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Development of PCM cool roof system to control urban heat island considering temperate climatic conditions

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ABSTRACT

The use of phase change materials (PCM) as a roof finishing material can decrease the surface temperature and help to control urban heat islands. In the present work, the thermal performance of different kinds of roof finishing materials in a temperate climate in South Korea was measured. Measurements were conducted in an artificial environment that simulated summer weather conditions and real winter environments. The PCM cool roof system was created using PCM doped tiles. The results show that the PCM doped tiles effect a temperature decrease in surface temperature while keeping the chamber temperature low in summer weather conditions. Furthermore, in winter conditions, the PCM doped tiles keep the surface temperature low while keeping the chamber temperature higher than cool paints. This means that PCM doped tiles are capable of controlling urban heat islands while reducing heating penalty.

1. Introduction

As a result of rapid urbanization and industrialization, the temperature within urban areas tends to be much warmer than rural regions. The urban heat island (UHI) is defined as the rise in temperature within man-made areas [1] and has been reported by many researchers in various climatic regions. Urban heat island intensity (UHII) is an indicator of urban heating, which is the maximum difference between urban and rural air. UHII varies from 5 to 14 °C with climate zone [2–5].

Elevated air temperature due to UHI has a negative effect on microclimates and on human health. The microclimates change to increase the air temperature, to reduce humidity, to reduce wind velocity, and to form ground level ozone [6,7]. Heat related mortality is also found to be higher in city centers due to an increased exposure to extreme thermal conditions [8]. Many mitigation strategies are available to counterbalance the phenomenon. These are classified under two broad categories: urban surface control and urban design. Green or cool roofs, cold pavements and green spaces in urban areas are all strategies that contribute to reducing surface temperature and energy consumption [9–11]. The distribution of urban buildings and structures in a city can determine the absorption of solar energy and the pattern of wind flow. Optimal design can control the wind and can be helpful in reducing the temperature.

In temperate climates, use of green roofs is widely known as a mitigation strategy for UHI, but green roofs have limits in applications to existing buildings due to problems of additional weight loads, drainage and waterproofing, and maintenance of vegetation. Recently, the proportion of new buildings with energy conserving designs has increased, but for buildings less than three years, these types of buildings only amount to 2.6% [12]. Therefore, it is hard to control UHI with newly built buildings. A strategy for existing buildings is needed to control UHI effectively.

The use of cool roofs with high solar reflectance (SR) and thermal emittance (TE) has recently emerged as one of the important strategies to decrease the peak ambient temperature [13] and save energy at a relatively low cost [14]. Consequently, retroreflective materials have been proposed to mitigate UHI. Rossi et al. [15] measured the solar radiation of retroreflective materials according to the radiation's angle of incidence and concluded that retroreflective materials have a higher cooling potential than traditional diffusing coatings. Ferrari et al. [16] tested cool-colored tiles with relatively high solar reflectance. A thin insulating layer was attached below the tiles, which were made of a silica-gel super-insulating material. This design can be integrated into cool roofs in traditional buildings and can reduce surface temperature. Cool materials provide a viable solution for a hot climate;

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however, in cold or humid continental climates, cool materials should be carefully selected because they can reduce useful heat gain through the roof or facade in winter [17,18]. Hossenini and Akabari noted that the roof may be covered with snow for most of the heating season in cold climates, therefore, snow can reduce the heating penalties for buildings with cool roofs [19]. However, regions with little snow may incur a heating penalty.

