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Cool colored coating and phase change materials as complementary cooling strategies for building cooling load reduction in tropics

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Abstract

Cool colored coating and phase change materials (PCM) are two passive cooling strategies often used separately in many studies and applications. This paper investigated the integration of cool colored coating and PCM for building cooling through experimental and numerical studies. Results showed that cool colored coating and PCM are two complementary passive cooling strategies that could be used concurrently in tropical climate where cool colored coating in the form of paint serves as the "first protection" to reflect solar radiation and a thin layer of PCM forms the "second protection" to absorb the conductive heat that cannot be handled by cool paint. Unlike other climate zones where PCM is only seasonally effective and cool paint is only beneficial during summer, the application of the proposed PCM cool colored coating in building envelope could be effective throughout the

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entire year with a monthly cooling energy saving ranging from 5 to 12% due to the uniform climatic condition all year round in tropical Singapore.

Keywords: cool colored coating; cool paint; phase change material (PCM); tropical climate; building cooling; cooling energy savings

1. Introduction

Building energy efficiency and saving strategies have gained considerable attention recently due to the increase of energy consumption and carbon emissions in building sectors [1]. Both governments and scientific communities around the world have made significant efforts to enhance energy efficiency in buildings. The World Green Building Council (WGBC) has partnered with leading cities around the world to dramatically ramp up energy efficiency within buildings. The European Commission has set a target for all new buildings to be nearly zero-energy buildings by 2020 [2]. In Singapore, the 2nd Green Building Masterplan also set a goal of achieving 80 percent green buildings in the nation by 2030 [3].

The energy consumption in HVAC (heating, ventilation and air conditioning) system accounts for the largest portion of the end-use energy both in residential and non-residential sectors, making it a primary objective for the energy efficiency enhancement [1]. Especially for space cooling, the energy demand has kept increasing in the last few decades due to the growing number of modern buildings with extensive glazing, the climate change effect and the increased thermal expectations [4,5]. In order to mitigate the cooling demand increase as well as to improve indoor thermal comfort, passive cooling strategies have been widely applied to buildings and intensive researches have been undertaken in this field [6-9]. Passive cooling strategies include all the preventive measures to reject external heat from entering through the envelopes of buildings through natural process of heat transfer, i.e. conduction, convection, radiation, and evaporation [10].

The application of cool color coating in the form of paint to building exteriors is a passive cooling strategy aimed to prevent overheating of buildings by solar radiation control. Cool paint is a type of cool material used on surfaces, characterized by high solar reflectance (SR) and high infrared emittance, which reduce the solar radiation absorbed by building envelopes and facilitate the heat dissipation to the outside [11]. With these two properties, cool paint is regarded as a promising technique to limit surface temperature increase and has been widely applied to buildings for cooling load reduction. A review article based on 27 literatures reported that cooling energy savings by the application of cool materials on residential and commercial buildings vary from 2% to 44%, with an average saving of about 20% [12]. Experiments conducted by Levinson et al. [13, 14] also indicated that the peak cooling demands of non-residential buildings were reduced by 10-30% by using cool materials. Simulation studies supported these results and allowed performance analysis in various climatic conditions. The numerical study conducted by Shi et al. [15] has concluded that in tropical climate, cool materials with high solar reflectance and high long-wave emissivity is the most favorable strategy to reduce building energy consumptions.

The use of phase change materials (PCM) as thermal energy storage materials in building envelope is another passive cooling measure aimed to absorb conductive heat. PCM is capable of absorbing and releasing massive latent heat during phase transition in a narrow temperature range, during which the thermal storage density is order-of-magnitude higher than normal building materials [16]. A variety of experimental and numerical studies on PCMs integrated into building envelopes have verified the performance of PCM to lower peak indoor temperatures and to reduce cooling demands in summer months for various regions [17-21]. The experiment conducted by Zhou et al. [17] showed that a PCM lining on the interior surface of the walls and ceiling reduced daily peak indoor temperature by up to 2°C in Beijing, China. The energy performance of a PCM plaster retrofitted building envelope was investigated numerically in Mediterranean climate and cooling energy savings up to 7.2% was reported [18]. The integration of PCM panels into a cubicle for space cooling was tested in Lleida, Spain [19]. It was found that the PCM could lower peak temperature up to 1°C and reduced cooling demands by 15%. Lei et al. [22] also showed that PCM with phase change temperature of 28°C applied to exterior wall surfaces can effectively reduce the heat gains through building envelopes in tropical climate.

