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Simulation on heat transfer of phase change material modified asphalt concrete for delaying black ice formation

블랙아이스 생성지연을 위한 상변화물질 아스팔트 포장의 열전달 모사

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ABSTRACT

PURPOSES : This study aims to determine the type (e.g., melting point, freezing point, latent heat fusion) and optimal content of phase change material (PCM) based on the numerical and experimental analyses evaluating the effects of heat transfer in PCM-modified asphalt pavement systems.

METHODS : The effect of PCM on the thermophysical properties of PCM-modified asphalt concrete can be taken as an effective volumetric heat capacity. The volumetric fraction of PCM was calculated using an iterative method. The numerical model was established and computed using the MATLAB 2020 software. The optimum PCM design tool was developed to select the type and contents of the PCM. The PCM was chosen based on the following criteria: black-ice-formation delay time, minimize temperature increase, and increase temperature area. To validate the numerical model, asphalt mixtures were modified with varying PCM contents, and the temperature response of the PCM-modified asphalt samples was examined via temperature test.

RESULTS : The numerical results showed that incorporating PCM into the asphalt mixture can slow the cooling rate of the pavement system. The predicted results from the optimum PCM design tool were highly consistent with the measured values from the laboratory temperature test.

CONCLUSIONS : The temperature of PCM-modified asphalt pavement can be predicted via numerical method. The effect of PCM on the thermophysical properties can be considered as effective volumetric heat capacity; while the volume fraction of PCM can be calculated via an iterative method. The accuracy of the numerical model was confirmed by a high agreement between the measured and predicted values.

Keywords
Asphalt Pavement, Phase Change Material, Numerical Model, Heat Transfer, Black ice

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1. Introductuon

1.1. Literature review

During the winter season in Korea, snow and ice, especially the black ice, can reduce the friction at the tire-surface interface. Black ice commonly occurs on the road surface at a temperature below 0℃ (Zheng et al., 2016). Black ice is highly transparent and difficult to see compared to snow for a thicker ice layer because it represents only a thin accumulation. Thereby, this condition makes driving and walking on black ice road surface extremely dangerous. Several methods have been developed to reduce this problem, such as spraying road salt, using a gas-fired system, and incorporating phase change material (PCM) in the asphalt mixture (Chen et al., 2011; Zhong et al., 2018; Bueno et al., 2019). However, road salt is environmentally harmful and causes damage to the metal on the vehicles, and using gas boiler releases huge carbon dioxide (CO_2) into the environment. Meanwhile, incorporating phase change material in the asphalt mixture is a promising solution.

Phase change material is a latent heat storage material that can absorb or release heat energy when undergoing a phase change. At the melting point (i.e., solid-liquid transition), PCM will absorb thermal energy. In contrast, PCM will release thermal energy when the surrounding temperature reaches freezing point. Various studies have revealed the effect of PCM on the thermophysical properties of asphalt mixture. For instance, Kakar et al. demonstrated the effectiveness of low-temperature thermoregulation by incorporating PCM in asphalt mixtures (Kakar et al., 2019). Manning et al. also indicated that the mixtures containing PCM-6 (phase change at 6℃) could delay or prevent the freezing of asphalt pavement (Manning et al., 2011). The phase change temperature is a critical factor that imposes a substantial impact on the warming or cooling temperature of asphalt mixture. The optimal transition temperature can reduce the adverse effects of asphalt concrete at low or extremely low temperatures. Wang et al. provided a method to adjust the phase change temperature of PCM by modifying the ratio of two PCMs (Wang et al., 2016).

However, related research also suggested that incorporating pure PCM in the asphalt mixture is restricted due to leakage during the melting process. The leaked PCM can reduce the adhesion between aggregate and asphalt binder, resulting in lower performance. Therefore, a packaging technology was developed to retain the pure PCM insider the container. The research from Wang et al. recommended a method to microencapsulate PCM with calcium carbonate shells (Wang et al., 2016). The encapsulated PCM can increase heat-transfer area, avoid leakage, and withstand the frequent volume when the phase change occurs. Besides, impregnation PCM in lightweight aggregates (LWAs) is an effective method. Impregnation/encased methods may bring economic benefits because several LWAs have the potential of high PCM absorption compared to the encapsulation method (Kheradmand et al., 2015).

