in the timescale ranging from a month to a year. Since it is believed that the peak temperature T_{Sp} is corresponding to the risk of rutting or aging and the variation of temperature ΔT_S is usually corresponding to the risk of thermal crack, the correlation between T_{Sp} and ΔT_S makes the peak temperature designated as an alarm index available, and lets our research focused on the regression of peak temperature of asphalt pavement, instead of paying attention to both the results.

3.1.2. Pavement with PCMs and TCMs

When TCMs and PCMs are applied simultaneously in asphalt pavements, the results of surface temperature T_S on a typical day (on April 10th) are depicted in Fig. 8 and compared with those with PCMs only as well as those without PCMs or TCMs. The peak surface temperatures T_{Sp} in the day are marked with yellow circles.

It is observed that the rising of T_S with PCMs is slowed down to a lower value (from 48 ℃ at 13:30 to 43.5 ℃ at 14:00). After the peak value is reached, the surface temperature T_S declines. However, in the declining process, T_S in the scenario of a pavement with PCMs is higher than that without PCMs, even though the surface temperature may be out of the range for phase-change. This is due to two reasons: (1) the release of heat during the solidification of PCMs and (2) the augment of thermal capacity due to the addition of PCMs. As a result, both the latent and sensible heat storage leads to the slower decline of surface temperature and the higher surface temperature at the end of the day.

As far as the effects of TCMs are concerned, the peak of surface temperature T_{Sp} is further regressed after the application of thermo-chromic process, i.e. from 43.5 ℃ to 34.3 ℃ at 14:00. Nevertheless, different from the effects of PCMs, the peak temperature is not delayed by the application of TCMs. Moreover, the temperature T_S at the end of the day for the asphalt pavement with TCMs and PCMs is lower than that with PCMs only. This is due to the fact that TCMs is able to modulate the heat flux at the surface of pavement, in the form of absorbed solar radiation, according to the surface temperature. When high surface temperature occurs, the absorption is reduced by the thermo-chromic property and therefore, less heat is added on the surface of pavement. As a result, slower temperature rise and lower peak temperature are available.

The peak temperatures T_{Sp} of pavements with TCMs and PCMs in a typical year are summarized in Table 5. Comparing the results in Table 4 and Table 5, it is found that the peak temperature is significantly reduced with the adoption of TCMs. The highest peak temperature is only 63.3 ℃ in the case of A1B1, as listed in Table 5, comparing with 103.1 ℃ and 101.8 ℃, as in Table 4. This implied a regression of peak temperature by 1.3 ℃, due to the adoption of PCMs, and more significant regression by 38.5 ℃, due to the further adoption of TCMs.

It is found that, if TCMs is applied, the peak temperature is less influenced by the amount of PCMs applied in asphalt pavements or the range of phase change temperature. As can be seen in Tables 4 and 5, the difference of T_{Sp} is much less among Groups. When TCMs is applied, T_{Sp} is the most in the case of A1B1 (63.3 ℃ in July) and the least in the case of A4B4 (58.4 ℃ in June), and the difference is 4.9 ℃. However, if no TCMs is adopted, T_{Sp} in these two cases is 101.8 ℃ in June and 94.8 ℃ in June or July, respectively. In these cases, the difference is 7 ℃. This implies that the property of TCMs makes PCMs amount and melting temperature range less influential on the peak temperature of pavements.

It is also interesting to conclude that the adoption of TCMs would help reduce the necessary amount of PCMs applied in asphalt pavements, as far as the peak temperature is concerned. For instance, T_{Sp} in the case of A1B1 with TCMs (the amount of PCMs is 5 %) is even lower than that in the case of A4B1 without TCMs (the amount of PCMs is 20 %). Since large amount of PCMs may result in the risk of PCMs leakage or asphalt destruction, the adoption of TCMs is potentially favored for

