



# Article A Study on the Influence of the Next Generation Colored Inorganic Geopolymer Material Paint on the Insulation Measurement of Concrete Building Shell

Yeou-Fong Li<sup>1</sup>, Ya-Xuan Xie<sup>1</sup>, Jin-Yuan Syu<sup>1</sup>, Chih-Hong Huang<sup>2,\*</sup>, Hsin-Hua Tsai<sup>2</sup>, Ta-Wui Cheng<sup>3</sup>, Yen-Chun Chen<sup>3</sup> and Wei-Hao Lee<sup>3</sup>

- <sup>1</sup> Department of Civil Engineering, National Taipei University of Technology, Taipei 10608, Taiwan; yfli@mail.ntut.edu.tw (Y.-F.L.); a0985877979@gmail.com (Y.-X.X.); t9679010@ntut.org.tw (J.-Y.S.)
- <sup>2</sup> College of Design, National Taipei University of Technology, Taipei 10608, Taiwan; hsinhua425@gmail.com
- <sup>3</sup> Institute of Mineral Resources Engineering, National Taipei University of Technology, Taipei 10608, Taiwan; twcheng@ntut.edu.tw (T.-W.C.); t107799001@ntut.edu.tw (Y.-C.C.); glowing955146@gmail.com (W.-H.L.)
- \* Correspondence: huangch@mail.ntut.edu.tw

Abstract: Many studies have shown that paint with reflective heat can effectively reduce the temperature of the building envelope and reduce the future energy consumption of the building. This study inspired the next-generation inorganic geopolymer material (IGM) color paint without volatile matter, which could be applied on concrete surfaces to reduce energy consumption in warm seasons. In this study, a total of five insulating IGM paints, white, red, green, blue, and yellow, were applied to a 50 cm imes 50 cm imes 12 cm concrete slab top surface. The highest average light reflectance of all the paints was 87.5% of white IGM paint, which was higher than plain concrete (36.4%). The heat flux and surface temperature were examined in the laboratory, and those test results were verified outdoor. The results showed that the IGM paints could effectively reduce the surface temperature and heat flux of the upper and lower surfaces of concrete slabs, and the white colored IGM paint was the best performer among all five colors, whereas the heat storage coefficient  $(S_f)$  of red, white, yellow, blue, and green IGM painted concrete slabs were 0.57, 0.53, 3.62, 2.95, and 1.91 W·m<sup>-2</sup>·K<sup>-1</sup>, respectively, lower than plain concrete (24.40  $W \cdot m^{-2} \cdot K^{-1}$ ). This coefficient was presented to externalize the thermal admittance. The overall measurement results showed that the concrete slab with colored IGM paints had better heat insulation ability than the plain concrete slab, especially in white IGM paint.

**Keywords:** inorganic; geopolymer; heat storage; light reflectivity; heat flux; sustainable cities and communities

### 1. Introduction

The problem of global warming caused by greenhouse gas emissions has continued to worsen in the last few decades. In hot seasons, the demand for air conditioners is increasing. Such demand is boosting the human consumption of energy, with carbon emissions swelling, which has intensified global warming. Without effective reduction of greenhouse gas emissions, the Earth will face unimaginable consequences. Thus, improving energy efficiency and reducing energy dependency are crucial and can be accomplished by effectively managing the use of energy or through insulation. The thermal capacity of building concrete envelope emerged and became one of the most important factors for urban energy balance, which could extensively affect the Urban Heat Island (UHI) in the urban climate [1,2]. It is also a key element to obtain sustainable cities and communities.

In addition to the traditional low thermal conductivity insulating bricks, the materials used for the energy-saving and heat-insulating improvement of the building shells are gradually introduced into the paints with thermal insulation effects. With light-reflective paints' effective insulation technology, many studies have shown that the light reflectance



Citation: Li, Y-F.; Xie, Y.-X.; Syu, J.-Y.; Huang, C.-H.; Tsai, H.-H.; Cheng, T.-W.; Chen, Y.-C.; Lee, W.-H. A Study on the Influence of the Next Generation Colored Inorganic Geopolymer Material Paint on the Insulation Measurement of Concrete Building Shell. *Sustainability* **2022**, *14*, 164. https://doi.org/10.3390/ su14010164

Academic Editor: Asterios Bakolas

Received: 24 November 2021 Accepted: 21 December 2021 Published: 24 December 2021

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). of cold-colored paint formulations was significantly higher than general paints, and the surface temperature was lower than general paints as well. The heat flux (or the thermal flux, sometimes referred to as heat flux density) was relatively low once the light-reflective paint was applied, and the surface temperature of the building wall and roof can be effectively reduced. The surface temperature of the walls was decreased enough to have an energy-saving effect [3–10]. In the past, studies on different paint colors also showed that the brighter the surface, the higher the light reflectance value created, which also significantly lowered the temperature [11–13].