Pavement temperature is also a hot topic because precise pavement temperature prediction provides a better understanding of the pavement mechanical properties. Incorporating PCM in the asphalt mixture can mitigate excessive thermal energy to ensure the suitable working temperature of asphalt pavement. Several numerical models have been established to determine the thermal behavior of PCM modified asphalt mixture. Mathematical modeling latent heat system is needed for optimal design and material selection of PCM (Dutil et al., 2011). One-dimensional modeling is used to simulate the heat transfer since pavement thickness is smaller than other dimensions. Shari et al. provided a 1D heat transfer model of PCM modified asphalt concrete using an effective heat capacity method (Sharifi et al., 2015). The upper boundary conditions include solar radiation and convection between the surface and the surrounding environment.

1.2. Research contents

This study evaluates the effect of phase change material on the heat transfer of PCM-modified asphalt pavement system. The effect of PCM on a PCM-modified asphalt concrete's thermophysical properties can be considered an effective volumetric heat capacity. The volume fraction of PCM was calculated by the iterative method. The numerical model was established and computed by MATLAB 2020 software. The optimum PCM design tool was developed to select the type (e.g, melting point, freezing point, latent heat fusion) and contents of PCM. Indoor asphalt mixtures were incorporated with various PCM contents to validate the accuracy of numerical model. The temperature response of the PCM-modified asphalt sample was examined by the temperature test. The promising results offer the numerical tool for calculating the optimum PCM and predicting the temperature of PCM-modified asphalt pavement based on the real weather conditions.

2. Model establishment

Table 1. Nomenclature

c_p	specific heat capacity ($Jkg^{-1}K^{-1}$)
k	thermal conductivity ($Wm^{-1}K^{-1}$)
L	latent heat fusion of PCM (Jg^{-1})
t	time (s)
T	temperature (^oC)
q_r	absorbed radiation heat flux (Wm^{-2})
q_e	emit radiation heat flux (Wm^{-2})
q_c	heat convection (Wm^{-2})
q_l	longwave length radiation (Wm^{-2})
Q	total boundary heat flux (Wm^{-2})
z	spatial coordinate (m)
ϕ	volume of addition PCM (%)
σ	Stefan-Botzmann constant ($5.67\times10^{-8}\ Wm^{-2}K^{-4}$)
ρ	density (kgm^{-3})
ξ	volume fraction of PCM (%)
dt	time step(s)
dz	depth increasement (m)
$\Delta\ T_{\min}$	minimum temperature increase (^oC)
A_{inc}	increased temperature area($^oC.h$)
$D_{black\ ice}$	delay black ice time (h)
Subscripts	
a	air
AC	asphalt concrete
PCM	phase change material
eff	effective
i	the i^{th} layer
l	liquid phase
s	solid phase
sur	surface
Superscripts	
m	intermediate time step
p	previous time step

2.1. Temperature in asphalt pavement

According to previous research, the one-dimensional heat transfer has been adopted to predict asphalt pavement temperature (Mrawira et al., 2002; Gavin et al., 2007). The 1D heat transfer equation for the pavement system is shown in Equation 1.

$$\rho c_p \frac{dT}{dt} = \frac{d}{dz}\left(k\frac{dT}{dz}\right) \tag{1}$$

The temperature in asphalt pavement can be influenced by external and internal factors (Si et al., 2020). The external factors include solar radiation, air temperatures, convection between the surface and surrounding air, and wind speed (Figure 1).