Table 5
Peak temperature of pavements with PCMs and TCMs.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
A1B1	34.1	36.1	***45.9***	***50.8***	***51.1***	***63.1***	***63.3***	***60.1***	***58.4***	***44.6***	37.6	34.2
A1B2	34.1	36.1	45.8	50.7	51.0	63.0	63.2	60.0	58.3	44.5	37.6	34.2
A1B3	34.1	36.1	45.8	50.7	51.0	62.9	63.1	59.9	58.2	44.4	37.6	34.2
A1B4	***34.2***	***36.1***	45.8	50.6	50.9	62.8	63.0	59.8	58.2	44.5	***37.7***	***34.2***
A2B1	33.9	35.4	***44.5***	***49.3***	***49.6***	***61.6***	***61.9***	***58.7***	***57.0***	***43.6***	36.8	34.0
A2B2	33.9	35.4	44.4	49.1	49.4	61.4	61.7	58.6	56.8	43.5	36.8	34.0
A2B3	34.0	35.5	44.4	49.1	49.4	61.2	61.5	58.4	56.7	43.5	36.9	34.1
A2B4	***34.0***	***35.6***	44.5	49.1	49.4	61.0	61.4	58.2	56.5	43.5	***37.0***	***34.1***
A3B1	33.7	35.0	43.4	***48.1***	***48.5***	***60.3***	***60.6***	***57.6***	***55.8***	***42.8***	36.2	33.8
A3B2	33.7	35.0	43.4	47.9	48.3	60.0	60.4	57.4	55.6	42.7	36.2	33.8
A3B3	33.8	35.0	43.4	47.9	48.2	59.8	60.1	57.2	55.4	42.7	36.3	33.9
A3B4	***33.8***	***35.1***	***43.5***	47.9	48.2	59.6	59.9	57.0	55.3	42.7	***36.4***	***33.9***
A4B1	33.4	34.9	42.5	***47.0***	***47.6***	***59.2***	***59.5***	***56.7***	***54.7***	***42.1***	35.6	33.6
A4B2	33.5	34.9	42.4	46.9	47.4	58.9	59.3	56.4	54.5	42.0	35.6	33.7
A4B3	33.6	34.9	42.5	46.8	47.3	58.6	59.0	56.2	54.2	42.0	35.7	33.7
A4B4	***33.6***	***34.9***	***42.7***	46.9	47.3	58.4	58.8	56.0	54.1	42.1	***35.9***	***33.8***

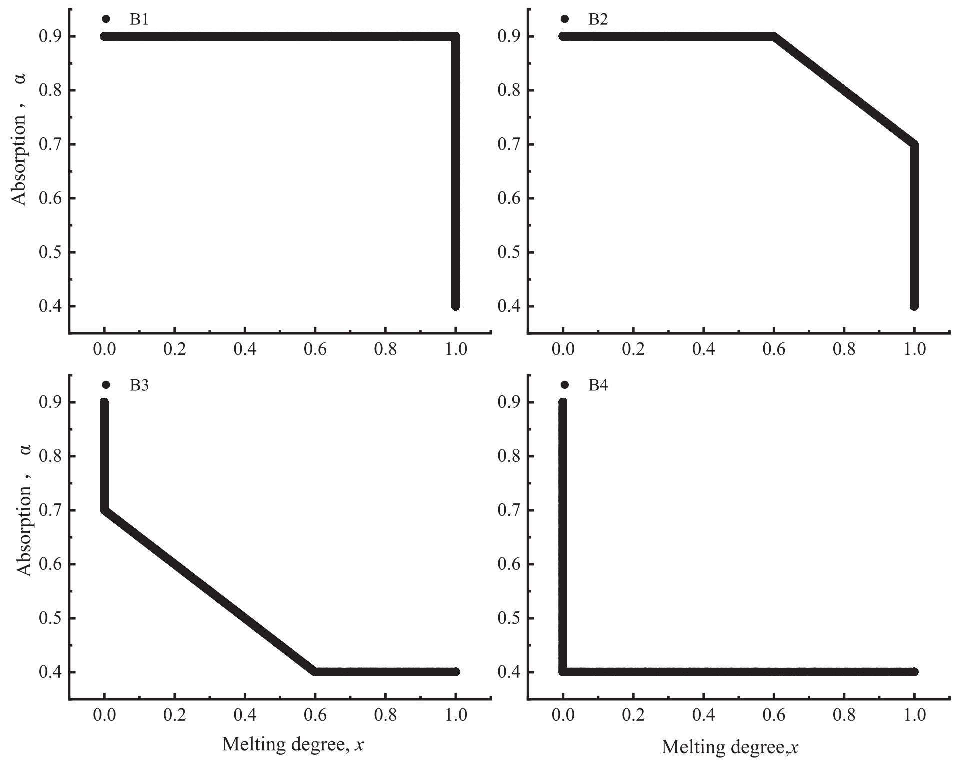

Fig. 9. Correlation of melting degree and absorptivity.

longevity.

3.2. Phase change properties

The melting degree x and the absorptivity α are depending on the temperature of PCMs and TCMs, respectively. According to Table 2, PCMs shares four temperature ranges, i.e. Group B from B1 to B4, while TCMs shares the single temperature range, according to Table 3. The correlation of x and α is concluded as four types and depicted in Fig. 9.

3.2.1. Variation of melting degree

The profiles of melting degree x for the asphalt pavement (A4B4) in the whole year without and with TCMs are depicted in Fig. 10.

It is obvious that the period of phase-change process, when the reaction degree x is between 0 and 1, is wider in the case of asphalt pavements without TCMs, almost covering the whole year as shown in Fig. 10a. On the contrary, if TCMs is adopted, the period of phase-change process is approximately half the year, ranging from 2000 h to 7000 h, as shown in Fig. 10b. This implies that the melting and solidification processes of PCMs are less frequent, due to the adoption of TCMs, which is also favored for the validity and longevity of encapsulated PCMs.