After the finding, buildings in many countries were beginning to be painted with bright colored paints such as Menton in France, Newfoundland in Canada, and Bristol in the UK. The development and research of paints with both reflective heat insulation and color diversity was booming. Further findings showed that not only could the shades of the paint color affect the reflection of the sunlight, when phase change materials were added to the paints under constant temperature conditions, they could also change the state of matter and provide latent heat to achieve thermal insulation [14]. Some researchers studied the paints with reflection and heat insulation by applying them to a wide variety of buildings and roads [15–18]. There were also studies on the use of white cement paint, high-gloss reflective gray or white paints, and environmental afforestation on the building rooftops, all aimed to accelerate the light-reflecting of the sunlight. In comparison, white paint proved to be more effective in reducing temperature than other heat-insulating methods [19–21]. Additional studies had pointed out that dust deposited on the roof surface was another effective method, which accelerated thermal conductivity and increased building cooling energy consumption [22].

The building envelope was one of the main thermal regenerators of the building; therefore, the quality of the heat storage capacity of the casing could also significantly improve any discomfort that is caused by the thermal in the room [23]. It has also been suggested from the past studies that the heat storage capacity affects the surface colors of different types of shells and the absorption, release, and temperature fluctuations of the shells facing them [24]. Working as the first line of defense, the outer casing was responsible for reducing the energy consumption of buildings. It was introduced with low heat storage technology, in addition to reflecting and blocking the heat of outdoor visible and infrared light that was passing through the building shell to the laboratory to reduce heat storage. Meanwhile, it could also embellish the city and improve energy savings.

Considering that available commercial paints were mostly composed of organic polymer resins, which allow them to be affected by ultraviolet radiation under long-term sunlight, resulting in aging, deterioration, and reduced thermal insulation properties. In the EU and the United States, the content of volatile organic compounds (VOCs) that might cause disease in paints must be strictly limited to below 30 g/L and 50 g/L, respectively. To meet the restrictions, the thermal insulation paints used in this study did not contain any volatile VOCs. The IGMs used in this experiment were consisted of compositions such as whetstone, kaolin, calcium magnesium carbonate, titanium dioxide and natural minerals, and an alkali solution. The alkali solution was made of glass, alkaline metal salt, nano-cerium dioxide, etc. It had a heat-reflective insulation capability and could be applied to concrete building shells as insulation materials and meet the energy-saving requirements of concrete building shells.

The process of the experiment was to first measure the reflection and heat insulation function of the IGM paints, while also considering a color that was suitable for the building. By adding 6% inorganic pigment blend, a variety of colors were produced for options to maintain the aesthetic appearance of the building shell. No volatile substances (VOCs) were emitted during construction and procedures. At the same time, the nano-mineral powder was added to overcome the problem when the porous surface was susceptible to dirt and affects the heat insulation. In all, this study conducted a series of material performance tests on white, red, green, blue, and yellow IGM paints in both laboratory and outdoor measurements to investigate the thermal insulation properties of this IGM paint.

## 2. Experimental Measurement and Theory of Thermal Property

#### 2.1. Light Reflectance Measurement

The light reflectivity possessed an important effect on the reduction of building energy consumption and surface temperature reduction, which was measured with the UV/VIS/NIR Spectrometer (LAMBDA 900, PerkinElmer Inc., Waltham, MA, USA) based on ASTM E1331-15, as shown in Figure 1. The spectrometer was used to measure the reflectivity of five colored IGM paint surfaces with the paint on the top of the steel plate (50 mm × 50 mm) with a thickness of 0.3 mm. The light reflectivity measurements of all five colored IGM paint surfaces and a plain concrete surface were repeated three times. The light source was separated by a diffraction grating and then irradiated into the paint sample through the instrument, and the light reflectance was measured according to the magnitude of the current. It could accurately measure visible light (VL, wavelength 390–700 nm), near-infrared radiation (NIR, wavelength 700–2000 nm), and the accuracy of reflective light grating in spectral ranges was 1 nm. The measurement underwent qualitative analysis and relatively reflectance relative to the preset values of the spectrometer in this article. According to the reference, the hemispherical solar irradiance on a 37° tilted surface (W·m<sup>-2</sup>·nm<sup>-1</sup>) between 390 nm to 2000 nm was 91.60% of 280 nm to 4000 nm [25].



Figure 1. UV/VIS/NIR Spectrometers.

## 2.2. Laboratory Measurement of Heat Flux and Temperature

A total of seven  $50 \times 50 \times 12$  cm concrete slabs were prepared for the laboratory's thermal insulation performance measurements; each concrete slab was painted with two layers of IGM paints with a total thickness of 0.3 mm. The density of the concrete slabs was  $2592 \text{ kg/m}^3$ . The seven test concrete slabs included one plain concrete and six others each painted in white, red, green, blue, and yellow IGM paint, and commercial white organic paint (white paint (com'1)). The IGM powder was a rutile type of titanium dioxide (TiO<sub>2</sub>) component with a heat-insulating reflection effect, and it was permeable, which allowed it to produce various colors by adding different metal oxide pigments. The test used an IGM powder mix which contained 6% colorant and alkali liquid, which included water, silicate solution, alkali salt, and silicon dioxide (SiO<sub>2</sub>). The weight ratio of the mixed powder to liquid was 1:1, and it was uniformly mixed to form a heat-insulating material for paint.