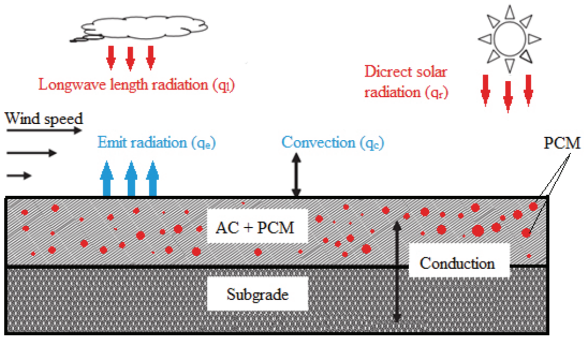

Fig. 1 Pavement Temperature Profile

At the pavement surface, the total boundary heat flux (Q) is involved in the heat exchange with the surroundings, as shown in Equation 2. The surrounding factors include of absorbed radiation (q_r), incoming longwave radiation (q_l), heat convection (q_c), and emit thermal radiation to the environment (q_e).

$$Q = q_r + q_l - q_c - q_e \tag{2}$$

2.2. Numerical model for PCM modified asphalt pavement

The effect of addition PCM in asphalt concrete is considered as an effective volumetric heat capacity($\rho c_{p_{eff}}$) (Chen et al., 2015; Anupam et al., 2020). This value is taken as a function of additional PCM volume (ϕ), the volume fraction of PCM (ξ), asphalt concrete's density (ρ_{AC}), PCM's density (ρ_{PCM}), and specific heat capacity (c_{ps}, c_{pl}, c_{pAC}). It can be referenced from Equation (3).

$$\rho c_{p_{eff}} = \phi\rho_{PCM}(\xi c_{pl} + (1-\xi)c_{ps}) + (1-\phi)\rho_{AC}c_{pAC} \tag{3}$$

Besides the effective volumetric heat capacity, PCM-modified asphalt concrete's thermal conductivity also depends on the matrix's thermal conductivity. The effective thermal conductivity can be expressed by the volume fraction and thermal conductivity of PCM and asphalt concrete. This is a tribute to the incorporation of PCM inside AC, which uses spherical microparticles. As considering dilute dispersion between embedded spheres, Karol recommended the effective thermal conductivity of spherical embedded in a continuous matrix by the Maxwell model (Karol and Tomasz, 2015) (Equation 4).

$$\frac{k_{eff}}{k_{AC}} = 1 + \frac{3\phi}{\frac{k_{PCM} + 2k_{AC}}{k_{PCM} - k_{AC}} - \phi} \tag{4}$$

The Maxwell model was able to validate for the case of PCM volume lower than 25%. The thermal conductivity of PCM is strongly related to the liquid and solid fractions. It can be approximately calculated by Equation 5.

$$k_{PCM} = \xi k_l + (1-\xi)k_s \tag{5}$$

The volume fraction of PCM is considered as a linear function of temperature $\xi(T)$, where T_s and T_l are able to determine from the Differential Scanning Calorimeter (DSC) curve. The expression of volume fraction is shown in Equation 6.

$$\xi(T) = \begin{cases} 0, \ T < T_s, \ Solid\ phase \\ \frac{T - T_s}{T_l - T_s}, \ T_s < T < T_l, \ Mushy\ phase \\ 1, \ T > T_l, \ Liquid phase \end{cases} \tag{6}$$

When the temperature PCM-modified asphalt concrete tends to the phase change temperature (Tm), PCM can absorb or release thermal energy during melting or crystallization, respectively. This thermal energy is defined by the latent heat fusion of PCM (L). Hence, the transient heat conduction of PCM modified asphalt concrete can be written in Equation (7).

$$\rho c_{p_{eff}} \frac{dT}{dt} = \frac{d}{dz}(k_{eff} \frac{dT}{dz}) - \phi \rho_{PCM} L \frac{d\xi}{dt} \tag{7}$$

2.3. PCM optimum design tool

Based on the numerical model of PCM modified asphalt concrete, the MATLAB R2020a was assigned to program and solve numerical equations (Matlab R2020a, 2020). To establish a numerical model, the pavement system has been divided into small layers. Each layer has thermophysical properties such as thermal conductivity (k_i), thickness (z_i), density (ρ_i), PCM fraction (ξ_i), which can be shown in a numerical equation (Figure 2).

