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Performance evaluation of phase change materials for active indoor thermal environment construction in winter

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ABSTRACT

Phase change materials (PCMs) own huge latent heat to regulate the thermal energy storage of building envelope and maintain comfortable indoor temperature range. While there were various kinds of PCMs, of which thermophysical properties were different, making it difficult to prepare and select the most suitable PCM. In this study, three fatty acids and four polyols were used to prepare the binary composite PCM, and four composite materials were preliminarily selected based on the indoor temperature required by ASHRAE Standard. The weight of melting temperature, latent heat, thermal conductivity, density and specific heat capacity were quantified with the analytic hierarchy process (AHP). The expected ranking of PCMs was given through subjective weight distribution and consistency test, and the optimal PCM for active indoor thermal environment construction in winter was identified.

Keywords: phase change material, analytic hierarchy process, optimal material, thermal environment construction

NONMENCLATURE

Abbreviations	
AHP	Analytic hierarchy process
PCMs	Phase change materials
Symbols	
T	Phase change temperature, ˚C
X	Mole fraction
R	Gas constant, 8.314 J/(mol·K)
H	Latent heat, kJ/kg
λ	Thermal conductivity, W/(m·K)
ρ	Density, kg/m^3
C_p	Specific heat capacity, kJ/(kg·K)
i	Substance *i*

1. INTRODUCTION

China's total energy consumption ranked first in the world with 3381 Mtoe in 2020[1], accounting for about 24% and 57% of global and Asian energy consumption, respectively. While the energy consumed for heating, ventilation and air conditioning (HVAC) systems was about 50% of the building sector, leading to that constructing the indoor environment with low energy consumption to be the focus of building energy conservation research.

Phase change materials (PCM) wallboard can absorb or release huge latent heat at a nearly constant temperature, hence effectively reducing the temperature fluctuation and delaying the peak or valley of temperature change. As reported by Meng et al.[2], the composite PCM could increase the room valley temperature by 9.48 ˚C and reduce the temperature fluctuation by 25.4%. While thermophysical properties of various PCMs had significant effect on the building heat storage performance[3]. Organic solid-liquid PCMs owned characteristics of high latent heat, good cycle stability and non-corrosiveness, which have been widely studied and applied. In practical application, melting temperatures of most fatty acids and polyols were above 40˚C, making them difficult to be applied in building envelope as the indoor temperature was 18-22˚C in winter[4]. A eutectic mixture with low melting temperature could be obtained by mixing materials in proportion, as summarized in Table 1. Actually,

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thermophysical properties of different PCMs varied greatly, wherefore this study provided a decision-making tool for screening available materials according to material parameters (e.g. latent heat, thermal conductivity, etc.) and requirement of indoor thermal environment construction in winter.

Table 1 Physical properties of mixed materials in previous studies.

Materials	Mass ratio	*T* (°C)	*H* (kJ/kg)	Refs.
CA-SA	0.83:0.17	24.91	165.37	[5]
CA-TD	9:1	32	167.2	[6]
CA-PA	0.85:0.15	27.48	151.54	[7]

2. MATERIALS PREPARATION

2.1 Raw materials

Three kinds of fatty acids and four kinds of polyols, including Capric acid (CP, 98%), Lauric acid (AR, 98%), Palmitic acid (AR, 97%), Dodecanol (AR, 98%), Tetradecanol (AR, 99%), Hexadecanol (AR, 98%) and Octadecanol (AR, 98%) were purchased from Shanghai Yien Chemical Technology Co., Ltd. (Shanghai, China). Their physical properties were shown in Table 2.

Table 2 Physical properties of raw materials.