Because solar irradiance contains 44% visible light and 53% infrared radiation, three 500 W halogen lamps and one 600 W infrared lamp were used to simulate the total irradiance of VL and NIR that emit to the concrete buildings. The heights of the lighting devices were erected to 20 cm for the halogen lamps and to 35 cm for the infrared lamp, respectively. The irradiance of the visible light and infrared radiation were 609 W/m<sup>2</sup> and 775 W/m<sup>2</sup>, respectively; the overall irradiance was 1384 W/m<sup>2</sup> in this experiment measurement. As a reference, in the Taipei area, the highest solar irradiance ever recorded in the recent ten years inferred to the Central Weather Bureau in Taiwan was 1409.7 W/m<sup>2</sup> at 1 p.m. on 10 July 2020. The heat flow patch (PHFS-01e, FluxTeq, Blacksburg, VA, USA) and the thermocouple (K-type, model TPK-01BN, TECPEL, New Taipei City, Taiwan) were attached to both the front and back sides of the concrete slab, and the heat flux and surface temperature of the upper and lower portions were measurement and the test setup photo are shown in Figure 2a,b, respectively. Thermal insulation performance measurements of the seven concrete slabs were repeated three times in the laboratory.



**Figure 2.** The heat flux and surface temperature measurement of concrete slab in the laboratory: (a) Schematic diagram; (b) Test setup photo.

#### 2.3. Outdoor Measurement of Heat Flux and Temperature

The seven concrete slabs were placed on the rooftop of the Civil Engineering building at the National Taipei University of Technology to simulate an outdoor condition with the ambient temperature at about 30 °C, then, the heat flux and temperature on the upper and lower surface of the painted concrete and the plain concrete specimens were measured and recorded throughout the experiment. In the meantime, the ambient temperature, wind speed, and humidity of the weather were recorded, and the solar irradiance was measured by a pyranometer. After comparing the five colored IGM paint concrete slabs with the commercial white paint and the plain concrete slabs, the thermal insulation performance results were obtained within a 24-h time frame in this outdoor experiment. Figure 3 demonstrates the outdoor setup of the concrete slabs including the pyranometer, heat flux sensor, and surface thermograph.



Figure 3. Outdoor concrete slab measurement setup.

# 2.4. Heat Absorption, Conduction, and Storage

Figure 4 showed the upper and lower heat fluxes and temperatures, heat transfer, and heat storage behavior of the concrete slab. In this study, solar irradiance was a measurement value of the solar radiation after passing through the atmosphere to the concrete surface. The upper surface of the concrete slab came in contact with the solar irradiance; part of irradiance was first reflected by the surface material, and the rest of the radiance was then converted to thermal energy and absorbed by the concrete slabs. The heat flux and temperature were two common physical behaviors of heat absorption.



Figure 4. The heat flux, transfer, and storage behavior of concrete slab.

According to thermodynamics, the thermal capacity was defined by the quantity of heat or energy a subject needed to increase a unit temperature change. It was related to the specific heat capacity and mass of the subject as in Equation (1). According to some research [26,27], the heat (Q) change in the system was related to the temperature change, subject mass, and its specific heat capacity. The quantity of heat in absorption and conduction and the specific heat capacity of the subject were hard to measure; thus,

Fourier's law of interface heat transfer was used to deduce the heat flux, reception surface area, and reception time length are shown in integral form of Equation (2):

$$C = \frac{Q}{\Delta T} = m \cdot C_s \tag{1}$$

$$Q = m \int_{T_0}^{T_x} C_s(T) \cdot dT = A \int_{t_0}^{t_x} F(t) \cdot dt$$
(2)

where *C* is heat capacity (J·K<sup>-1</sup>); *Q* represents the heat or energy added or subtracted into the system (J);  $\Delta T$  is temperature changes (K); *m* is the mass of the concrete slab (kg); and *C*<sub>s</sub> is specific heat capacity (J·kg<sup>-1</sup>·K<sup>-1</sup>). In Equation (2), *T*<sub>0</sub> and *T*<sub>x</sub> are the initial and final temperatures (K); *F*(*t*) is the heat flux (W·m<sup>-2</sup>); *t*<sub>0</sub> and *t*<sub>x</sub> are the initial and final time (*s*), respectively, and *A* is the area between concrete and ambient air boundary (m<sup>2</sup>).

From Equations (1) and (2), the specific heat capacity  $C_s$  of the subject could be rebuilt based on the heat flux, as shown in Equation (3):

$$C_s = \frac{F(t) \cdot A}{m \cdot \frac{dT}{dt}} = \frac{\Delta F \cdot A \cdot t}{m \cdot \Delta T}$$
(3)

Equation (4) defined the relationship between the heat flux, the thermal conductivity coefficient, and the temperature gradient as in Fourier's law in one dimension [28–30]. Regarding Equation (4), the thermal conductivity coefficient can be calculated by heat flux, thickness, and temperature variation of concrete specimens, as shown in Equation (5):

$$F = -k \cdot \nabla T = k \cdot \frac{-\Delta T}{L} \tag{4}$$

$$k = \frac{F \cdot L}{-\Delta T} \tag{5}$$

where *L* is the thickness of concrete slab (m), and *k* is the thermal conductivity coefficient.