As is known that the temperature regulation of PCMs is mainly attributed to its phase-change property, the phase change process happens when the melting degree x is ranging from 0 to 1. The difference of maximum and minimum melting degree in each day, before and after the adoption of TCMs is depicted in Fig. 11 and Fig. 12, respectively.

It is clear that both the maximum and the minimum melting degree of PCMs in each day of a year are reduced, due to the adoption of TCMs, if any differences exist. The difference of maximum melting degree is mainly in the two ends of time axis, corresponding to the winter and spring seasons, and trends to spread to the whole year, if the melting temperature range is uplifted, i.e. from Group B1 to B4. On the contrary, the difference of minimum melting degree is mainly in the middle of time axis, corresponding to the summer and autumn seasons, and trends to shrink or diminish, from Group B1 to B4.

Comparing Fig. 11 and Fig. 12, it is concluded that the melting temperature range shows stronger effects on the differences of maximum and minimum melting degrees, than the amount of PCMs applied; the difference of minimum melting degree is much more influenced by the property of PCMs, comparing with the difference of maximum melting degree. It is interesting to find that in some cases, for instance, in the Group of B4, the difference of maximum melting degree is -1.0, which indicates that the maximum melting degree is 0 for pavements with TCMs, but 1 for those without. In these cases, PCMs is completely melted in the pavement with PCMs only, but has not melted yet, if temperature is further regulated with TCMs. This phenomenon is more obvious, if the melting temperature range is higher.

3.2.2. Extreme conditions for PCMs

The performance of temperature regulation with latent heat in phase change process is expected, only when the melting degree x is ranging between 0 and 1. Therefore, there are three types of PCMs status in each day, i.e. always equal to 0, always equal to 1 and varies between 0 and 1. The number of days with three statuses of x are listed in Table 6 and the difference of number of days before and after the adoption of TCMs is depicted in Fig. 13.

It is clear that the number of days with always solid status of PCMs ($x = 0$) increases with the melting temperature range, when PCMs varies from Group B1 to B4 or with the amount of PCMs applied, when PCMs varies from Group A1 to A4. The number of days when PCMs is always in the phase of liquid ($x = 1$) decreases, if PCMs varies from Group B1 to B4, but increases if PCMs varies from Group A1 to A4.

After the adoption of TCMs, the number of days always with $x = 1$ decreases and that always with $x = 0$ increases. If x varied between 0 and 1 in a single day is concerned, the number of days increases in the Group of B1 and B2, but decreases in the Group of B3 and B4. This means that if PCMs is considered with a low melting temperature range, the phase change process occurs in more days, after the adoption of TCMs. However, it happens less, if TCMs is adopted in pavements with PCMs at high melting temperature. This is due to the interaction between TCMs and PCMs, as shown in Figs. 10–12.

With the adoption of TCMs, the heat flux due to solar radiation is

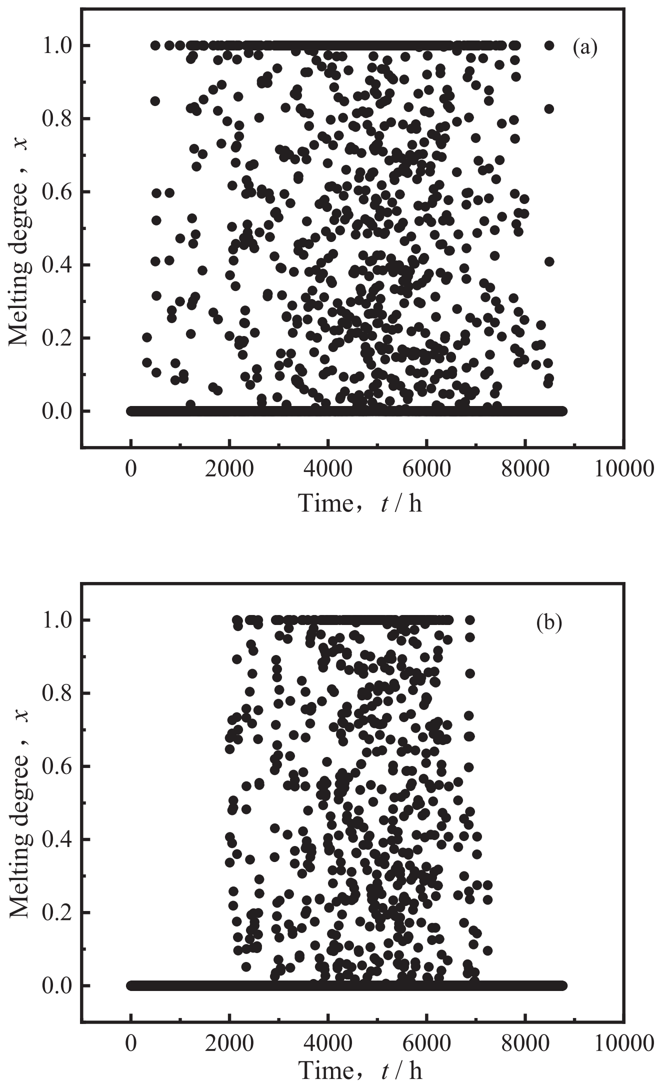

Fig. 10. Melting degree for A4B4 in the whole year. (a) Without TCMs and (b) With TCMs.

modulated, therefore, the conduction heat transfer within and between the layers of pavement may be less in hot seasons, resulting in a reduced amount of latent heat stored in PCMs. Thus, the period for the maximum melting degree of PCMs is less with the adoption of TCMs, especially when the melting temperature range is higher than thermo-chromic temperature range, as in the case of B4. At the same time, the period for the minimum melting degree of PCMs is more, after the adoption of TCMs.