Categories	Materials	Molecular formula	*T* (°C)	*H* (kJ/kg)
Fatty acids	CA	$C_{10}H_{20}O_2$	32.2	174.9
	LA	$C_{12}H_{24}O_2$	46.8	187.9
	PA	$C_{16}H_{32}O_2$	64.1	223.3
Polyols	DE	$C_{12}H_{26}O$	25.2	221.1
	TD	$C_{14}H_{30}O$	35.3	229.4
	HD	$C_{16}H_{34}O$	52.9	247.7
	OD	$C_{18}H_{38}O$	60.5	257.0

2.2 Theoretical calculation of melting point

The melting temperature of eutectic mixture was usually lower than that of its components. Eqs. (1) and (2) predicted the melting temperature and latent heat of the mixture, respectively[8]:

$$T_{\mathrm{m}} = \frac{1}{T_{\mathrm{i}}} - (R \ln X_i) / H_i, i = A, B \qquad (1)$$

$$H_{\mathrm{m}} = T_{\mathrm{m}} \sum_{i=1}^{n} \frac{X_i H_i}{T_i} \qquad (2)$$

During the calculation, the sum of mole ratio for components *A* and *B* was 1, and the mole ratio varied between 0.5 and 0.95. The abscissa of curve intersection denoted the optimal mole ratio as depicted in Fig. 1., and the calculated results were presented in Table 3.

2.3 Preparation of composite PCMs

Components *A* and *B* were placed into a beaker, heated in a 70 °C water bath for 30 minutes, and fully mixed by a stirrer at 180 rpm. Then the binary eutectic PCM was obtained after being placed in a 20 °C thermostatic chamber for 8 hours. The experimental process was shown in Fig. 2. DSC (TA DSC25) was used to test the phase change temperature and latent heat with a accuracy of ±0.1˚C and ±0.1%, respectively, and test results were depicted in Fig. 3.

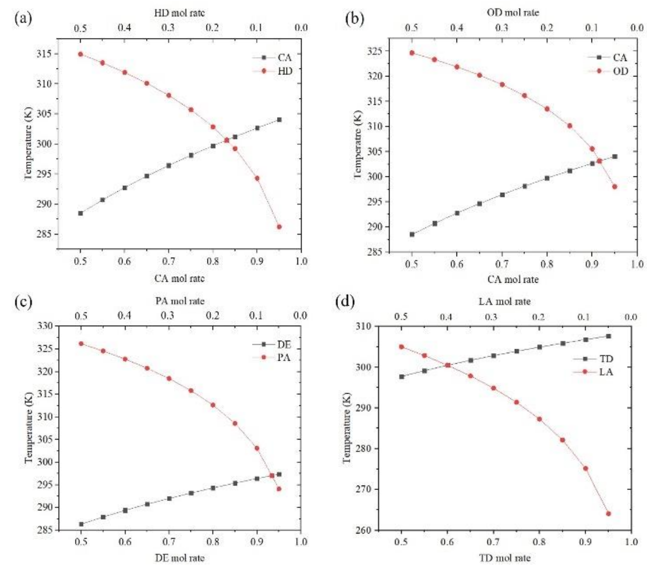

Fig. 1. Optimum mole ratio of composite PCMs: (a) TD-LA, (b) CA-OD, (c) DE-PA and (d) CA-HD.

Table 3 Theoretical thermophysical parameters of binary eutectic mixtures.

Component *A*	Component *B*	Mole ratio	T (°C)	H (KJ/Kg)
CA	HD	0.84:0.16	27.8	183.9
CA	OD	0.92:0.08	30.0	181.1
DE	PA	0.93:0.07	24.0	218.1
TD	LA	0.60:0.40	27.4	205.4

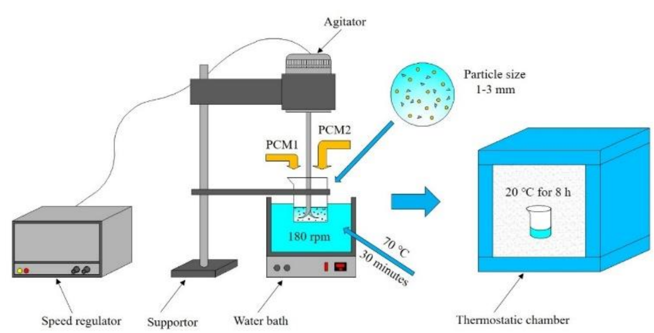

Fig. 2. Preparation process of composite PCMs.