Moreover, the heat storage coefficient that had been studied in the past was used here to clarify the heat storage ability in heat transfer processes as in Equation (6) [31] with unit  $W \cdot m^{-2} \cdot K^{-1} \cdot s^{0.5}$  and Equation (7) [32] with unit  $W \cdot m^{-2} \cdot K^{-1}$ :

$$S = \sqrt{kC_s\rho} \tag{6}$$

$$S_f = \sqrt{\frac{2\pi}{t}kC_s\rho} \tag{7}$$

where *S* is heat storage coefficient ( $W \cdot m^{-2} \cdot K^{-1} \cdot s^{-0.5}$ ); *S*<sub>*f*</sub> is the quantity of heat storage coefficient effect of periodic fluctuation ( $W \cdot m^{-2} \cdot K^{-1}$ ).

It was assumed that the thermal conductivity of the concrete slab was constant, and the heat transfer within the concrete was linear. Under such assumption, the heat storage coefficient of the tested concrete slabs for 20 h in the laboratory was defined as S and  $S_f$  as in Equations (10) and (11), which described the heat absorption and its release based on the heat flux and temperature differences (Equations (8) and (9)). As a result, the heat storage coefficient  $S_f$  of painted and plain concrete slabs was presented:

$$\Delta F = F_{upper} - F_{lower} \tag{8}$$

$$\Delta T = T_{mean} - T_{ambient} = \frac{T_{upper} + T_{lower}}{2} - T_{ambient}$$
<sup>(9)</sup>

$$S = \sqrt{kC_s\rho} = \sqrt{\frac{\Delta F \cdot A \cdot t}{m \cdot \Delta T} \cdot \frac{\Delta F \cdot L}{\Delta T} \cdot \rho} = \frac{\Delta F}{\Delta T} \cdot \sqrt{t}$$
(10)

$$S_f = \sqrt{\frac{2\pi}{t}kC_s\rho} = \sqrt{\frac{2\pi}{t}\cdot\frac{\Delta F\cdot A\cdot t}{m\cdot\Delta T}\cdot\frac{\Delta F\cdot L}{\Delta T}\cdot\rho} = \frac{\Delta F}{\Delta T}\cdot\sqrt{2\pi}$$
(11)

where  $F_{upper}$  is the heat flux from paint to concrete slab under the light (W·m<sup>-2</sup> = J·m<sup>-2</sup>·s<sup>-1</sup>);  $F_{lower}$  is the heat flux from the back of concrete to the ambient (W·m<sup>-2</sup> = J·m<sup>-2</sup>·s<sup>-1</sup>);  $T_{mean}$  is the mean temperature in concrete under a linear gradient that changed over time (K);  $T_{ambient}$  is the ambient temperature that changed over time (K).

#### 3. Light Reflectance Measurement Results

From the studies, the light reflectance of commercial organic white paints could reach 80 to 86% [4,12]. The rest, including the light reflectance measurement results of the five colored IGM painted surfaces and the plain concrete, were shown in Figure 5 and Table 1. As shown in Figure 5 and Table 1, the first finding indicated that between the SR (390–2000 nm) spectral range, the average light reflectance of the white IGM painted surface reached 87.5%, followed by yellow, blue, green, and red IGM paints, and the plain concrete was 36.4%. The second finding indicated that IGM was tested higher in the light reflectance values of NIR than in VL.



**Figure 5.** The light reflectance distribution of plain concrete and colored IGM paints in the wavelength range of 390–2000 nm.

| Light | Wavelength – | Average Light Reflectance (%) |       |        |      |       |      |  |
|-------|--------------|-------------------------------|-------|--------|------|-------|------|--|
|       |              | Plain Concrete                | White | Yellow | Blue | Green | Red  |  |
| VL    | 390–700 nm   | 30.7                          | 94.0  | 53.9   | 59.6 | 43.7  | 36.6 |  |
| NIR   | 700–2000 nm  | 37.7                          | 86.0  | 76.6   | 67.1 | 61.9  | 62.0 |  |
| SR    | 390–2000 nm  | 36.4                          | 87.5  | 72.2   | 65.6 | 58.4  | 57.1 |  |

## 4. Laboratory Heat Flux and Surface Temperature Measurements

4.1. Laboratory Heat Flux Measurement Results

For 20 h, the upper surface of all seven concrete specimens were shined under both halogen lamp (visible light, VL) and near-infrared lamp (NIR) simultaneously. Figure 6 showed the heat flux changes in both the upper surface and lower surface of the seven concrete slab specimens over time. Table 2 showed the heat flux changes in both the upper surface and lower surface of the seven concrete slab specimens in the 20th hour. In short, IGM painted specimens showed lower heat flux in both charts.



**Figure 6.** The heat flux of concrete specimens under SR over time: (**a**) Upper surface heat flux; (**b**) Lower surface heat flux.