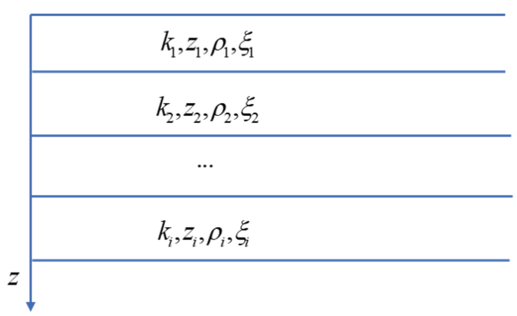

Fig. 2 Schematic Diagram of Asphalt Pavement

The numerical incremental recursive model has been used to analyze the transient temperature response of pavement (Mrawia et al., 2002). The discrete form of Fourier equations within the layer of PCM modified asphalt concrete can be written as Equation (8).

$$\begin{aligned} \rho c_{p_{eff}} (\frac{T_i^{p+1} - T_i^p}{\Delta t})\Delta\ z = k_i(\frac{T_{i-1}^p - T_i^p}{\Delta z}) \\ - k_i(\frac{T_i^p - T_{i+1}^p}{\Delta z}) - \phi \rho_{PCM} L(\frac{\xi_i^{p+1} - \xi_i^p}{\Delta t})\Delta z \end{aligned} \tag{8}$$

At the beginning of each time step (t^{p+1}), the unknown volume fraction of PCM (ξ_i^{p+1}) is calculated based on the temperature of the previous time step (t^p). By solving Equation 8, an intermediate temperature T_m^{m+1} is calculated. Then, the T_m^{m+1} is used to update the unknown ξ_i^{p+1}. This iterative process repeated until the $||T^{m+1} - T^m|| < 10^{-5}$ (Kousksou et al., 2006). Equation 9 expresses the iterative method.

$$\begin{aligned} \rho c_{p_{eff}} (\frac{T_i^{m+1} - T_i^p}{\Delta\ t})\Delta\ z = k_i(\frac{T_{i-1}^p - T_i^p}{\Delta\ z}) - k_i(\frac{T_i^p - T_{i+1}^p}{\Delta\ z}) \\ - \phi \rho_{PCM} L(\frac{\xi_i^{m+1} - \xi_i^p}{\Delta\ t})\Delta\ z, m = 1, 2, 3, \ldots \end{aligned} \tag{9}$$

An optimum PCM design tool was developed by MATLAB App Designer (Matlab R2020a, 2020). The developed tool provides a method to decide the optimum PCM. A guide user interface (GUI) of the PCM optimum design tool is showed in Figure 3. The properties of phase change material and asphalt pavement can be adjusted in “PCM designer”tab. The weather data (e.g., time, air temperature, wind speed, solar radiation) can be imported via CSV file. After calculating, the results show the temperature behaviors of asphalt pavement with and without PCM.

To predict the optimum phase change material in this study, the weather data at Gimpo station on December 5th, 2010, was used to analyze. The weather data is shown in Figure 4. Thermophysical properties of asphalt pavement are shown in Table 2, referenced from previous research (Gavin et al., 2007). The asphalt concrete layer has a thickness of 10.2cm, density of 2288 kgm^{-3}, thermal conductivity of 1.2 $Wm^{-1}K^{-1}$, and specific heat capacity of 950 $Jkg^{-1}K^{-1}$. Meanwhiles those values of subgrade are 15.2cm, 1950 kgm^{-3}, 1.0 $Wm^{-1}K^{-1}$, and 1100 $Jkg^{-1}K^{-1}$, respectively. The effect of PCM on the temperature of pavement structure was variable in PCM contents (Case 1 – Case 3), phase change temperature (Case 4 – Case 6), and latent heat fusion (Case 7 – Case 9). Therefore, in this model, the three above factors were varied to find the optimum PCM. The variable of PCM properties is shown in Table 3.