As reviewed above, both cool paint and PCM were studied separately as passive cooling strategies to lower surface temperatures and thus reduce cooling load of buildings. While cool paint can effectively reduce the solar radiative heat absorbed by building envelopes, it has little effect in preventing conductive heat transfer through building envelopes. In this regard, the addition of PCM would be an ideal candidate to complement the cooling performance of the cool paint. Lu et al. [23] developed an energy efficient roof by adding a bulk PCM layer in the middle layer of the roof and a cool coating layer on the roof top. The field test showed that the proposed roof is able to reduce the incoming heat flux. Few studies investigated PCM-modified cool color coating by directly mixing microencapsulated PCM (MPCM) into cool paint. MPCM possesses several advantages over the bulk PCM in applications, including large surface area for quick heat transfer, easy integration into conventional construction materials and protection against destruction [24, 25]. Jeong et al. [26] investigated the compatibility between the MPCM and different types of paint. Results indicated that MPCM has better compatibility, thermal property and durability in the hydrophilic paint than that in the hydrophobic counterpart. Karlessi et al. [27] reported that a MPCM-modified cool paint could further reduce surface temperatures by 0.6-2.6°C when compared to the surfaces coated with only the cool paint. Chung et al., however, found no significant difference of surface temperatures between the two in summer weather condition [28]. This highlights the uncertainty and limited understanding of combing these two cooling strategies for building applications.

This paper investigated the efficacy of adopting cool paint and PCM as complementary cooling strategies for building cooling load reduction in tropics through experiments and numerical simulations. It has been reported that the amount of PCM applied to building envelopes is a critical factor for building cooling applications [22]. Sufficient amount of PCM is necessary to achieve required cooling performance. As reported by Lei et al. [22], the envelope heat gain can be reduced by 10% when a PCM layer of 3 mm was applied on the building envelope. This highlights the limitation of applying MPCM-modified cool paint on building envelope for cooling load reduction as the thickness of the paint layer is very small (usually about 50-100 μm) and the total amount of PCM engaged is very limited. To increase the PCM loading, a PCM cool colored coating system was developed in current study by incorporating MPCM into a cement-based skim coat with cool paint applied on the surface of the skim coat. The cooling performance in terms of surface and indoor air temperatures of the resulting PCM cool colored coating system was tested experimentally on a scale-down model simulating a cubic room exposed to direct solar radiation. Moreover, a whole building energy simulation was carried out to evaluate the cooling energy savings of a calibrated model building adopting such PCM cool colored coating system in tropical Singapore.

2. Materials and methods

2.1 Materials

The skim coat used was a type of cementitious rendering mortar, which is the construction material commonly used to smooth the exterior surfaces of concrete or brick constructions, supplied by EMIX Ltd. The skim coat consists of cement, sands, fibers, cellulose ether, polymer powder, and water-repellent additives. PCM micro-capsules, which consist of 85-90 wt.% paraffin encapsulated by a polymer-based shell with an average capsule size of 17-20 μm and melting temperature of 28°C were supplied by Microtek Lab Inc. [29]. The selection of the phase change temperature of 28 ^{o}C was to ensure PCM can be fully discharged during the night in Singapore climate [22]. The polymer-shell PCM micro-capsules were chemically stable and inert and do not react with the skim coat [30]. To fabricate the PCM cool colored coating system, 20 wt. % of the PCM micro-capsules were incorporated into the skim coat. Solar reflective cool paint and normal paint with the same color (light grey) were provided by Nipsea Tech Pte Ltd. Both are acryl-based and suitable for exterior use of buildings and infrastructures. The cool paint is mainly composed of acrylic emulsion binders, fillers (calcite, kaolinite) and solar reflective pigments (titanium dioxide and other functional color pigments). The SRs of the normal and the cool paint were measured to be 0.19 and 0.38, respectively. The cool paint exhibited higher SR due to the incorporation of the solar reflective cool pigments.

2.2 Sample preparation

Four types of coating systems were prepared to investigate the cooling performance of combining cool paint and PCM. Type 1 (Control) is a control system where normal skim coat was coated with normal paint on the surface and type 2 (CP) is the normal skim coat with cool paint coated on the surface. Type 3 (PCM) adopts PCM-modified skim coat with the normal paint coated on the surface while type 4 (CP+PCM) is the PCM cool colored coating system where the PCM-modified skim coat was coated with the cool paint on the surface.

The skim coat was prepared by a planetary mixer. The fresh mixtures (both the normal and PCM-modified skim coat) were cast into molds with a dimension of 70 mm × 200 mm × 5 mm and cured in an environmental chamber with a temperature of 28°C and relative humidity of 99%. The samples were demolded after 24 hours and stored in the same condition for another 6 days before surface painting and further tests.

The density and thermal properties of the normal and PCM-modified skim coat were measured and summarized in Table 1. The thermal conductivity and the heat capacity were measured by using the Hot Disk thermal constants analyzer in accordance with the transient plane source (TPS) method in BS EN ISO 22007-2:2015 [31]. During the measurement, a 3.189 mm radius TPS probe was sandwiched horizontally between the two identical hardened samples of either the normal or PCM-modified skim coat prepared described above and placed in a closed chamber to minimize the impact of the air flow around the samples. After an equilibrium time of 30 minutes in the laboratory (25°C), measurements were carried out with an output power of 0.08 W and measurement time of 10 seconds. As can be seen, the PCM-modified skim coat has a lower density and thermal conductivity due to the low density and thermal conductivity of the paraffin wax. The melting temperatures and latent heat of fusion of the encapsulated PCM and PCM-modified skim coat were determined by differential scanning calorimetry (DSC) tests and the DSC curves were shown in Fig. 1. For the test of PCM-modified skim coat, the fresh mixture was directly casted into the DSC sample pan and the DSC measurement was conducted 7 days after the casting. Both the PCM capsules and PCM-modified skim coat were tested with a temperature variation from 5 to