3. OPTIMAL MATERIAL IDENTIFICATION

The selection of PCMs was regarded as an important factor to realize building energy conservation. The analytic hierarchy process (AHP) was a multi-attribute

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decision analysis method proposed by Saaty in the 1970s. AHP was a top-down analysis method to construct a hierarchical value evaluation tree. It analyzed various elements, gave standardized weight of each index, calculated the score of each plan, and then selected the optimal target. In this section, the AHP was divided into three layers, i.e. the target layer, criterion layer and decision layer, as illustrated in Fig. 4.

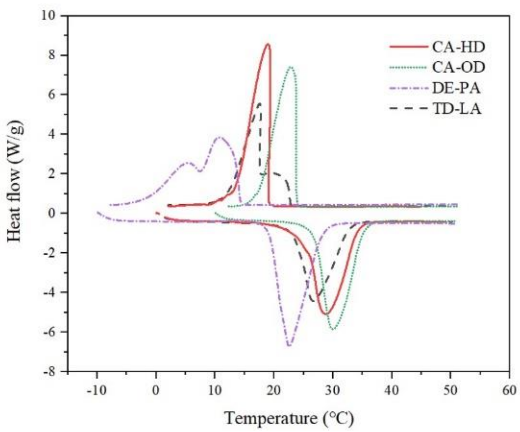

Fig. 3. DSC test results.

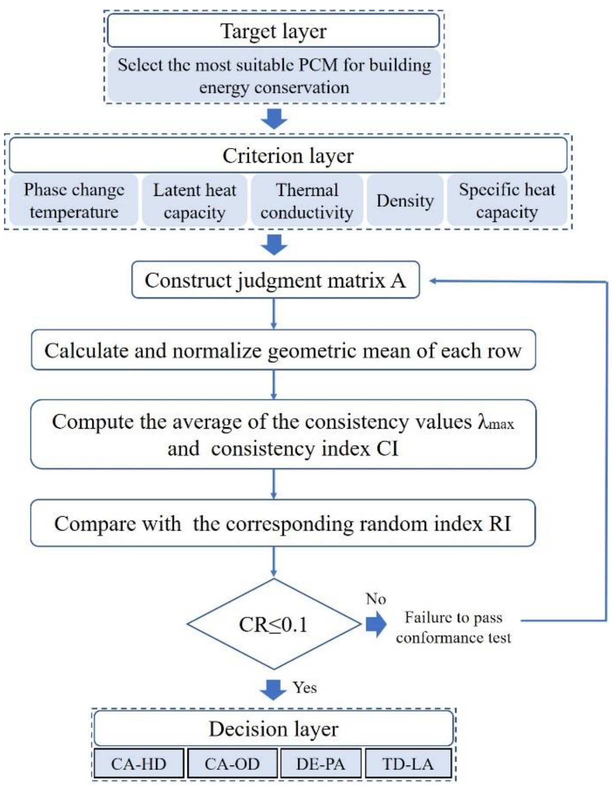

Fig. 4. Arithmetic flowchart of AHP method.

The target was defined in the top floor. To meet the requirements of target layer, considered characteristics included the melting temperature (T), latent heat (H), thermal conductivity (λ), density (ρ) and specific heat capacity (C_p). These characteristics were used as the evaluation standard in the criterion layer. Various phase change materials were put in the bottom layer to make a decision on selecting the optimal material. Thermal conductance tester (Dazhan DZDR-S) was used to evaluate the thermal conductivity of PCMs with an accuracy of ±3%. Electronic balance (Youke YP20002) and measuring cylinder were used to calculate the density by Aarchimedes drainage method, and its accuracy was ±2.4%. Physical parameters of 4 alternative composite PCMs were presented in Table 4.