If the phase of PCMs in each time point is considered, the status of PCMs in solid, liquid or phase-change is summarized in Table 7.

It is found that, as a matter of fact, due to the adoption of TCMs, the time of liquid-phase PCMs is always reduced, which increases from Group A1 to A4 but is the most in the Group B3. For instance, number of time points is decreased by 504, if TCMs is adopted in the pavement with A1B1; it is decreased by 1222 in the pavement with A1B3; the decrement is 1161 in the pavement with A1B4. Similar phenomenon is also found in Groups A2 to A4. This may infer to the existence of optimal group of TCMs and PCMs, which is under further consideration.

The time of solid-phase PCMs increases with the amount of PCMs (from Group A1 to A4) and decreases with the melting temperature range (from Group B1 to B4). This is different from the statistic results for days, as shown in Fig. 13. This means that with more PCMs applied in pavements, PCMs on those days experiencing phase change process tends less in the phase of solid. After the adoption of TCMs, the time of solid-phase PCMs increases in all the cases, and the variation degree increases from A1 to A4 and from B1 to B4. However, the variation degree increases from A1B1 to A3B1 and decreases from A3B1 to A4B1 in the Group of B1.

When the phase change process is considered, if no TCMs is applied, the time tends less from Group A1 to A4 or from B1 to B4. However, when TCMs is adopted in pavements, the time mainly increases from Group A1 to A4 and peak in Group B2. After the adoption of TCMs, more time is in the phase of phase change, for B1 to B3, but less for B4. This indicates the complex interaction between TCMs and PCMs, since there are only four types of correlation, as shown in Fig. 9. Further discussion is under consideration.

4. Conclusion

The performance of asphalt pavements with PCMs and TCMs is numerically analyzed with Abaqus and the effects of TCMs on the performance and property of PCMs are discussed. The results concluded in this paper imply that the adoption of PCMs and TCMs in asphalt is an effective method for temperature regression of pavements, resulting in less thermal destruction and potential longevity. The main conclusions are summarized:

(1) The incorporation of PCMs resulted in a reduction of peak pavement temperatures by 1.3 °C, while the addition of TCMs further decreased temperatures by an additional 38.5 °C. Both PCMs and TCMs are able to regress the peak surface temperature of asphalt pavement. The adoption of TCMs in the pavement with PCMs results in a deeper regression. The time of peak temperature is delayed by PCMs above half-hour, but not further delayed by TCMs.
(2) The peak temperature is positively correlated with the variation of surface temperature. The regression of peak surface temperature refers to the reduction of temperature variation in each day, which are both beneficial for asphalt pavement.
(3) Although the properties of PCMs and TCMs are strongly interconnected by temperature, the effects of TCMs on the operation of PCMs are not the same in the cases considered, except that the melting degree is reduced, implying complicated interactions.
(4) With the adoption of TCMs, it is possible to decrease the amount of PCMs, necessarily to be applied for temperature regression in asphalt pavements. After the adoption of TCMs, more time of PCMs is in the phase of solid and less time in the phase of liquid. If low melting temperature range is concerned, PCMs shares more time of phase change.

CRediT authorship contribution statement

Wang Cheng: Conceptualization, Investigation, Methodology, Supervision. **Yu Yue:** Writing – original draft, Software, Investigation. **Yang Junnan:** Investigation, Data curation. **Xu Shixuan:** Software. **Zhu Ye:** Formal analysis, Project administration, Writing – review & editing. **Song Qi:** Software, Methodology. **Guo Xiaofeng:** Methodology, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