50°C and a heating rate of 2 °C/min. As can be seen, the peak phase change temperatures of the encapsulated PCM and the PCM skim coat are both around 28°C while the phase change ending temperature of the encapsulated PCM was few degrees higher than that of the PCM skim coat. This may be attributed to the presence of air gaps between the PCM capsules which retards the thermal response when compared with the PCM-modified skim coat where the air gaps are filled with cement paste.

Table 1 Physical properties of the normal skim coat and the PCM-modified skim coat

Physical property	Normal skim coat	PCM-modified skim coat
Density (kg/m^3)	1570	1260
Thermal conductivity (W/m K)	0.76	0.43
Specific heat capacity (J/kg K)	894	1405
Latent heat of fusion (J/kg)	-	38890

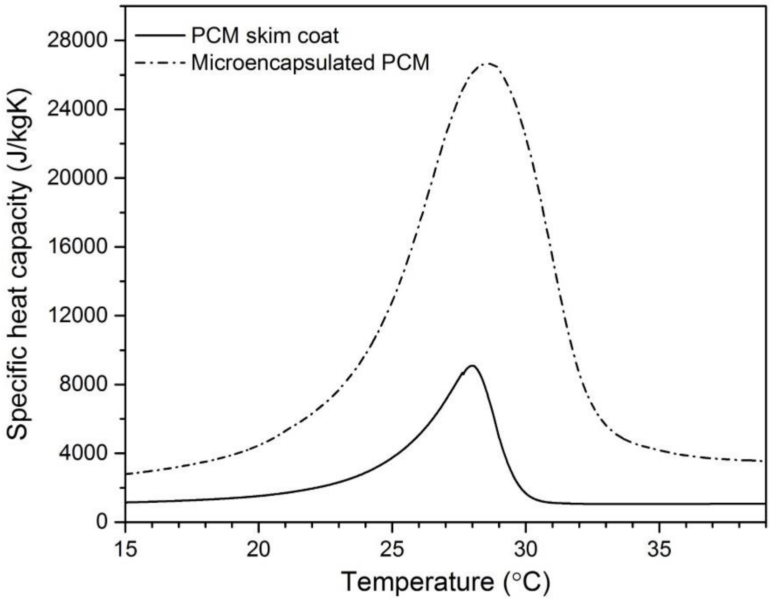

Fig. 1. Heat capacity curves of the microencapsulated PCM and the PCM-modified skim coat.

2.3 Experimental procedures

The test setup is schematically showed in Fig. 2. The sample was fitted in a well-insulated cubic box with the dimension of 70 mm × 200 mm × 130 mm. The top surface of the sample with the paint faced to a halogen tungsten lamp, simulating a natural sunlight condition over the box, with average irradiance of 680 W/m^2 at the level of the top surface, which is close to the average daily solar irradiance in Singapore [22]. The setup was placed in a controlled room with air temperature of 25°C to maintain similar exposure conditions of each test by minimizing impacts of other outdoor environmental factors, such as unstable wind and shading.

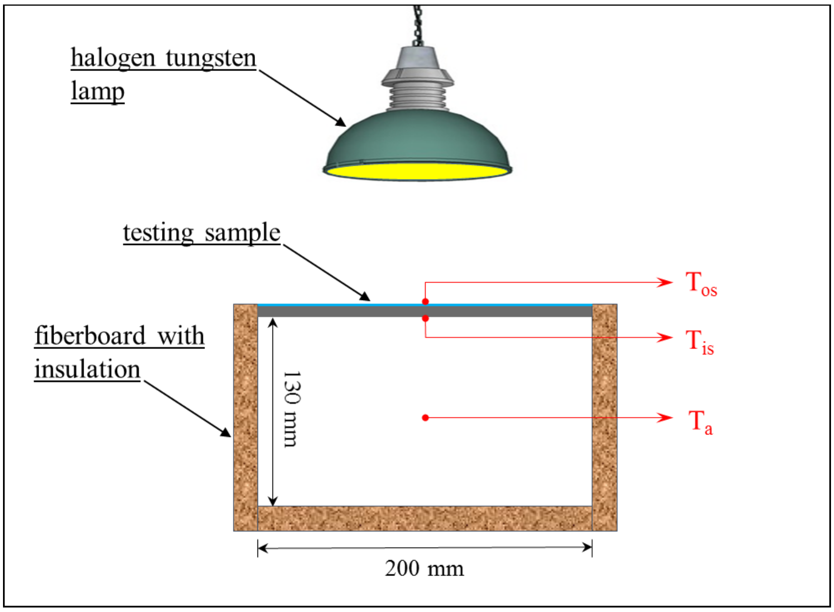

Fig. 2. Schematic diagram of experimental setup for thermal behavior test.