Table 4 Physical properties of selected PCMs.

Alternatives	Melting/ Solidfication temperature (°C)	H (kJ/kg)	λ (W/m·K)	ρ (kg/m^3)	C_p (kJ/kg·K)
CA-HD	25.43/19.23	179.0	0.24	761.3	2.05
CA-OD	26.9/23.76	183.0	0.20	861.6	2.07
DE-PA	19.3/14.28	193.2	0.24	809.4	2.15
TD-LA	23.67/17.35	143.2	0.24	852.9	2.24

Selection steps for different PCMs were as follows:

Step 1: Established a judgment matrix to compare two criteria, as shown in Table 5. The judgment matrix used the relative importance scale to represent the weight of one criterion to another (A_{ij} to A_{ji}), and number n (1 to 9) represented the relative importance of element i to j. Number 1 meant equally important and 9 meant absolutely important. It was noteworthy that each element on main diagonal of judgment matrix was compose of unit values, and rest elements of A_{ij} and A_{ji} were reciprocal to each other.

Table 5 Judgment matrix of alternatives respecting different criteria.

The pairwise comparison	Meaning (i respect to j)	Relative Importance	Matrix Element	
			A_{ij}	A_{ji}
T/H	Moderate strong	3	3	1/3
T/λ	Fairly strong	5	5	1/5
T/ρ	Very strong	7	7	1/7
T/C_p	Absolute strong	9	9	1/9
H/λ	Moderate strong	3	3	1/3
ρ/λ	Slightly less important	1/3	1/3	3
C_p/λ	Less important	1/5	1/5	5
C_p/H	Much less important	1/7	1/7	7
ρ/H	Less important	1/5	1/5	5

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ρ/C_p	Moderate strong	3	3	1/3

Step 2: Computed the consistency index *CI* as shown in Eq. (3):

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (3)$$

where λ_{max} represented the maximum eigenvalue of square matrix, and *n* denoted the square matrix order.

Step 3: Computed the consistency ratio *CR* as shown in Eq. (4):

$$CR = \frac{CI}{RI} \quad (4)$$

where *RI* represented the random index and its value corresponding to the number of attributes in matrix was given in Table 6.

Table 6 Random index corresponding to the number of attributes in matrix.

Number of attributes in matrix	3	4	5	6	7
Random index (*RI*)	0.52	0.89	1.11	1.25	1.35

The upper limit of consistency ratio *CR* was 0.1. If the calculated *CR* did not exceed 0.1, the calculation result was acceptable. Otherwise, the judgment matrix would be reconstructed for iterative calculation until *CR* was equal to or less than 0.1. The ranking of Table 7 indicated that the weight of CA-HD was the highest, up to 0.374. Followed by TD-LA and DE-PA, of which weights were 0.270 and 0.213 respectively. The weight of CA-OD was the lowest with a value of 0.143.

Table 7 The weight of four alternatives respecting different criteria.

Alternatives	Relative weight			
	CA-HD	CA-OD	DE-PA	TD-LA
T	0.534	0.067	0.045	0.354
H	0.215	0.215	0.531	0.039
λ	0.300	0.100	0.300	0.300
ρ	0.047	0.520	0.094	0.340
C_p	0.078	0.200	0.200	0.522
Total relative weight	0.374	0.143	0.213	0.270

4. CONCLUSION

The preparation and selection of composite PCMs depended on thermophysical parameters of raw materials and requirements of appllication occasions. In this study, a decision-making tool was presented with the aid of analytic hierarchy process (AHP), and the phase change temperature was selected as the key factor, followed by the latent heat, thermal conductivity, density and specific heat capacity. The expected ranking of PCMs was given through subjective weight distribution and consistency test. The AHP results showed that the weight of CA-HD was 0.374, demonstrating CA-HD to be the best choice as considering thermophysical parameters affect. While in practical application, more parameters including the leakage rate, stability and unit cost needed to be comprehensive evaluated.

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