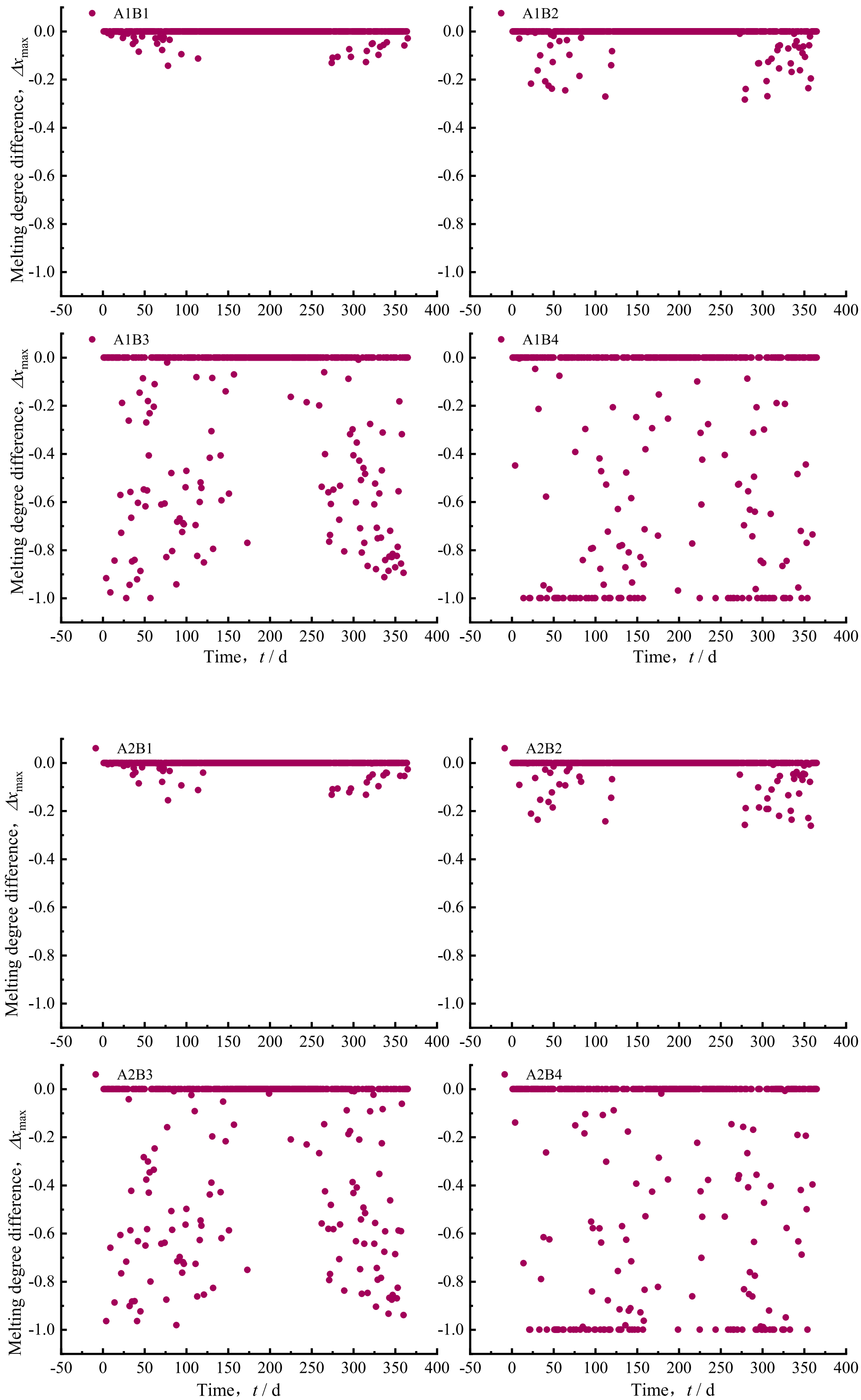

Fig. 11. Difference of maximum melting degree before and after the adoption of TCMs.