One heating and cooling cycle consisting of a 15-minute-heating (lamp on) followed by a 15-minute-cooling (lamp off) was performed for each test. The heating time of 15 minutes was selected so that the temperature on the exterior surface of the control sample (skim coat with normal paint) was similar to that on the building envelope exposed to direct solar radiation in Singapore, which is observed usually from 24-25°C in the morning to the highest temperature of 50-60°C in the afternoon. While the constant radiation of 15-minute-heating did not represent the real environment where variable conditions are expected, it provided a rapid evaluation and comparison of the cooling performance of different coating systems. The performance of the coating systems in the real environment was evaluate in the next section through the whole building energy simulation of a calibrated model building by taking the variable climatic conditions and shading effects into consideration.

Both the exterior and interior surface temperatures (T_{es} and T_{is}) of the sample were measured using T-type thermocouples with an accuracy of ± 0.5°C, which were calibrated by using an isothermal calibration bath. The internal air temperature (T_a) of the box was measured using a factory-calibrated Pt 100 resistance temperature detector (RTD) with an accuracy of ± 0.25°C. The temperature signals from the thermocouples and the RTD were recorded simultaneously into a data acquisition system with an acquisition rate of 2 Hz during the whole period of the test.

2.4 Numerical simulation

Whole building energy simulations were conducted by using the software EnergyPlus to evaluate the cooling energy savings through the combining use of cool paint and PCM in tropical climate. EnergyPlus is capable to simulate the material like PCM with variable specific heat and thermal conductivity by using the conduction finite difference (CondFD) solution as the heat balance algorithm [32], which was introduced in the previous work [22]. The accuracy of the general heat transfer calculations and the CondFD solution algorithm in EnergyPlus have been validated by many researchers and the EnergyPlus developer team [33].

A numerical building model was developed based on a single-story building located in Nanyang Technological University, Singapore. It is a rectangular-shaped building consisting of two rooms, i.e. a test room and a store room as shown in Fig. 3. The test room was an air-conditioned room while the store room was non-air-conditioned. The construction and modelling details of the building were reported in [34]. This numerical building model has been successfully calibrated based on the experimental results of the roof and ceiling temperatures [34].

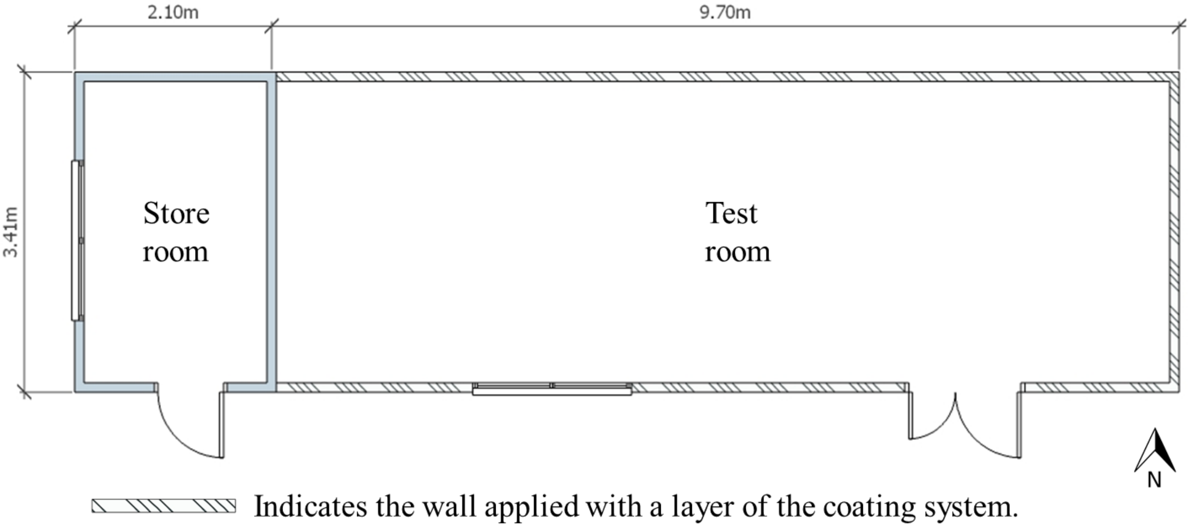

Fig. 3. Plan view of the simulated building.

Singapore is situated near the equator and has a typically tropical climate with uniformly high temperatures and high humidity all year round. The weather data used in the simulation was the TMY weather data for Singapore obtained from the EnergyPlus weather dataset and the monthly weather data is shown in Table 2. As can be seen, it has an average annual temperature of 27.5°C with a small diurnal temperature range between a minimum of 24-26°C and a maximum of 29-32°C.