The roof is the main source of thermal loss in the building envelope. Therefore, one of the practices to enhance the thermal performance of roofs is to increase their thermal storage capacity using phase change materials (PCM). A variety of numerical and experimental options for the integration of PCM into roofs has been developed and found to be effective in minimizing energy consumption in buildings. Li [20] proposed a sloped roof with PCM for residential buildings and measured the thermal behaviors of the roofs. The results showed that the PCM roofs had a temperature delaying effect on the room. Pasupathy and Velraj [21] experimented with the effects of a double layer PCM roof panel. The PCM roof panel reduced fluctuations in the internal air temperature during the winter season. However, the PCM roof panel was not suitable for the summer season as the PCM remained in the liquid state at all times. Therefore, the phase change temperature should be chosen carefully, taking into consideration the temperature fluctuation range. Chou et al. [22] proposed a novel metal sheet using PCM which incorporated two corrugated metal roofing material layers as well as PCM, with an insulator placed in the middle of the corrugated metal sheets. This novel metal sheet could save energy compared to the normal insulated roof and could also be useful in the winter in Taiwan (a humid subtropical climate). Kosny et al. [23] proposed a naturally ventilated roof with a Photovoltaic module and PCMs to serve as a heat sink. The PV-PCM roofs showed that about 30% heating and 50% cooling load reductions are possible with the experimental roof configuration. Most studies verify PCM thermal performance as thermal storage. Based on PCM thermal characteristics, this paper proposes the PCM cool roof system to control urban heat islands. The thermal storage capabilities of PCM can make up for heating penalties. This paper aims to evaluate the PCM cool roof system as a control strategy for urban heat islands while reducing heating penalties. The main objective of the research is to evaluate the impact of roof finishing materials on roof surface temperature and chamber air temperature for buildings located in Seoul, Korea. The roof finishing materials were selected from the most popular roof finishing materials and other finishing materials used to control urban heat islands like cool paints and PCM. In Section 2, the PCM cool roof system is proposed, and experiment materials as well as the set up are presented in Section 3. The results in two different seasons will be discussed in Section 4.

2. Definition of PCM cool roof system

2.1. Climatic conditions

Seoul, S. Korea is classed as having a temperate climate with four distinct seasons, but temperature differences between the hottest part of the summer and the depths of winter are extreme. Table 1 reports the climatic conditions in Seoul. The climatic conditions for this area describe the air temperature, global solar radiation, relative humidity and wind speed, as well as the heating degree days and cooling degree days. These data represent a typical meteorological year and are obtained by the Korea meteorological administration [24] and the Korean Solar Energy Society [25]. The weather includes climatological values averaged from 1981 to 2010. The annual average air temperature is 17.0 °C, the annual mean wind speed is 2.3 m/s, and the annual mean relative humidity is 64%. Summer is hot and humid while winter is cold and dry. There are 2602 heating degree days (HDDs) with a base temperature of 18 °C and 2210 cooling degree days (CDDs) with a base temperature of 10 °C. The HDDs and CDDs were calculated according to the ASHRAE method [26]. The Korean climate zone is heating dominated. The main energy usage in a typical Korean house is from space heating (63%), whereas the energy usage from space cooling including electric energy use is 14% [27]. Cooling and heating energy use breakdown for a typical office are 6% and 38%, respectively.

Kim and Baik [28] investigated UHI in Seoul and reported that the average maximum UHII over a 1-year period is 2.2 °C. The average maximum UHII was strongest at 0300 LST (3.4 °C) and weakest at 1500 LST (0.6 °C). The Seoul UHI patterns were found to contain several warm cores located at the main commercial and industrial sectors and the local topography.

2.2. PCM cool roof system

The roof is the main source of heat loss for the building envelope and is an influential factor for UHI. The reflective roof is good for mitigating UHI and reducing cooling load but it might also increase heating load. This paper proposes a roof material containing phase change material (PCM) to make up for the heating penalty. PCM, which melts and solidifies at a certain temperature, is capable of storing and releasing heat energy. There have been a lot of studies dealing with building materials with PCM. The types of building materials studied were gypsum, wall boards, ceiling boards, shutters, tiles, and so on [29]. Most studies focused on indoor thermal comfort and energy savings. Especially, Karlessi [30] investigated PCM as an exterior material and reported that PCM doped cool colored coatings have the potential to reduce the surface temperature. Chou et al. [22] proposed a metal-sheet cool roof with PCM that

Table 1
Climatic conditions of Seoul, S. Korea.

Month	Daily maximum temperature (°C)	Mean temperature (°C)	Daily minimum temperature (°C)	Global solar radiation (MJ/m^2)	Relative humidity (%)	Mean wind speed (m/s)	$HDD_{18°C}$[a]	$CDD_{10°C}$[a]
Jan	1.5	−2.4	−5.9	219.6	59.8	2.4	590	0
Feb	4.7	0.4	−3.4	276.2	57.9	2.6	471	0
Mar	10.4	5.7	1.6	389.9	57.8	2.8	336	7
Apr	17.8	12.5	7.8	471.2	56.2	2.8	146	95
May	23.0	17.8	13.2	521.8	62.7	2.5	23	260
Jun	27.1	22.2	18.2	477.7	68.1	2.2	26	378
Jul	28.6	24.9	21.9	369.2	78.3	2.3	0	486
Aug	29.6	25.7	22.4	391.5	75.6	2.1	0	466
Sep	25.8	21.2	17.2	367.0	69.2	1.9	27	331
Oct	19.8	14.8	10.3	329.4	64.0	2.0	84	172
Nov	11.6	7.2	3.2	214.7	62.0	2.2	347	15
Dec	4.3	0.4	−3.2	187.3	60.6	2.3	552	0

[a] *Source*: Weather in a typical meteorological year from the Korean Solar Energy Society.