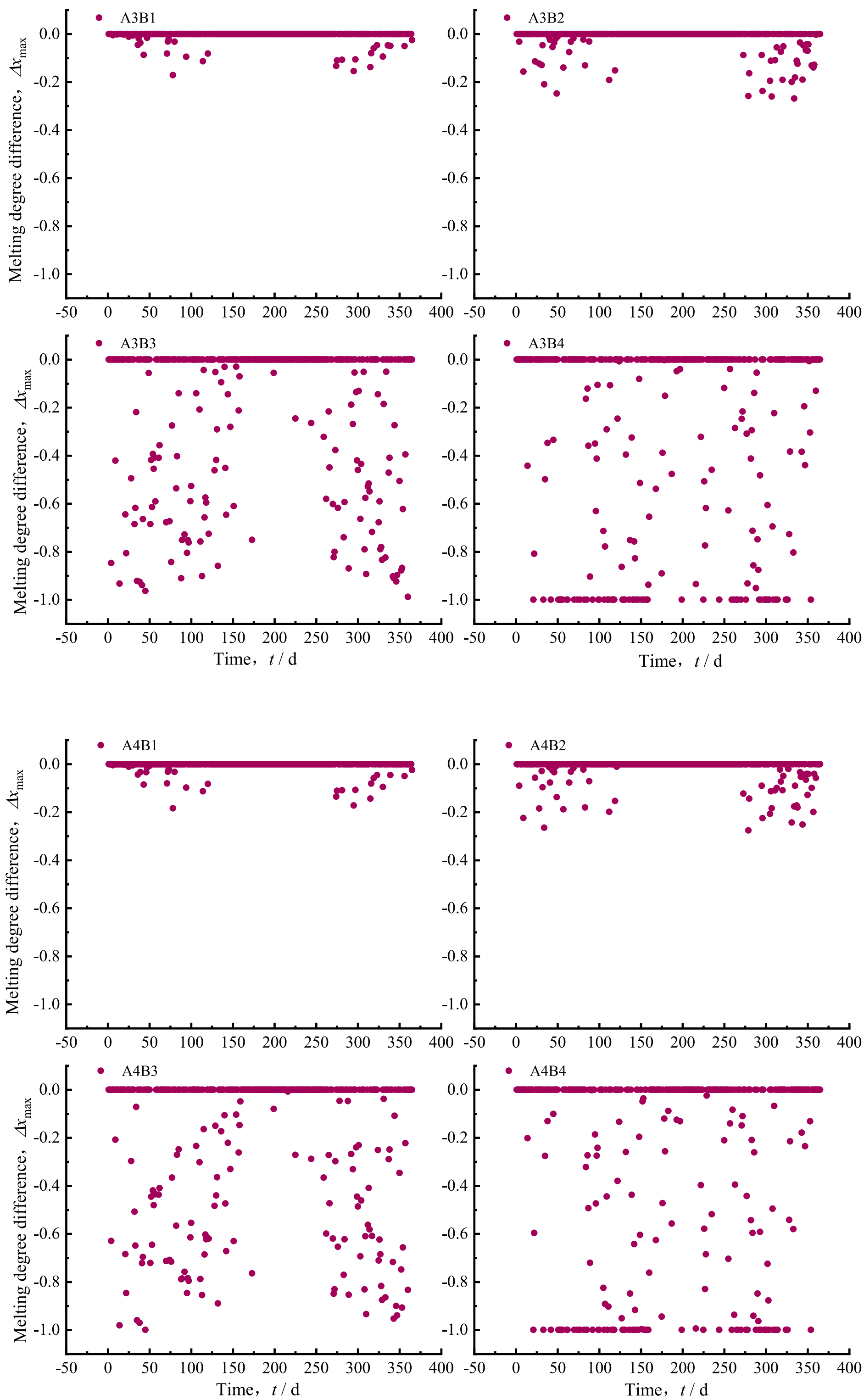

Fig. 11. (*continued*).