Table 2. TMY weather data of Singapore used in the simulation

Month	Mean daily max. temp. [°C]	Mean daily min. temp. [°C]	Mean daily temp. [°C]	Relative humidity [%]	Global solar radiation [MJ/m^2]	Mean wind speed [m/s]
Jan	29.2	24.2	26.1	81.1	377.9	3.3
Feb	31.3	24.1	27.0	76.3	427.9	3.5
Mar	30.8	24.6	27.0	80.0	486.9	2.2
Apr	31.9	24.9	27.7	78.9	501.3	2.3
May	32.1	25.2	28.2	78.1	491.7	1.5
Jun	31.2	25.4	28.1	77.4	464.6	1.7
Jul	32.0	25.7	28.`6	74.3	526.3	2.2
Aug	31.2	25.1	27.9	80.2	517.0	1.8
Sep	31.3	25.1	27.9	79.7	477.4	1.8
Oct	31.1	24.7	27.4	83.8	463.2	1.6
Nov	30.9	24.9	27.2	85.3	402.9	1.9
Dec	29.5	24.7	26.6	84.8	366.7	2.8

To evaluate the performance of the PCM cool color coating compared with the other three types of coating systems (Control, CP and PCM), each type of the coating with 5 mm in thickness was applied to the most outside surfaces of the exterior walls and roof of the test room as indicated in Fig. 3. The discharging cycle of the PCM has been systematically studied and reported in our previous work [22]. It is critical to ensure PCM can be fully discharged and become solid again during the night so that the heat storage capacity of PCM can be restored every morning for the next cycle. This in turn depends on climatic conditions, phase change temperature selected, and location where PCM applied, e.g. interior or exterior surfaces. Our previous study concluded that PCM with phase change temperature of 28°C applied on the exterior surfaces of building enveloped in the climate of Singapore showed optimum performance for cooling load reduction and PCM was able to discharge fully and became solid again at night. Therefore, the same configurations were adopted in the current study. The measured density and thermal properties of the samples shown in Table 1 were used as the inputs for the skim coat layer. Due to the thin layer of the paint in several tens to hundreds of microns, the thermal resistance of the paint was neglected and the SR of the exterior surfaces was modified accordingly in the model to simulate the effect of the cool paint and the normal paint.

The ideal load HVAC system, which removes the heat at 100% efficiency to meet the indoor thermal requirements, was defined to be employed in the test room in the model. The cooling set point of the indoor air temperature was kept constant at 24°C. The simulation period was set for one year and the energy consumption of the air-conditioner of the test room was obtained from the simulation results. The energy saving rate of the four types of coating systems was calculated based on the following equation:

$$\text{Energy saving rate} = \left(1 - \frac{E_{coating}}{E_{control}}\right) \times 100\% \qquad (1)$$

where $E_{control}$ represents the energy consumption of the air-conditioner when the control coating system (Type 1) was used and $E_{coating}$ represents the energy consumption when the other coating systems (Types 2-4) were adopted, respectively. In addition, a parametric study on the thickness of the PCM cool colored coating was conducted, in which the thickness of the PCM-modified skim coat was varied in a range of 3-100 mm.

3. Results and discussion

3.1 Temperature reduction by PCM cool colored coatings from experiments

Fig. 4 shows the temperature profiles of the exterior and interior surfaces of the samples and the internal air. It is obvious to see a significant temperature decrease when the cool paint instead of the normal paint was applied on the exterior surface. For instance, the peak exterior surface temperature of the type 2 (CP) was 8.9°C lower than that of the control system, leading to a reduction of internal air temperature of 2.7°C. It indicates that the higher SR of the cool paint significantly reduced the radiation absorbed by the top surface, which effectively limited the surface temperature increase under high radiation loads.