Table 2. The upper surface and lower surface heat fluxes in the 20th hour.

| Color                      | Upper Surface Heat Flux<br>(W/m²) | Lower Surface Heat Flux<br>(W/m <sup>2</sup> ) |  |
|----------------------------|-----------------------------------|--|--|
| Plain Concrete (unpainted) | 463.40                            | 83.50  |  |
| White Paint (com'l)        | 170.10                            | 56.35  |  |
| Red IGM Paint              | 73.99                             | 74.06  |  |
| White IGM Paint            | 59.07                             | 55.04  |  |
| Yellow IGM Paint           | 95.40                             | 55.40  |  |
| Blue IGM Paint             | 89.88                             | 55.83  |  |
| Green IGM Paint            | 89.70                             | 69.23  |  |

In detail, the results of the heat fluxes of the specimens stated that the IGM paint was more effective in blocking the heat created by the halogen lamp and the infrared lamp compared to the commercial white paint and to the plain concrete in the upper surface. The lower surfaces showed similar results regarding the IGM paint, the commercial white paint, and then the plain concrete. Note that the lower surfaces of the seven specimens were not painted. In other words, the results proved that the IGM paint had a better heat barrier property that could effectively reflect the radiant of the portion it covered and slowed the heat flow into the lower surface of the concrete slabs as well.

#### 4.2. Laboratory Surface Temperature Measurement Results

Figure 7 showed the duration of the temperature changes of both the upper and the lower surface of concrete specimens under the illumination of a halogen lamp and infrared lamp in the laboratory, and Table 3 showed the measured values of the steady-state temperature of the upper and lower surfaces under the same settings.



**Figure 7.** The surface temperature of concrete specimens under VL and NIR over time: (**a**) Upper surface temperature; (**b**) Lower surface temperature.

| Color                      | Temperature (°C) |               |               |  |  |  |
|----------------------------|------------------|---------------|---------------|--|--|--|
|                            | Average Ambient  | Upper Surface | Lower Surface |  |  |  |
| Plain Concrete (unpainted) | 29.77            | 84.59         | 54.82         |  |  |  |
| White Paint (com'l)        | 30.49            | 72.60         | 47.39         |  |  |  |
| Red IGM Paint              | 28.57            | 74.83         | 45.65         |  |  |  |
| White IGM Paint            | 31.18            | 73.10         | 44.66         |  |  |  |
| Yellow IGM Paint           | 32.04            | 72.38         | 48.75         |  |  |  |
| Blue IGM Paint             | 32.21            | 75.53         | 49.33         |  |  |  |
| Green IGM Paint            | 30.14            | 74.28         | 49.70         |  |  |  |

**Table 3.** The upper surface and lower surface temperatures of the concrete slabs under VL and NIR at a steady-state condition.

All seven concrete specimens were irradiated under the halogen lamp and the infrared lamp, and the temperature of each concrete slab specimen's upper surface was measured and shown in Figure 7a and Table 3. The lowest temperature measured was the concrete slab painted with the yellow IGM paint, followed by the ascending order of white IGM, white paint (com'l), red IGM, green IGM, and blue IGM plain concrete specimens. In comparison, the lower surface temperature of each concrete slab specimen was also measured, and the lowest temperature was the white painted concrete slab specimen, followed by the red IGM, white paint (com'l), yellow IGM, blue IGM, green IGM, and then the plain concrete specimens in an ascending order in Figure 7b and Table 3.

In the concrete slabs under the illumination of the light source experiment, the white IGM paint had the best thermal insulation ability of all the colored IGM paints, and it was superior to the commercially available white paint and plain concrete. In general, the thermal insulation abilities of the painted concrete specimens were all better than the plain concrete.

#### 4.3. Laboratory Surface Temperature Measurement Results after Turn off the Light

Figure 8 showed the temperature drop gradation of the specimens to describe the heat release of paint concrete slabs when the lamps were turned off. Each slope showed the gradation in temperature changes for each concrete specimen from their starting temperature (after 20 h of the illumination) until 30 min later.



Figure 8. Cont.



**Figure 8.** The surface temperature drop gradation of the concrete slabs over time: (**a**) Upper surface; (**b**) Lower surface.

According to Figure 8, the upper surface temperature of the plain concrete was the worst among all specimens in cooling off, whereas the upper surface cooling rate of the IGM paints were over  $1.72 \,^{\circ}\text{C}\cdot\text{min}^{-1}$  better than the plain concrete in the first 5 min of the 30 min cooling process. In addition to that, the heat release of the white IGM paint concrete slab was better than the commercial white paint concrete slab. Regarding the lower surface measurements, the cooling outcomes of the white and blue colors were the best. It showed that the painted concrete slabs could cool off more rapidly than the plain concrete slab. That is to say that the paint layer could effectively dissipate the heat stored inside the specimen.

## 4.4. Thermal Admittance Calculation and t-Test Analysis

Thermal admittance is an important index in describing the heat absorbing and releasing in relation to spaces of the building materials over time. In this article, the changes of the heat storage coefficient were used to label the thermal admittance. Table 4 showed the specific heat capacity and heat storage coefficient of the colored IGM paint specimens and the plain concrete specimen based on the laboratory test results. The plain concrete had the highest heat storage coefficient (Thermal Admittance), while the white IGM paint concrete specimen had the lowest. Evidently, IGM paint could reduce the quantity of the heat absorption of concrete. As the heat flux into a concrete specimen decreased, the heat storage coefficient decreased as well, and such an interaction is shown in Figure 9. The heat absorption quantity was found in the experiment as shown in Figure 10, which agreed with the concept of when the heat storage of a building concrete gradually decreased and the heat flux slowed under SR over time.