Fig. 3 PCM Optimum Design Tool

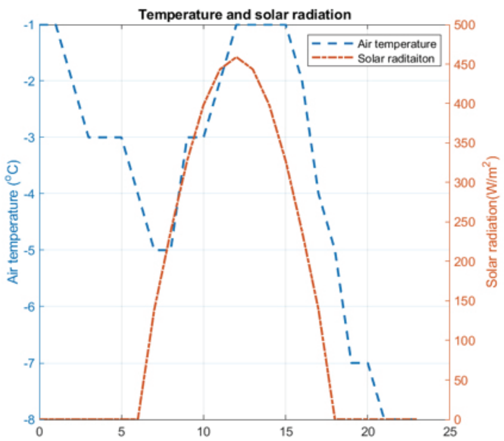

Fig. 4 Weather Data on December 5th, 2010

Table 2. Thermophysical Properties of Asphalt Concrete

	Thickness	ρ	k	c_p
AC pavement	10.2 cm	2288	1.2	950
Subgrade	15.2 cm	1950	1.0	1100

Table 3. Trial Cases to Select the Optimum PCM

Case	PCM content (%)	Melting point (^oC)	Freezing point (^oC)	Latent heat (Jg^{-1})
0	0	-	-	-
1	0.5	3	-8	50
2	1.0	3	-8	50
3	1.5	3	-8	50
4	1.5	5	-2	50
5	1.5	3	-4	50
6	1.5	-3	-6	50
7	1.5	3	-8	100
8	1.5	3	-8	150
9	1.5	3	-8	200

Based on the trial results, the following criteria were developed to select the optimum PCM, including the delay of black ice, minimum temperature increase, and increased temperature area. The delay black ice $(D_{black\ ice})$ is the total time that the temperature of conventional pavement (without PCM) is lower than 0℃ while that of PCM modified pavement is higher than 0℃. The minimum temperature increase ($\Delta T_{\min}$) is calculated by the lowest surface temperature at the time i^{th} subtract the air temperature at the time i^{th} (Equation 10). The area between the air temperature curve and surface temperature is defined as the increased temperature area (A_{inc}) (Equation 11).

$$\Delta T_{\min} = \min(T^i_{sur}) - T^i_{air} \tag{10}$$

$$A_{inc} = \sum (T^i_{sur} - T^i_{air}) \times \Delta t \tag{11}$$

3. Select the optimum PCM and temperature tests

3.1. Select the optimal PCM

The trial results are shown in Table 4. It can be concluded that the mix containing PCM shows an increase in the surface temperature of asphalt concrete. In the case 0 (without PCM), the minimum temperature increase was 0.14℃ and the delay black ice time was 0h. Meanwhile, the higher PCM content (case 1 - case 3) acquired greater temperatures during the cooling process, which indicates a potential to delay the formation of black ice. Larger PCM volume will release more latent heat, which increases the temperature of the whole sample. This finding agrees with the preliminary research about PCM efficiency by Si et al., 2020. Also, it can be found from the test results that the melting, freezing temperature of PCM material (case 4 – case 6) considerably increases the minimum temperature. It can be explained through the following mechanism. When phase change temperature was close to the minimum of air temperature, it helps PCM release the latent heat fusion, which indicated that the $\Delta T_{\min}$ would increase. Finally, the higher latent heat fusion (case 7 – case 9) acquired a greater increased temperature area, which was approximately 79.34℃.h (case 9). Considering the above factors and laboratory conditions, the Case 3 was chosen as the optimal PCM. In this ideal mixture, the PCM content is 1.5% by weight of the total mix, the freezing point is –8℃, and the latent heat fusion is 50J/g. The results of case 3 are shown in Figure 5.