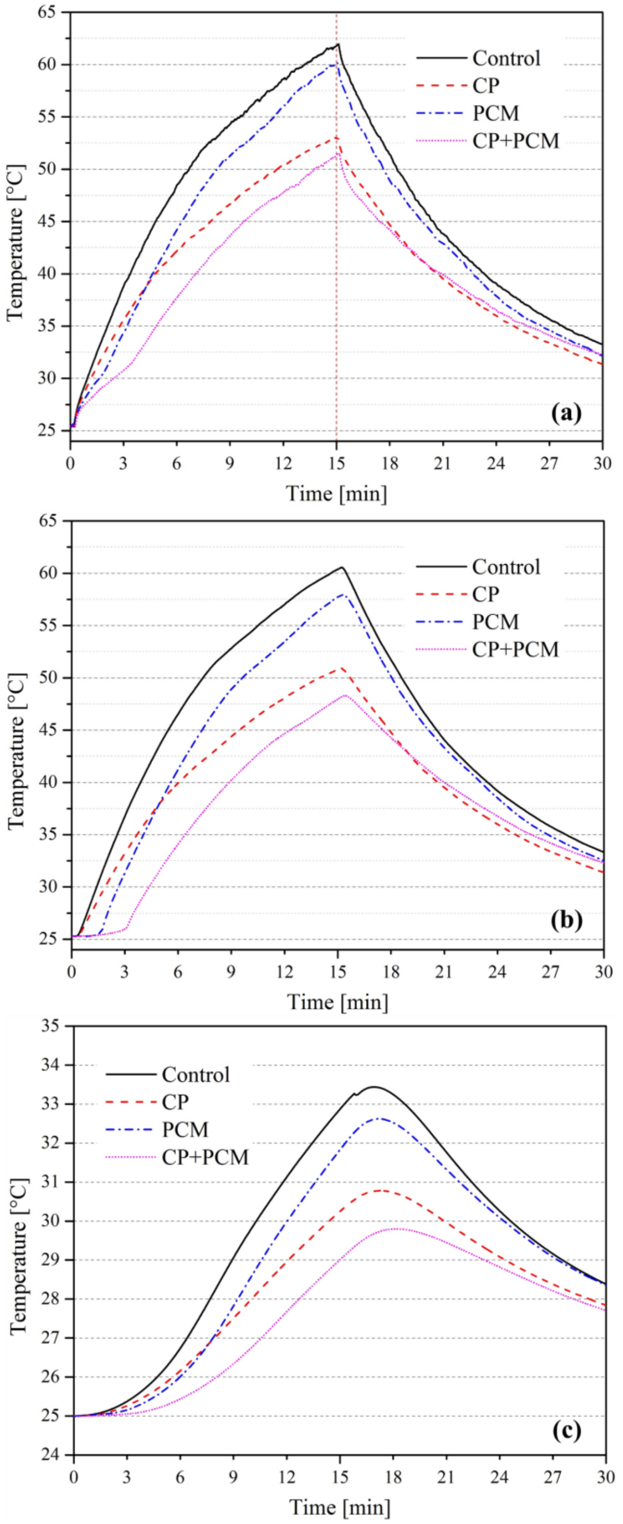

Fig. 4. Temperature profiles of the (a) exterior surface and (b) interior surface of the sample, and (c) the internal air during the thermal tests of type 1-4

The incorporation of 20 wt. % PCM microcapsules into the skim coat also leads to a reduction of the peak exterior and interior surface temperatures as well as interior air temperature. For example, the peak exterior and interior surface temperatures of the type 3 (PCM) was 1.8°C and 2.6°C respectively lower than that of the control system, leading to a reduction of internal air temperature of 0.8°C. The temperature reduction is partially due to the reduction of thermal conductivity of the sample as shown in Table 1. More importantly, the PCM with high latent heat of fusion is able to absorb the incoming heat through phase change without much increase of temperature. In this way, the PCM could delay and limit the temperature increase of the coating layer. It is confirmed by the observation that the initial slop of the surface temperature rise is much gentler for type 3 (PCM), especially for the interior surface, of which the temperatures are almost stable in the first few minutes. After all the PCM were fully melted the temperature rising rate then increased close to that of the sample without PCM.

The combination of cool paint and PCM (type 4) further reduced the surface and air temperatures by comparing with all other three types (control, CP, and PCM) as shown in Fig. 4. In this PCM cool colored coating, the cool paint acted as the “first protection” to partially reflect away the high density of solar radiation and the PCM formed the “second protection” to absorb the conductive heat caused by the non-reflected part that heated up the surface. It is also interesting to note that the interior surface temperature of the type 4 (CP+PCM) initially kept stable for a longer time (3 minutes) than that of the type 3 (1.5 minutes) as shown in Fig. 4(b), indicating that the application of cool paint on the exterior surface prolonged the phase transition process of the PCM, so that the PCM maintained its phase change temperature without rapid temperature increase for a longer time. It is attributed to the higher SR of the cool paint that larger proportions of radiation loads were reflected away, leading to lower heat flux into the PCM.

3.2 Cooling energy savings by PCM cool colored coating from simulations

Fig. 5 shows the annual energy consumption of the air-conditioner and the energy saving rate when different type of coating system was applied in the numerical model. As can be seen, the application of the PCM cool colored coating (CP+PCM) achieved the largest energy savings of 8.5% while the application of cool paint and PCM alone registered an energy savings of 7.2% and 1.4%, respectively. The energy savings of PCM cool colored coating is almost equal to the summation of the energy savings from cool paint and PCM, which suggests cool paint and PCM in the cool coating system work complementarily. This is mainly attributed to the fact that cool paint and PCM rely on different mechanisms to prevent heat gains where cool paint reflects solar radiation and PCM prevents conductive heat transfer. Based on this result, the combined use of cool paint and PCM further reduces envelope heat gain and cooling load of buildings in tropical Singapore.