**Table 4.** Calculation of specific heat capacity and heat storage coefficient at a steady-state condition (last 5 h average) under the light.

| Color                         | T <sub>mean</sub><br>(°C) | T <sub>ambient</sub><br>(°C) | Δ <i>T</i><br>(°C) | $\Delta F$ (W·m <sup>-2</sup> ) | $C_s$ (J·kg <sup>-1</sup> ·K <sup>-1</sup> ) | $S = (W \cdot m^{-2} \cdot K^{-1} \cdot s^{0.5})$ | $S_f$ (W·m <sup>-2</sup> ·K <sup>-1</sup> ) |
|-------------------------------|---------------------------|------------------------------|--------------------|---------------------------------|--|---|---|
| Plain Concrete<br>(unpainted) | 69.94                     | 29.74                        | 40.203             | 391.34                          | 126.96                                       | 9.73  | 24.40                                       |
| White Paint (com'l)           | 60.19                     | 30.66                        | 29.533             | 114.18                          | 50.43  | 3.87  | 9.69  |
| Red IGM Paint                 | 60.49                     | 28.70                        | 31.785             | 7.21                            | 2.96   | 0.23  | 0.57  |
| White IGM Paint               | 59.26                     | 31.42                        | 27.841             | 5.88                            | 2.76   | 0.21  | 0.53  |
| Yellow IGM Paint              | 61.09                     | 32.28                        | 28.806             | 41.66                           | 18.86  | 1.45  | 3.62  |
| Blue IGM Paint                | 62.88                     | 32.50                        | 30.382             | 35.73                           | 15.34  | 1.18  | 2.95  |
| Green IGM Paint               | 62.54                     | 30.44                        | 32.096             | 24.41                           | 9.92   | 0.76  | 1.91  |





Figure 9. The heat storage coefficient of plain concrete slab and six painted slabs over time.



Figure 10. The heat absorbed accumulation of plain concrete slab and six painted slabs over time.

The cooling rate of the plain concrete slab was slower than the other painted concrete slabs. After the painted concrete slabs were illuminated by the light, some of the heat could be reflected first due to the influence of the paint layer. So, the heat absorbed by the test body was relatively reduced. In consequence of the lower amount of heat travelling to the lower surface, the temperature was lower in respect to the effect of the paint layer. This proved that the next generation of IGM paint has good reflective heat insulation and low heat storage capacity. If it could be effectively applied to the insulation of building shells, it was believed that it would be able to improve the energy efficiency of urban buildings and reduce the energy consumption of all buildings.

According to the above experimental results above, the *t*-test analysis between the VL reflectance, SR reflectance, and heat storage coefficient of different-colored IGM paints and plain concrete were calculated in this study. The Pearson correlation coefficient (Pearson's *R*) between the reflectance of the SR, VL, NIR and heat storage coefficient ( $S_f$ ) were about -0.763, -0.504, and -0.819, respectively; the *t*-values were about -1.313, -1.340, and -1.306, respectively. In addition, the *p*-value (one-tailed) were about 0.123, 0.119, and

0.124, respectively, and all the *p*-value were higher than 0.05. These results designated that the reflectance of the color paints might not be a primary effective factor of the thermal absorption of concrete. However, as stated by the results of the correlation coefficient, the light reflectance of color paints had the negative relationship with the heat storage coefficient that was crucial enough to affect the outcomes. According to physics, light is a major form of energy radiation; therefore, increasing the light reflectance was a good way to reduce the heat absorption of concrete. The results also indicate that IGM paints show a promising interaction between the NIR reflectance and the heat storage coefficient ( $S_f$ ) since heat radiation was often presented as a type of infrared radiation. Namely, the NIR reflectance and the heat storage coefficient should be carefully considered and analyzed in thermal absorption obstruction assessments for painted concrete.

### 5. Outdoor Heat Flux and Surface Temperature Measurements

All concrete slabs were placed outdoors for 24 h to measure heat flux and temperature properties, and the results were presented in subsequent sections.

#### 5.1. Outdoor Heat Flux Measurement Results

The heat fluxes of the upper and lower surfaces are shown in Figure 11. In addition, the solar irradiance is shown in Figure 12. Table 5 shows the maximum values of the upper surface and lower surface heat fluxes of concrete slabs over 24 h. The results indicate that the upper surface and lower surface heat fluxes of the painted specimens were lower than that of the plain concrete, even when the solar irradiance in the colored paint specimens was higher than in the plain concrete specimens according to the pyranometer. The white IGM paint had the best heat insulation performance among all specimens, while the plain concrete specimen had the poorest thermal insulation. The outdoor measurement results of all concrete specimens were similar to the laboratory measurement results in comparison.



Figure 11. Cont.