Table 4. Trial Results

Case	$\Delta T_{\min}(^oC)$	$A_{inc}(^oC.h)$	$D_{black\ ice}(h)$
0	0.14	36.19	0
1	1.24	67.76	1.32
2	1.56	69.43	1.54
3	2.86	72.33	2.56
4	2.56	63.67	1.27
5	2.78	65.45	1.57
6	2.57	68.49	1.76
7	2.92	73.45	2.65
8	2.98	77.23	2.78
9	2.97	79.34	2.89

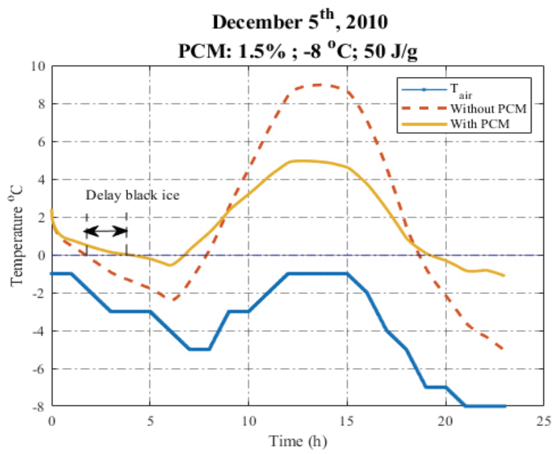

Fig. 5 Case 3 Trial Result

3.2. Samples preparation

The PCM modified asphalt samples were prepared for the measurement of the temperature response of PCM-modified asphalt concrete. The measured temperature values were used to compare with predicted value from the numerical model. Based on the trial results from optimum PCM design tool, the PEG (Polyethylene Glycol) was selected as the phase change material. PG64-22 asphalt binder was used in this experiment with a content of 5.4%. The nominal maximum aggregate size was 13 mm. Figure 6 shows the phase change properties of PEG material.

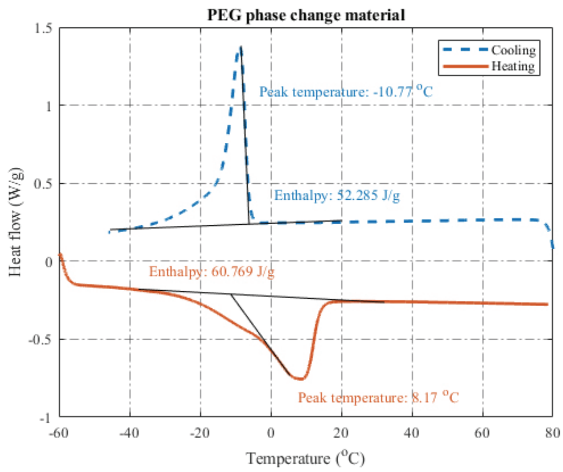

Fig. 6 PEG Phase Change Properties

Three PCM contents (0.5%, 1.0%, and 1.5% by weight of total mix) were used in this experiment. In the mixing process, PCM was thoroughly mixed with aggregate for 60 seconds. Then, the asphalt binder was poured into the mixture and they were continuously mixed for another 60 seconds. All cylindrical samples were prepared with 100 mm in diameter, 62.5 mm in height, and designed air voids of 7±1%(Figure 7).

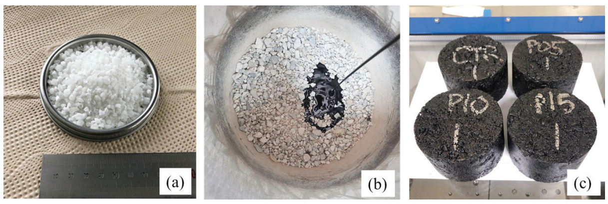

Fig. 7 (a) PEG PCM, (b) Mixing Process, (c) PCM Modified Asphalt Sample

3.3. Temperature tests

3.3.1. Temperature test procedure

A group of four samples was checked to evaluate the temperature response of PCM modified asphalt concrete. All samples were conditioned in a cooling chamber at 10℃ for 6 hours. An infrared camera, positioned 30cm above the samples, was employed to record the surface temperature of the specimens (Figure 8a-b). The cooling process consists of dropping the temperature from 10 to –10℃ with a cooling rate of 1℃/h and conditioning at –10℃ for 2 hours. During the testing process, the surface temperature was recorded every 2 minutes.