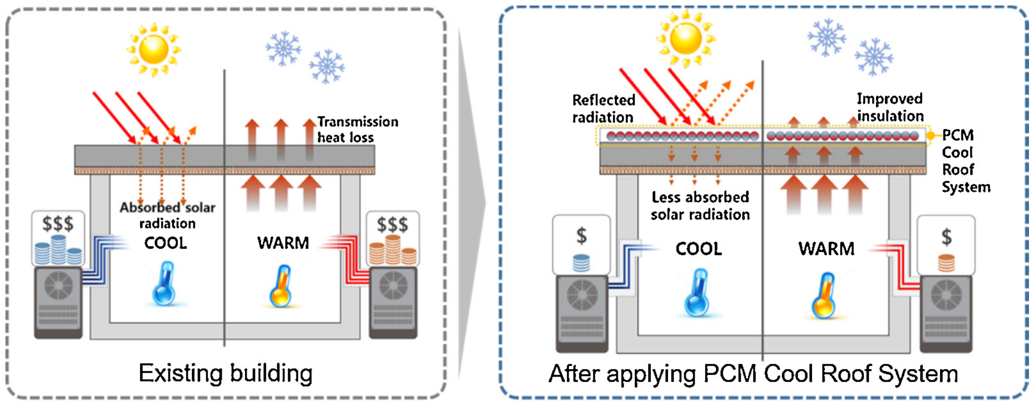

Fig. 1. Concept of PCM cool roof system.

could lower the cooling load of the house. They also found that the melting property of PCM could be utilized to store thermal energy and improve the thermal insulation of the combined PCM structure. Similar to the previous research, this study focuses on the use of a PCM with reflective materials to control UHI.

The PCM cool roof system is developed to prevent overheating in the summer and to reduce heating penalty in the winter using PCM with reflective materials. When the temperature of the PCM reaches its melting temperature, heat is stored as latent heat and the roof temperature can be maintained at a constant temperature. This can prevent overheating and reduce the heat transfer through the roof and ceiling to the building inside. The PCM cool roof negates the heating penalty associated with cool materials. The main concept is that the cool materials reflect incident solar radiation and the PCM absorbs the remaining incident solar radiation. Therefore, the downward heat flow created by the absorbed solar radiation to the building inside decreases during the day (see Fig. 1).

3. Materials and methods

3.1. Materials

In this study, PCM tiles covered with shape stabilized PCM (SSPCM) were used to assess the feasibility of a PCM cool roof system. The SSPCM was produced by mixing hydrophilic paint with microencapsulated PCM (MPCM). The paint used was an exterior paint with acrylic emulsion resin and silicone water repellent. Water repellent coating on hydrophilic paints prevents corrosion and surface deterioration of buildings due to water penetration. Furthermore, MPCM mixed with hydrophilic paint has better PCM performance than hydrophobic paint alone. The SSPCM was made of 60 g hydrophilic paint diluted in 5 wt% (3 g) of water. 20 wt% (12 g) of MPCM was added, and the mixture was stirred at 500RPM for 5 min. The size of the tiles was about 200 mm × 200 mm × 7 mm and the PCM tiles were painted with 10 g of SSPCM mixed with hydrophilic paint (see Fig. 2). N-octadecane PCMs were used for the production of SSPCM and the melting temperature was 28 °C. The latent heat of fusion was around 256.5 J/g.