**Figure 11.** The heat flux of the concrete slabs during 24 h outdoor measurement: (**a**) Upper surface; (**b**) Lower surface.



Figure 12. The solar irradiance of the concrete slabs during 24 h outdoor measurement.

**Table 5.** The maximum values of the upper surface and lower surface heat fluxes of concrete slabs during the 24 h of observation.

| Color                      | Upper Surface Heat Flux<br>(W/m²) | Lower Surface Heat Flux<br>(W/m <sup>2</sup> ) |  |
|----------------------------|-----------------------------------|--|--|
| Plain Concrete (unpainted) | 158.10                            | 34.80  |  |
| White Paint (com'l)        | 40.58                             | 25.16  |  |
| Red IGM Paint              | 35.96                             | 31.66  |  |
| White IGM Paint            | 13.49                             | 15.28  |  |
| Yellow IGM Paint           | 32.00                             | 33.53  |  |
| Blue IGM Paint             | 37.17                             | 19.72  |  |
| Green IGM Paint            | 40.47                             | 31.60  |  |

#### 5.2. Outdoor Surface Temperature Measurement Results

Sometimes, the sun was obscured by the clouds during the daytime, which would affect the solar irradiance and temperatures. The average temperature of the upper and lower surfaces and the solar irradiance of the tested specimens were compared. The results were divided into two time sections, one from 10:00 to 17:00 (daytime) and another from 19:00 to 5:00 (nighttime).

Table 6 shows the average temperature and temperature changes of the upper surfaces of all seven specimens during the daytime. The white IGM paint had the lowest average temperature and the smallest changes of temperature, followed by the blue IGM, the green IGM, the commercial white, the red IGM, the yellow IGM, and the plain concrete had the highest average temperatures and the biggest temperature changes. Similarly, as seen in Table 6, the lower surface temperature differences of the six painted concrete slab specimens were all lower than the plain concrete. In Table 7, the nighttime average temperature of both the upper and the lower surfaces of the six painted concrete specimens were all lower than the plain concrete specimen. Moreover, the average temperature and temperature difference of the white IGM paint specimen had the lowest among the six painted specimens. Based on the data of the solar irradiance recorded in the experiment, the white IGM paint specimen had a lower solar irradiance than all the others due to the weather conditions.

**Table 6.** Average daytime (10:00–17:00) temperature, humidity, and wind speed mean values of the outdoor measurement.

| Color                      | Ambient<br>Temperature (°C) | Humidity (%) | Wind Speed (m/s) | Upper Surface<br>Temperature<br>(°C) | Lower Surface<br>Temperature<br>(°C) |
|----------------------------|-----------------------------|--------------|------------------|--------------------------------------|--------------------------------------|
| Plain Concrete (unpainted) | 31.12                       | 56.94        | 1.43             | 42.24                                | 40.90                                |
| White Paint (com'l)        | 34.17                       | 48.47        | 4.30             | 42.42                                | 40.07                                |
| Red IGM Paint              | 35.80                       | 43.84        | 2.38             | 45.97                                | 41.91                                |
| White IGM Paint            | 33.02                       | 57.47        | 2.46             | 35.41                                | 35.23                                |
| Yellow IGM Paint           | 33.89                       | 55.29        | 4.23             | 44.92                                | 39.88                                |
| Blue IGM Paint             | 34.44                       | 50.67        | 3.02             | 40.75                                | 38.16                                |
| Green IGM Paint            | 33.70                       | 56.50        | 3.23             | 42.37                                | 38.75                                |

**Table 7.** Average nighttime (19:00–05:00) temperature, humidity, and wind speed mean values of the outdoor measurement.

| Color                      | Ambient<br>Temperature<br>(°C) | Humidity<br>(%) | Wind Speed (m/s) | Upper Surface<br>Temperature<br>(°C) | Lower Surface<br>Temperature<br>(°C) |
|----------------------------|--------------------------------|-----------------|------------------|--------------------------------------|--------------------------------------|
| Plain Concrete (unpainted) | 26.49                          | 81.72           | 1.16             | 31.64                                | 33.98                                |
| White Paint (com'l)        | 30.06                          | 68.90           | 2.67             | 29.47                                | 30.46                                |
| Red IGM Paint              | 29.38                          | 72.80           | 1.28             | 29.19                                | 30.32                                |
| White IGM Paint            | 31.02                          | 68.46           | 1.69             | 30.63                                | 31.49                                |
| Yellow IGM Paint           | 29.45                          | 82.07           | 3.50             | 30.36                                | 31.17                                |
| Blue IGM Paint             | 29.32                          | 78.75           | 1.50             | 29.82                                | 30.86                                |
| Green IGM Paint            | 29.67                          | 74.30           | 1.95             | 28.84                                | 29.65                                |

In the outdoor measurement, the white IGM paint specimen had the best thermal insulation ability in all colors. The thermal insulation ability of the plain concrete had the poorest insulation ability among all specimens. These outdoor measurement results were similar to the laboratory measurement results. Regardless of either the laboratory or the outdoor measurements, the thermal insulation ability of the IGM-painted concretes were all better than the plain concrete and commercial paint concrete.