3.3.2. Model validation test procedure

To simulate 1D heat transfer, the bottom and the sides of the samples were insulated with polyurethane foam to minimize heat loss to the outer environment (Figure 8c). The infrared camera was set 30cm above the PCM sample. During the testing process, the surface temperature was recorded for every 2 minutes. The cooling chamber's temperature was cooled from 10℃ to –10℃ and then raised back to 10℃ in 20 hours.

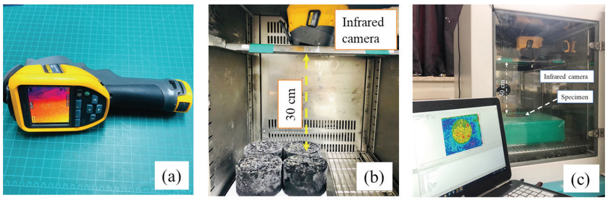

Fig. 8 (a) An Infrared Camera, (b) Temperature Test Set Up, (c) Simulation of 1D Heat Transfer in Cooling Chamber

4. Results-discussion

4.1. Temperature response of PCM-asphalt concrete

The temperature of PCM modified samples is shown in Figure 9. The PCM10 and PCM15 acquired a higher temperature than CTR00 (control) and PCM05. At –5℃, PCM05 was approximately 1℃ than the control sample. The sample containing 0.5% PCM presented an insignificant increase in temperature. Meanwhile, the PCM10 and PCM15 samples gained 2-3℃ higher than the control sample. Adding an appropriate amount of PCM in an asphalt mixture helps increase the temperature in the asphalt mixtures at low temperature (Cheng et al., 2011). The effect of PCM on the regulation temperature was clearly shown at temperatures of –7.5℃ to –10℃. The PCM_{10} and PCM_{15} samples yielded higher temperatures than the control sample, which were

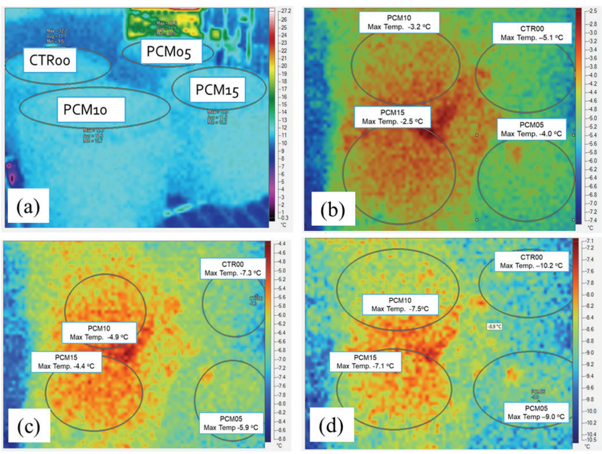

Fig. 9 Temperature of samples at (a) 10 ℃, (b) at -5 ℃, (c) at -7.5 ℃, (d) at -10 ℃

2.5℃ and 2.9℃, respectively. This can be explained by the PCM released latent heat during the phase change temperature (Figure 6).