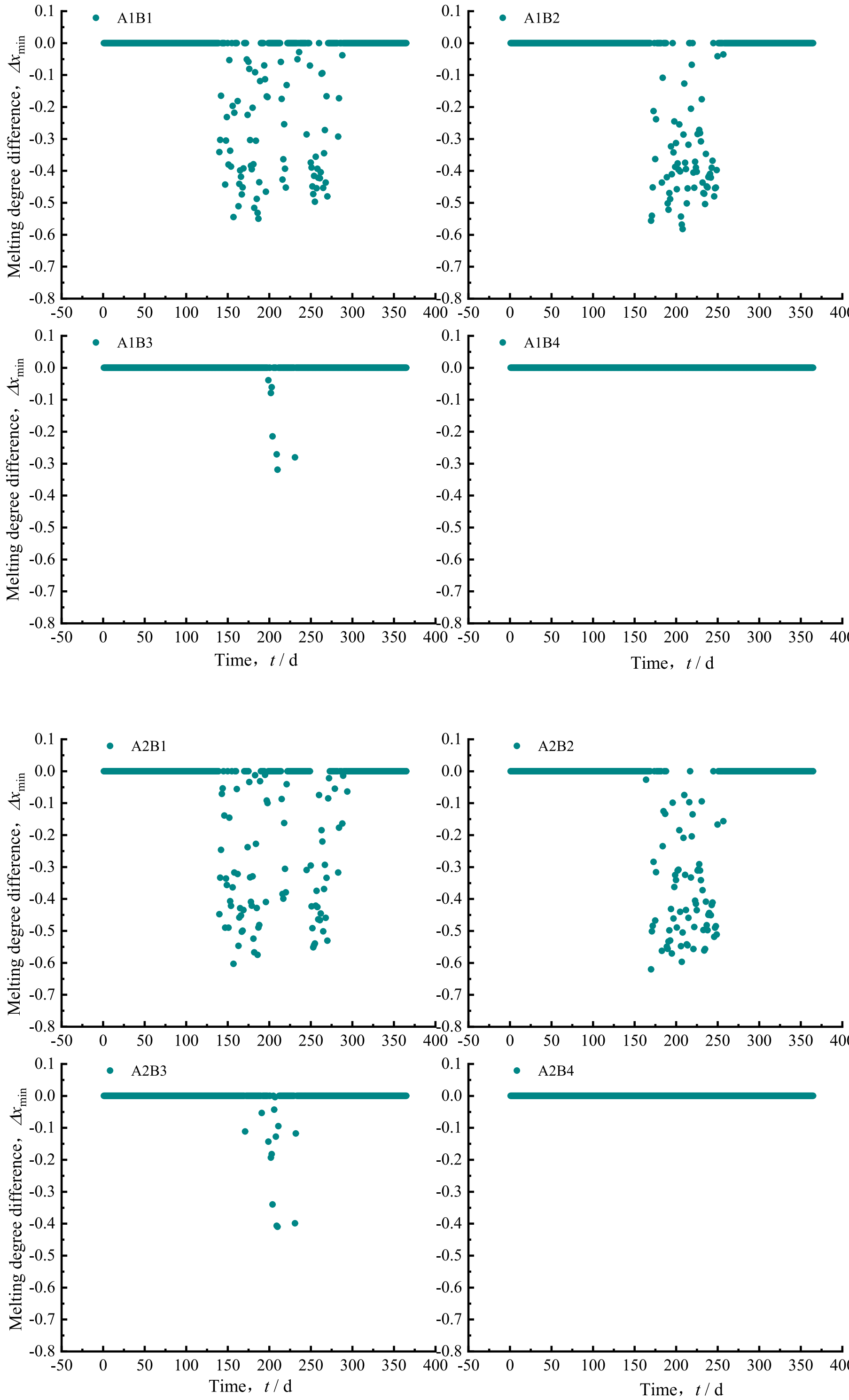

Fig. 12. Difference of minimum melting degree before and after the adoption of TCMs.

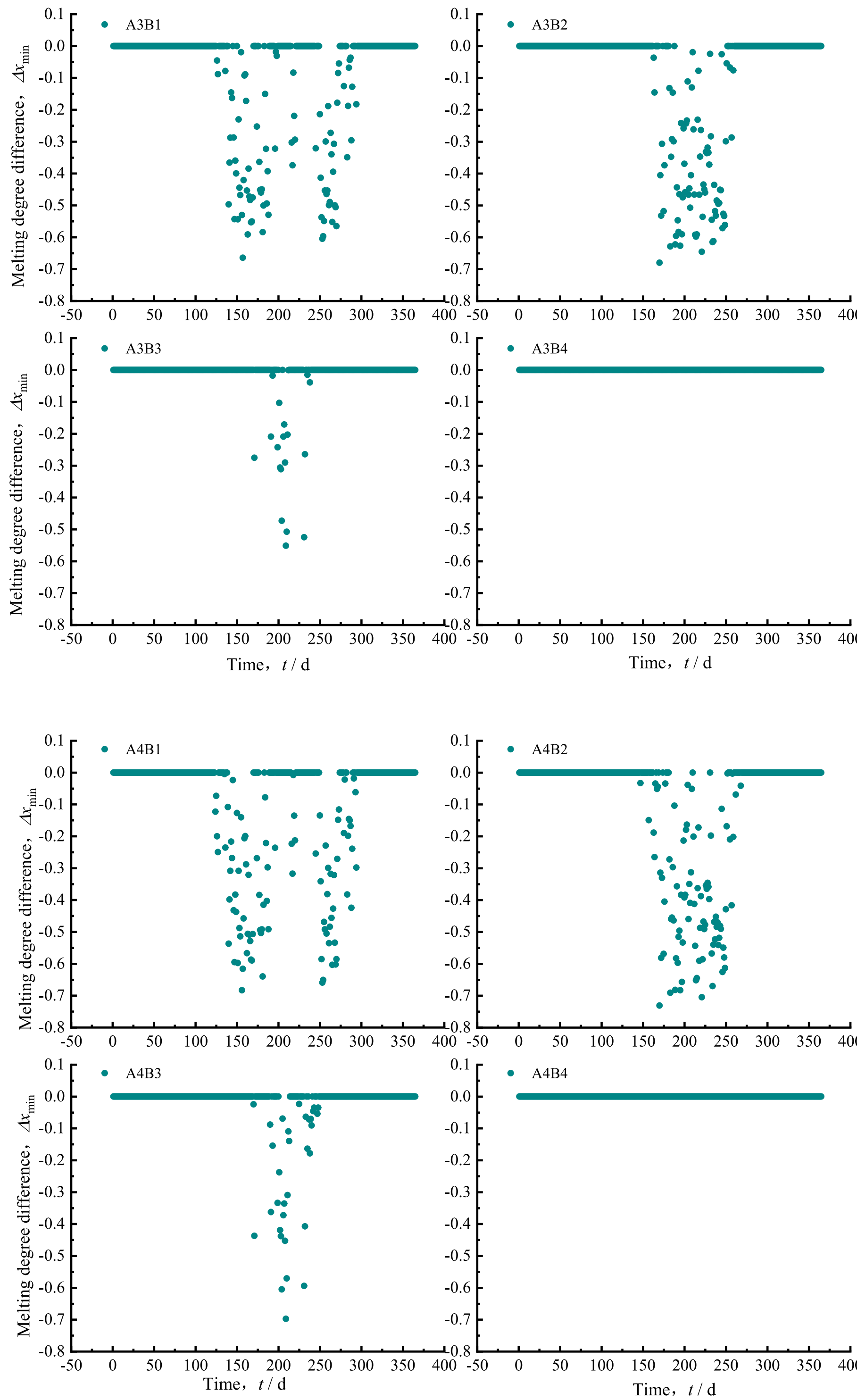

Fig. 12. (*continued*).