The scale model was built by taking actual roof conditions into account as shown in Fig. 3. The size of the scale model was 600 mm × 600 mm × 600 mm. Applicable roof surface variables were green urethane waterproofing, gray water proofing mortar, cool paint, normal tiles, and PCM doped tiles. Different types of emulsions such as green urethane waterproofing, gray water proofing mortar, and cool paint were painted on the concrete mortar. Different types of tiles such as normal tiles and PCM tiles were placed on the concrete mortar. Green urethane waterproofing and gray waterproofing mortar are common roof finishing materials in Korea. These materials are used as waterproofing materials in flat roofed buildings. Cool paint and tiles were used as comparison variables. Cool paint was selected from products that meet the ENERGY STAR guidelines. Heat flow through a roof is influenced by thermal conductivity, density, thickness, albedo, thermal emissivity and so on. The thermal properties of the scale model were controlled, except for the roof finishing materials. The SR of the tested materials was measured by an albedometer according to the ASTM E1918. The SR of green urethane waterproofing, gray water proofing mortar, cool paint, normal tiles, and PCM doped tiles were measured as 0.18, 0.26, 0.57, 0.41, and 0.55, respectively. The typical roof finishing materials, namely green urethane waterproofing and gray water proofing mortar, had lower SR. The SR of the PCM doped tiles was increased by the addition of white hydrophilic

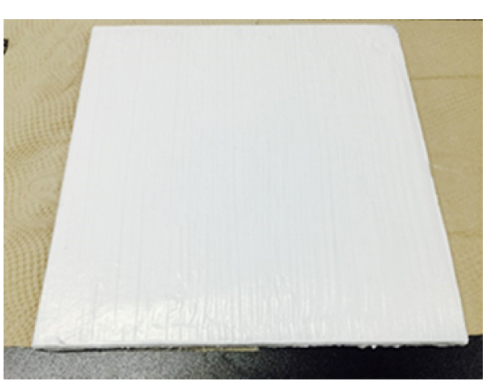

Fig. 2. A PCM tile.

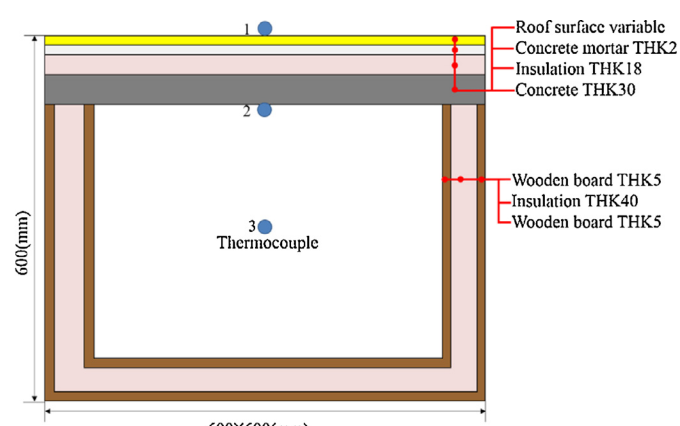

Fig. 3. The scale model.

Fig. 4. The artificial environment test.

paint compared to normal tiles. The temperatures of the layers were measured as shown in Fig. 3. Three measuring ports were installed at each measuring point for ease of access to the t-type thermocouples, which were located at the center of the surface. The thermocouples' standard limit of error was 1.0 °C or 0.75% above 0 °C. Temperature data was recorded using a data logger (GL820, Graphtec Corporation) programmed to record the average for all measurements simultaneously every 60 s. The measured temperature was presented as an average from the 3 measuring ports.

3.2. Experiment setup

The experiment was conducted in a laboratory and in external conditions. The laboratory test was performed in an artificial environment (see Fig. 4) and the external test was conducted in actual outdoor conditions (see Fig. 5).

In general, thermal performance tests are conducted in outdoor conditions by using roof variables to assess the possibility of UHI mitigation. However, outdoor experiments can be conducted for only a limited period. The artificial environment test room was created in order to overcome these limitations and to conduct continuous tests regardless of weather conditions. The roof temperature is influenced by climatic condition such as air temperature, wind speed, irradiance, cloud cover, precipitation and so on. The artificial environment test room was set as the sunny summer condition. The average summer temperature and wind speed are around 25 °C and 2.6 m/s, respectively, according to the record from the Korea meteorological administration. The temperature in the artificial environment was maintained at about 26–30 °C. Wind speed influences surface temperature [31] but is negatively correlated with UHI intensity [28]. Therefore, in this study, the artificial environment was maintained without air flow. The artificial light source comprised of 4 halogen light bulbs with color temperatures of 3200 K and 5000 K at 650 W. Solar irradiance was set to the irradiance of a typical summer day based on the weather for a typical meteorological year [25]. A typical summer day was selected from among clear days by comparing the solar irradiance. The maximum irradiance on a summer day is 7059 W/m^2 and the average irradiance on summer days is 3709 W/m^2. The average irradiance was calculated, including rainy and cloudy days. Thus, the solar irradiance of the artificial environment, typical clear summer day was designed as the mean solar radiation between the maximum and the annual average solar irradiance (Table 2). Solar irradiance control simulated the changes in solar irradiance over time from sunrise to sunset in four steps. The lights were turned on for 11 h and turned off for 13 h.

