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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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HIGHLIGHTS

- Cool colored coating and PCM are two complementary passive cooling strategies.
- A PCM cool colored coating system is developed.
- The coating reduces cooling energy by 8.5% and is effective yearly in tropical Singapore.

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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 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.

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

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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 and Zhang [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 °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.