Table 6
Number of days with three statuses of x in a whole year.

	0		0–1		1	
	OnlyPCMs	PCMs and TCMs	OnlyPCMs	PCMs and TCMs	OnlyPCMs	PCMs and TCMs
A1B1	23	24	276	296	66	45
A1B2	61	63	297	302	7	0
A1B3	87	111	278	254	0	0
A1B4	112	200	253	165	0	0
A2B1	28	30	265	283	72	52
A2B2	63	67	289	298	13	0
A2B3	93	113	272	252	0	0
A2B4	118	206	247	159	0	0
A3B1	33	34	252	272	80	59
A3B2	67	68	282	297	16	0
A3B3	97	118	268	247	0	0
A3B4	124	215	241	150	0	0
A4B1	36	36	240	268	89	61
A4B2	68	69	266	294	31	2
A4B3	101	123	264	242	0	0
A4B4	129	218	236	147	0	0

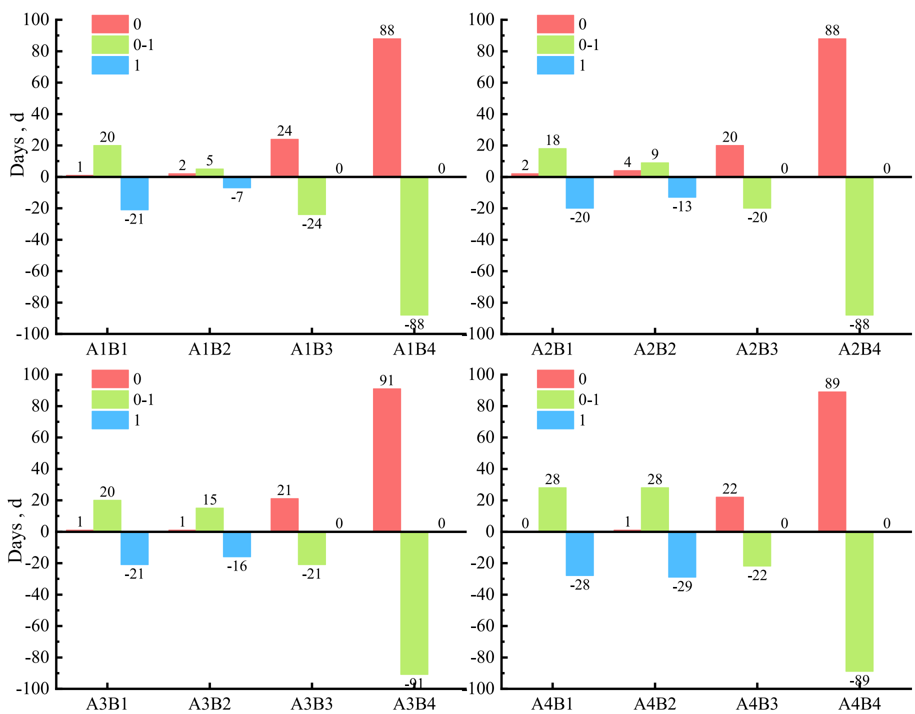

Fig. 13. Variation of number of days after the adoption of TCMs.

Table 7
Statistic of status of PCMs in each time point.

	0			0–1			1		
	OnlyPCMs	PCMs and TCMs	variation	OnlyPCMs	PCMs and TCMs	variation	OnlyPCMs	PCMs and TCMs	variation
A1B1	3266	3622	356	1140	1288	148	4354	3850	−504
A1B2	4395	4904	509	1085	1389	304	3280	2467	−813
A1B3	5471	6288	817	827	1232	405	2462	1240	−1222
A1B4	6287	7515	1228	552	485	−67	1921	760	−1161
A2B1	3202	3572	370	1113	1275	162	4445	3913	−532
A2B2	4295	4834	539	1076	1437	361	3389	2489	−900
A2B3	5348	6252	904	909	1293	384	2503	1215	−1288
A2B4	6239	7535	1296	598	507	−91	1923	718	−1205
A3B1	3134	3507	373	1102	1310	208	4524	3943	−581
A3B2	4216	4798	582	1075	1445	370	3469	2517	−952
A3B3	5250	6225	975	987	1351	364	2523	1184	−1339
A3B4	6211	7562	1351	623	539	−84	1926	659	−1267
A4B1	3092	3461	369	1074	1325	251	4594	3974	−620
A4B2	4136	4761	625	1066	1469	403	3558	2530	−1028
A4B3	5164	6206	1042	1041	1396	355	2555	1158	−1397
A4B4	6170	7590	1420	665	553	−112	1925	617	−1308

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