Fig. 5. The external test in winter conditions.

Thermal analysis of the roof materials was carried out in experiments consisting of three main phases: (i) the verification of the artificial environment and (ii) the artificial environment test using the roof materials. Additionally, (iii) an external test in winter conditions was carried out to assess the thermal performance in the winter season.

4. Results and discussion

4.1. Verification of artificial environment

Verification of the artificial environment was conducted by comparing the layer temperature for a typical roof material (green urethane waterproofing) in an artificial laboratory and in external conditions (Table 3). The total irradiation on one day in the artificial environment was set to 5104 W/m^2 day and ambient air temperatures were kept around 26–30 °C. Surface temperature monitoring was conducted in outdoor conditions over the course of a week to compare the temperature and irradiation. Irradiation is affected by clouds, wind, shading from surrounding buildings, and so on. A day with even radiation was selected and the day's total solar irradiation was determined to be 5716 W/m^2 day. The average air temperature was 22.4 °C and the average wind speed was 2.9 m/s. The maximum ambient air temperature for the artificial and outdoor environments was 30.9 and 30.1 °C, respectively. The maximum surface temperature for the artificial and outdoor environments was 72.2 and 57.5 °C, respectively. The difference in surface temperature was due to wind speed. Wind speed is a crucial factor that determines the temperature distribution [31]. Wind also increases the rate of heat loss and reduces the temperature of warmer objects to the ambient temperature at a faster rate. The measured day's average wind speed was greater than the

Table 2
Artificial solar irradiance control.

Time		8	9	10	11	12	13	14	15	16	17	18	Total
The weather in a typical meteorological year	Maximum day (W/m^2)	316	475	669	788	875	897	833	783	669	488	266	7059
	Selected typical clear day (W/m^2)	255	383	511	641	586	658	575	569	464	188	208	5038
	Average day (W/m^2)	61	222	347	538	438	597	519	338	272	250	127	3709
Artificial environment solar irradiance setting	Control day (W/m^2)	191	354	528	528	634	634	634	528	528	354	191	5104
	The step of lighting control	1 (25%)	2 (50%)	3 (75%)	3 (75%)	4 (100%)	4 (100%)	4 (100%)	3 (75%)	3 (75%)	2 (50%)	1 (25%)	–

Table 3
Comparison of artificial and external environment.

	External environment		Artificial environment	
	Surface	Ambient	Surface	Ambient
Max	57.5	30.1	72.2	30.9
Mean	28.8	22.4	46.9	28.9
Min	10.3	16.2	32.1	26.8

annual average wind speed. Furthermore, in an artificial environment, there is little air flow compared to the outdoor environment. Hence the maximum surface temperature for the outdoor environments was much higher than that for the artificial environments even though the day's total solar irradiation of outdoor environments was higher than that of the artificial environments.

4.2. The artificial environment

The thermal behavior test for different roof materials was conducted in the artificial environment and each test lasted for 24 h. The results are shown in Figs. 6–8. The temperatures for the green urethane waterproofing, gray waterproofing mortar and cool paint were sensitive to changes in the lighting control and ambient temperature because of their thinness. Green urethane waterproofing and gray waterproofing mortar are typical roof finishing materials. The surface temperatures for these materials were as high as 70 °C when the lights were on. The PCM doped tiles and cool paint reached a high of 53 °C while the unpainted normal tiles reached 63 °C. The surface temperature of the PCM doped tiles was 10–20 °C cooler than the other materials. The PCM doped tiles kept the temperature as low as the cool paint because of the heat storage performance of the tiles combined with PCM.

The ceiling temperature with the standard finishing roof materials was as high as 43 °C and the chamber air temperature surpassed 35 °C. The ceiling temperature with the PCM doped tiles and cool paint showed similar patterns, reaching up to 34 °C. The ceiling temperature with PCM doped tiles was 3 °C lower than with normal tiles and almost 10 °C lower than with typical finishing roof materials. The chamber air temperatures showed similar patterns as the ceiling temperature. The PCM doped tiles had the lowest temperature, 30.9 °C, with a narrow fluctuation range compared to normal tiles and cool paint.