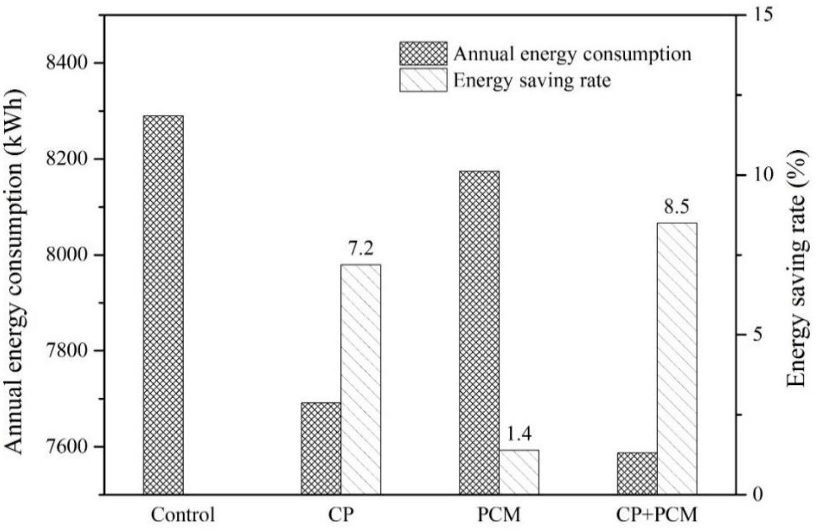

Fig. 5. Annual energy consumption and energy saving rate when a layer of coating of type 1-4 was applied respectively.

The monthly energy saving rate when different type of coating system was applied in the numerical building was plotted in Fig. 6. It showed that both the cool paint and PCM are effective throughout the entire year with monthly energy savings of 3.9-10.7% and 1.0-1.9%, respectively. Unlike other climate zones where PCM is only seasonally effective and cool paint is only beneficial during summer, the application of the PCM cool colored coating could be effective throughout the whole year in Singapore due to the uniform climatic condition all year round. Overall, the monthly energy saving of 5-12% could be achieved by using the PCM cool colored coating in tropical Singapore.

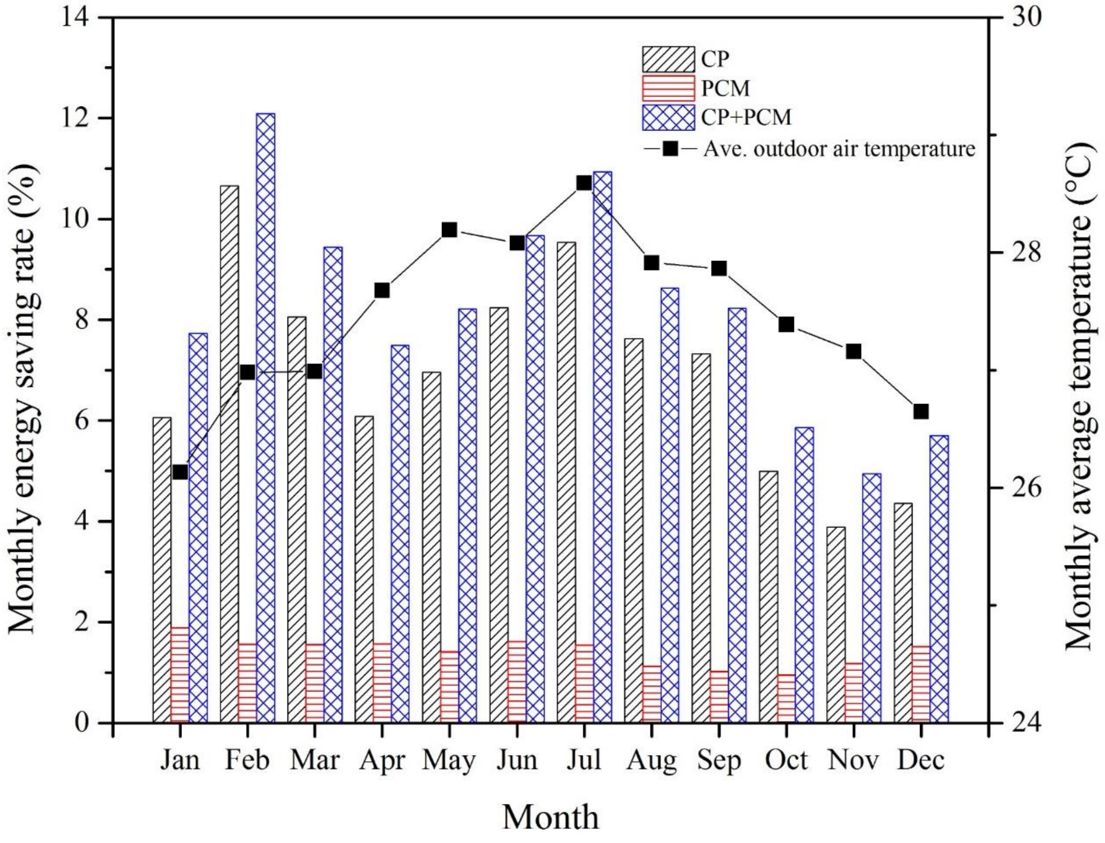

Fig. 6. Monthly energy saving rate based on Singapore's weather data when a layer of coating of type 2-4 was applied respectively.