4.2. Model validation

Among four mixtures, the CTR00 (control mixture) presented the lowest temperature of –8.5℃ and the minimum temperature delay was approximately 30 minutes (Figure 10). The asphalt concrete constructed with PCM offers a certain temperature adjustment. The increasing temperature effect was insignificant when the content of PCM is 0.5%. This is because PCM's effect is strongly dependent on the volume fraction (Si et al., 2020). At the freezing range temperature of PCM, the delayed temperature clearly showed. Meanwhiles, the delay time of minimum temperature was clearly shown at the higher PCM content, especially the PCM10 and the PCM15 mixture. Containing 1-1.5% PCM helps asphalt mixtures gain a 2-3℃ higher than that of the control sample. Within the interval from –6℃ to –10℃, the PCM will release latent heat, which increases the temperature sample and delay minimum temperature. The potential of PCM is more prominent when the T_{air} drops from –8℃ to –10℃ where the PCM-modified asphalt mixtures gently reach the minimum temperature with around peak shape in contrast to the spike peak shape of the control sample.

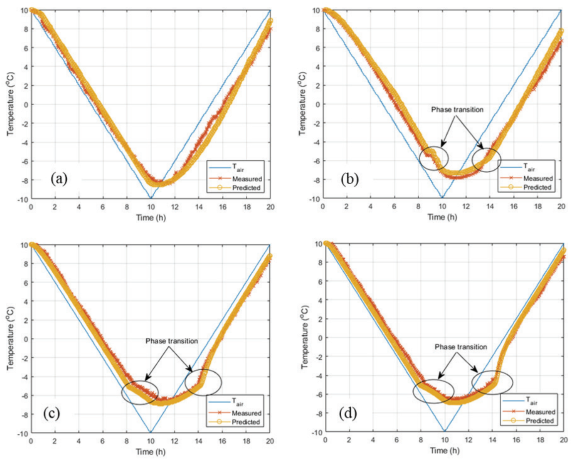

Fig. 10 Temperature Responses of (a) CTR00, (b) PCM05, (c) PCM10, (d) PCM15 Sample

Overall, the simulation results show a strong agreement with the temperature values corresponding to the indoor experiment (Figure 11). Most of the temperature values are located close to the 45° counter line. This indicates a small difference between the measured and predicted values, which were approximately 0.2-0.5℃. The high accuracy of the model may come from the indoor conditions, where temperature and wind speed highly controlled the effect of solar radiation and long wave length radiation were mitigated.

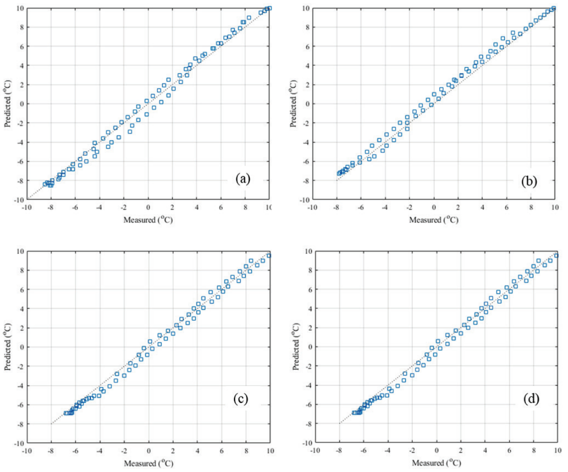

Fig. 11 Comparison between Predicted and Measured Temperature of (a) CTR00, (b) PCM05, (c) PCM10, (d) PCM15

5. Conclusions

In this study, a numerical heat transfer model was established to evaluate the effect of phase change material in asphalt concrete under low temperature. The optimum PCM design tool was developed to select the optimal PCM content in asphalt concrete by considering real weather conditions. The findings of this study can be summarized as follows:

- It is able to predict the temperature of PCM-modified asphalt pavement by numerical method. The effect of PCM on asphalt concrete can be taken as effective volumetric heat capacity, while the volume fraction of PCM can be calculated using an iterative method.
- The numerical analysis results showed that incorporating PCM in asphalt mixtures can slow down the cooling temperature of the pavement, resulting in a delay in the formation of black ice.
- The accuracy of the numerical model was confirmed by the high agreement between the measured and predicted values.
- This research provides a numerical tool for simulating and predicting the temperature of PCM modified under real weather conditions.

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