4.3. External test in winter season

The temperature on the layers was measured from January 19 until 21 in 2015 for the external condition. The mean air temperature was 0.1 °C and the air temperature was as high as 9.7 °C at 13:05. The daily wind speed was 1.9 m/s. As shown in Fig. 9, the temperatures for the typical roof materials, green urethane waterproofing and gray waterproofing mortar, were higher than the air temperature, with peak temperatures of about 23.3 and 19.8 °C, respectively. However, the temperatures for cool paint and PCM doped tiles were lower than the air temperature, with peak temperatures of 5.0 and 4.9 °C, respectively. The temperatures for the normal tiles and PCM doped tiles peaked after 14:00, specifically at 14:26 and 14:40, respectively. This time lag is due to the higher thermal storage capability of the PCM tiles because the change of phase for PCM does not occur at lower temperatures. The PCM doped tiles and normal tiles had a similar temperature pattern during the day. The PCM doped tiles had peak temperatures that were almost 5 °C lower than those of the normal tiles because of the increased albedo. However, at nighttime, the mortar surface temperature of the PCM doped tiles was almost 1 °C higher than that of the normal tiles due to the thermal property of the PCM.

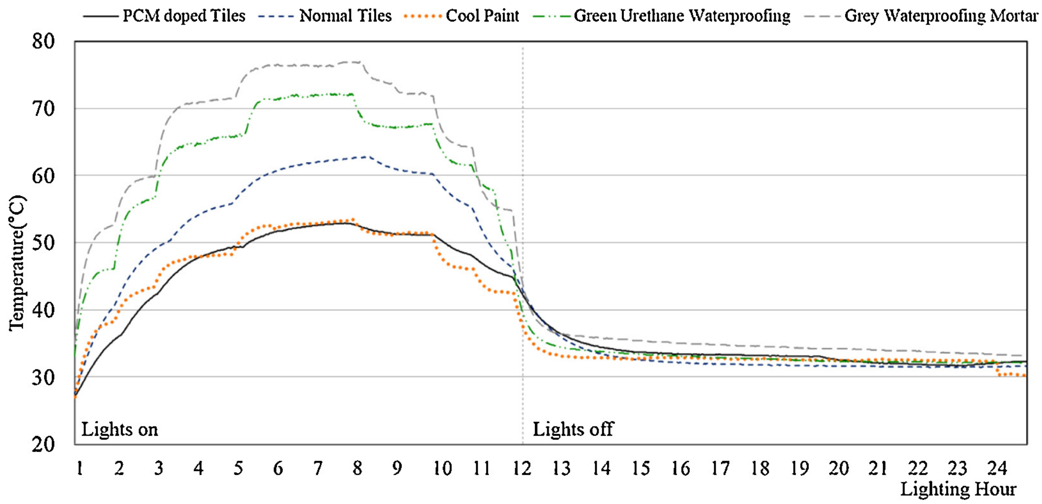

Fig. 6. Mortar surface temperature in an artificial environment.