The relationship between the energy saving rate and the thickness of the PCM-modified skim coat with normal paint (type 3: CP) and cool paint (type 4: CP+PCM) is shown in Fig. 7. As can be seen, the energy saving rate increases with increasing thickness of the PCM-modified skim coat. This is mainly attributed to larger amount of incoming heat could be absorbed by the thicker PCM-modified skim coat. However, the slopes of the curves reduce as the thickness increases, indicating the efficiency and cost-benefit reduce when thicker PCM skim coat is applied to the building envelope. This suggests a tradeoff between the total energy savings and the efficiency and cost-benefit of using PCM for building passive cooling.

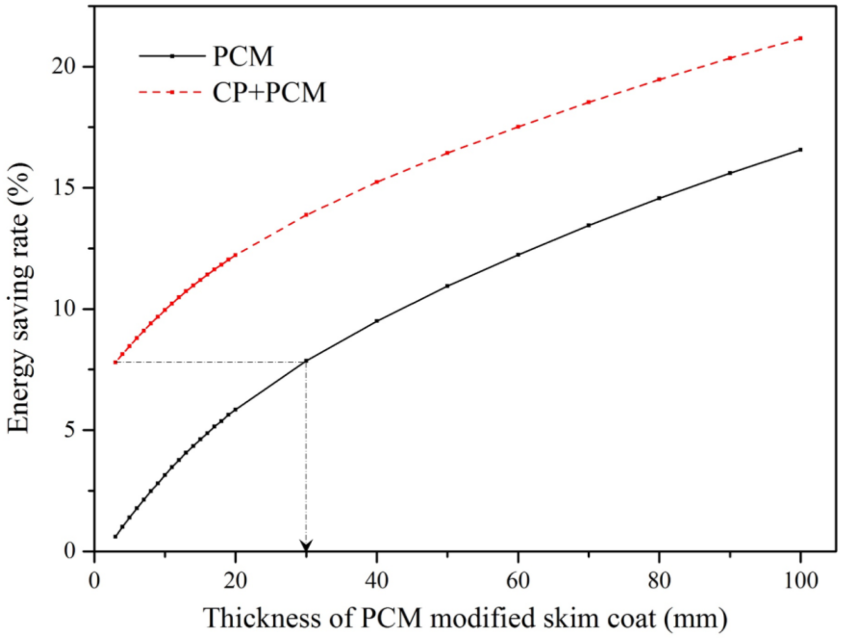

Fig. 7. Energy saving rate as a function of the thickness of PCM skim coat when type 3 and 4 were applied respectively

Due to the high density of solar radiation in tropical regions, the use of PCM alone to absorb the incoming heat into the building environment is not cost effective. With the integration of cool paint and PCM, a thin PCM cool colored coating (type 4: CP+PCM) of 5 mm can achieve the same energy saving rate as a 30 mm PCM-modified skim coat (type 3: PCM) as shown in Fig. 7. This highlights the potential of the combing use of cool paint and PCM where cool paint serves as the “first protection” to reflect solar radiation and a thin layer of PCM forms the “second protection” to absorb the conductive heat that cannot be handled by the cool paint.

4. Conclusions and outlook

This paper investigated the integration of cool colored coating and PCM for building cooling through experimental and numerical studies. A PCM cool colored coating was developed by incorporating the microencapsulated PCM into cementitious skim coat with cool paint applied on the exterior surface. The cooling performance of the coating was tested experimentally. A whole building energy simulation was carried out to evaluate the cooling energy savings of a calibrated model building adopting such PCM cool colored coating in tropical Singapore. Main conclusions drawn from the current study include:

- From the experimental study, the PCM cool colored coating further reduced the surface and air temperatures as compared to other three configurations, i.e. control, cool paint alone, and PCM alone. In addition, the PCM cool colored coating maintained its phase change temperature without rapid temperature increase for a longer duration when compared with the PCM alone case.
- From the numerical investigation, the PCM cool colored coating registered the largest annual energy saving of 8.5% and a consistent monthly energy saving of 5-12% throughout the entire year in tropical Singapore. The cool paint and PCM in the cool coating system worked complementarily because they rely on different mechanisms to prevent heat gains. A 5 mm thick PCM cool colored coating can achieve the same energy saving rate as a 30 mm thick PCM-modified skim coat.

Cool paint and PCM are two complementary passive cooling strategies that could be used concurrently in tropical climate where cool paint serves as the “first protection” to reflect solar radiation and a thin layer of PCM forms the “second protection” to absorb the conductive heat that cannot be handled by cool paint. Unlike other climate zones where PCM is only seasonally effective and cool paint is only beneficial during summer, the application of the proposed PCM cool colored coating in building envelope could be effective throughout the entire year due to the uniform climatic condition all year round in tropics.

The PCM cool color coating system developed in current study can be readily applied to concrete structures, especially for energy retrofitting of existing buildings, where ease of implementation is the key consideration [35]. The PCM-modified skim coat, used to smooth the surface of concrete, can be easily applied to exterior surfaces of building without structure modification of building components. After the hardening of the skim coat in few hours, the cool paint can be coated on the surface. Life cycle and life cycle cost analyses shall be conducted in the future to reveal the environmental and economic benefits of applying the PCM cool color coating system on building enveloped.

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