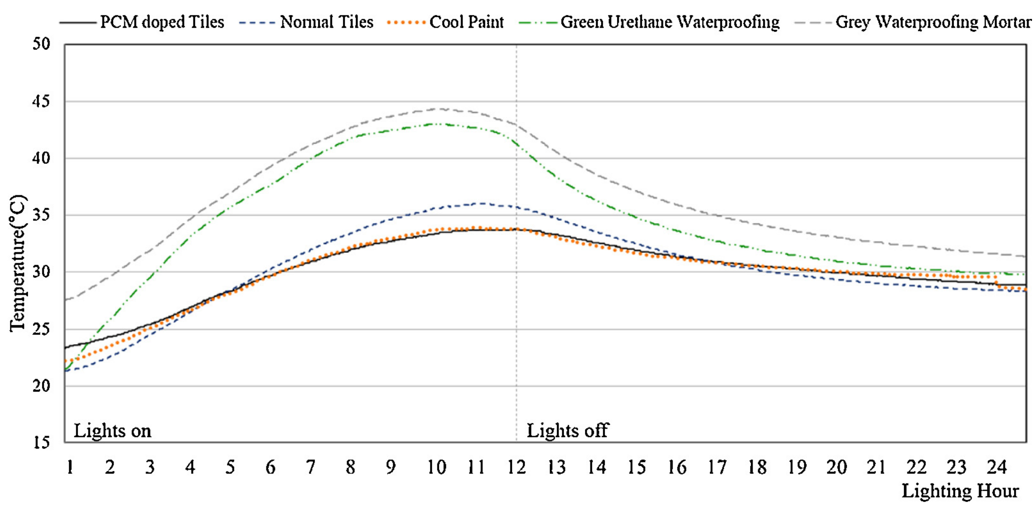

Fig. 7. Ceiling temperature in an artificial environment.

The increased albedo has little effect on the surface temperature at nighttime.

Ceiling and chamber air temperatures are shown in Figs. 10 and 11. The chamber was not heated on test days. Green urethane waterproofing had the highest ceiling and chamber air temperatures as well as the lowest albedo. The cool roof had the lowest ceiling and chamber air temperatures, with peak values of about 4.3 °C and 4.5 °C, respectively. Regarding the

Fig. 8. Chamber air temperature in an artificial environment.

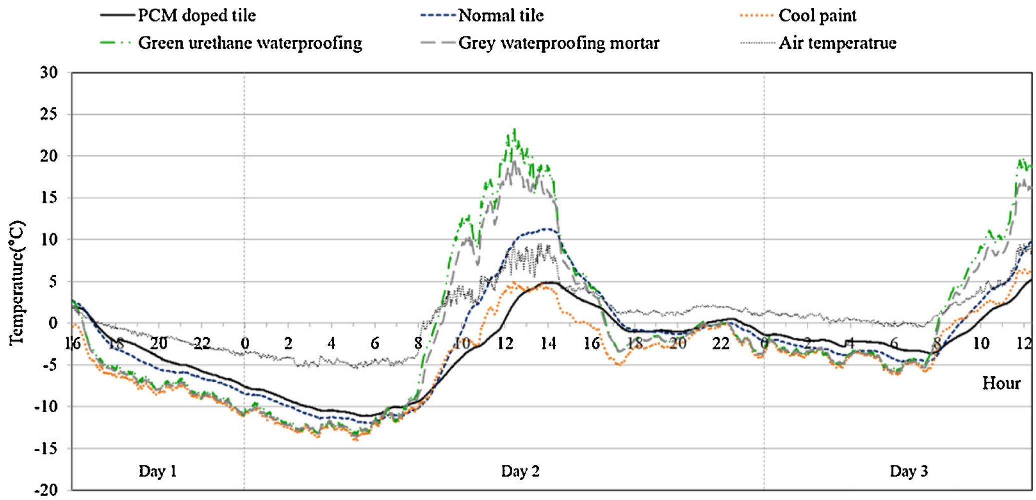

Fig. 9. Mortar surface temperature in an external environment.

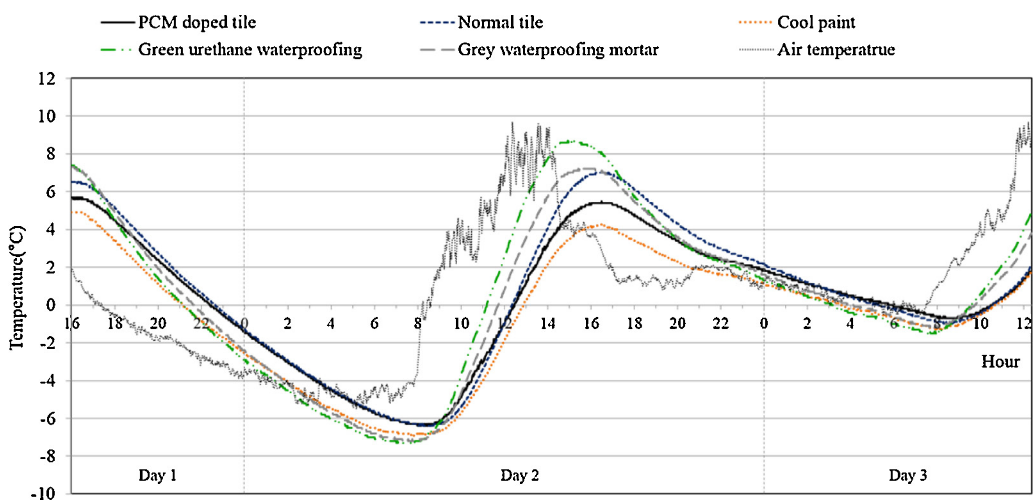

Fig. 10. Ceiling temperature in an external environment.

chamber air temperature, PCM doped tiles had higher values than cool paint, even though the mortar surface peak temperatures were similar. Hence, it is possible to infer thermal performance improvement when PCM doped tiles are used instead of cool paint. With both tiles, the chamber temperature reached a maximum at 16:00, which was 1 h later than other finishing materials. The greatest diurnal variation was 14.5 °C with green urethane waterproofing while the smallest was 11.1 °C with

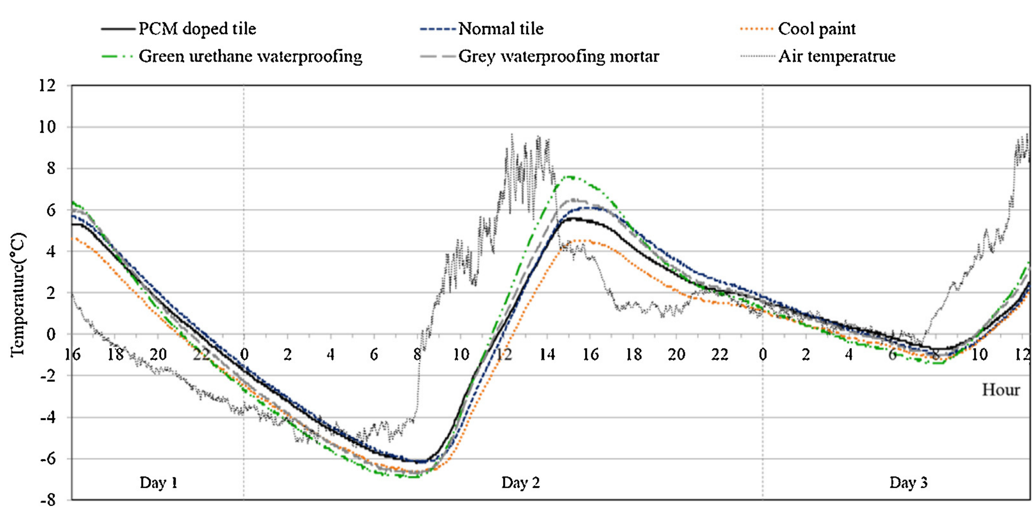

Fig. 11. Chamber air temperature in an external environment.

cool paint. The diurnal variation with PCM doped tiles was 11.8 °C.

5. Conclusion

Many mitigation strategies for UHI have been proposed. Especially, cool materials are fast becoming an appealing option in various regions. However, cool materials can have a winter heating penalty because they reflect the solar heat that would help warm the building. This study presents experimental results for the impact of solar reflective coatings applied to building surfaces on indoor chamber temperature under artificial conditions in summer and real weather conditions in winter. Five types of finishing materials were applied to scale models and their temperatures were compared.

In the artificial environment, the results indicate that the PCM doped tiles had a significant effect on reducing building surface temperatures and chamber temperatures. PCM doped tiles demonstrated the lowest diurnal variation with 7.2 °C. These tiles can be combined with thermal mass and solar reflective materials like cool paint. Therefore, PCM can keep the surface temperature and chamber air temperature low in summer weather conditions. The measurement in the winter season was conducted in actual winter conditions. Cool paint incurs a heating penalty in comparison with existing roof finishing materials. The chamber air temperature of cool paint is approximately 2–4 °C lower than that of existing room finishing materials. On the other hand, PCM doped tiles can reduce the heating penalty compared with cool paint. PCM doped tiles can also maintain a higher chamber air temperature than cool paints, with a similar maximum mortar surface temperature. The temperature patterns of the surface variables are mostly similar to those of albedo but the differences are not proportionate to the differences for albedo in both artificial environment and real external environments.

This study evaluated the potential for reducing surface temperature to control heat islands using PCM. It can be seen from the results that the application of PCM is beneficial for reducing surface temperature and improving indoor thermal performance by decreasing the maximum temperatures in the summer and increasing the maximum temperatures in the winter. However, in this study, the amount of PCM used was too small to observe a significant time lag effect. In the future, studies will be conducted to evaluate a building's thermal performance depending on the amount of PCM as well as the type of PCM packing used.

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