## 6. Conclusions

Solar radiation is the main heat source for most concrete building rooftops; therefore, finding out how to minimize the concrete's heat absorption and ameliorate the heat releas-

ing of the concrete buildings has become crucial in order to achieve a greener building code. This study attempted to improve the light reflectivity of concrete surfaces with color IGM paints to reduce the heat absorption of concrete. Some conclusions of this study are stated as follows:

- 1. The average light reflectance values of various color paint materials were obtained by the light reflectance test. In the range of 390–2000 nm, the highest average light reflectance value of all the covering materials was the white IGM at 87.5%, and the light reflectance of the plain concrete was 36.4%.
- 2. It is known from the thermal insulation results in the laboratory that the IGM paint had good thermal insulation properties. Under the influence of environmental factors, the measurement results were inevitably challenged. Nevertheless, the results of the experiment were still considered to be objective under the circumstances. That is, under the irradiance of simulated sunlight, the thermal insulation performance of the concrete specimens painted with the IGM paints were better than the plain concrete specimen.
- 3. Thermal admittance was described in place of the changes of the heat storage coefficient in this research. The results indicated that the IGM paints could reduce the quantity of heat absorption of the concrete slabs. The heat storage coefficient of red, white, yellow, blue, and green IGM-painted concrete slabs were 0.57, 0.53, 3.62, 2.95, and 1.91 W·m<sup>-2</sup>·K<sup>-1</sup>, respectively, which were lower than the plain concrete specimen (24.40 W·m<sup>-2</sup>·K<sup>-1</sup>). Based on the changes of the heat storage coefficient over time, it was confirmed that the heat absorption of specimens through the IGM paints and then into the concrete under the light was slowed, and it was lower than the commercial white paint specimen and the plain concrete specimen.
- 4. The results of outdoor measurement showed that the IGM painted specimens had good thermal insulation ability, and these results were similar to the measurement results in the laboratory. The concrete specimens painted with IGM had better thermal insulation performance than the plain concrete specimen. Furthermore, the thermal insulation performance of the white IGM paint was also better than the commercial white paint.
- 5. Through various physical properties and thermal insulation measurement results, it was clear that the next generation of colored IGM paints had high reflectivity, good thermal insulation, and low heat storage capacity. The next generation of colored IGM paint could be applied to various building shells and especially to concrete building shells in sustainable cities and communities. Its strong and practical characteristics could effectively reduce the indoor temperature and attain an energy-saving effect in subtropics.

Author Contributions: Conceptualization, Y.-F.L.; data curation, Y.-X.X. and Y.-C.C.; formal analysis, Y.-X.X., J.-Y.S. and H.-H.T.; investigation, Y.-X.X., J.-Y.S. and W.-H.L.; methodology, Y.-F.L. and C.-H.H.; project administration, Y.-F.L. and C.-H.H.; supervision, Y.-F.L., W.-H.L. and T.-W.C.; writing—original draft, Y.-X.X. and T.-W.C.; writing—review and editing, Y.-F.L. and C.-H.H. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Ministry of Education of Taiwan, under contract No. L7081101-4, and the "Research Center of Energy Conservation for New Generation of Residential, Commercial, and Industrial Sectors" from the Ministry of Education of Taiwan, under contract No. L7091101-19.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

# References

- Crawford, B.; Krayenhoff, E.S.; Cordy, P. The urban energy balance of a lightweight low-rise neighborhood in Andacollo, Chile. *Theor. Appl. Clim.* 2016, 131, 55–68. [CrossRef] [PubMed]
- 2. Rapsomanikis, S.; Trepekli, A.; Loupa, G.; Polyzou, C. Vertical Energy and Momentum Fluxes in the Centre of Athens, Greece During a Heatwave Period (Thermopolis 2009 Campaign). *Boundary-Layer Meteorol.* **2015**, *154*, 497–512. [CrossRef]
- 3. Akbari, H.; Bretz, S.; Kurn, D.M.; Hanford, J. Peak power and cooling energy savings of high-albedo roofs. *Energy Build*. **1997**, *25*, 117–126. [CrossRef]
- 4. Zinzi, M.; Fasano, G. Properties and performance of advanced reflective paints to reduce the cooling loads in buildings and mitigate the heat island effect in urban areas. *Int. J. Sustain. Energy* **2009**, *28*, 123–139. [CrossRef]
- 5. Bozonnet, E.; Doya, M.; Allard, F. Cool roofs impact on building thermal response: A French case study. *Energy Build*. **2011**, *43*, 3006–3012. [CrossRef]
- 6. Guo, W.; Qiao, X.; Huang, Y.; Fang, M.; Han, X. Study on energy saving effect of heat-reflective insulation coating on envelopes in the hot summer and cold winter zone. *Energy Build.* **2012**, *50*, 196–203. [CrossRef]
- Garg, V.; Somal, S.; Arumugam, R.; Bhatia, A. Development for cool roof calculator for India. *Energy Build*. 2016, 114, 136–142. [CrossRef]
- 8. Ferrari, C.; Libbra, A.; Cernuschi, F.M.; De Maria, L.; Marchionna, S.; Barozzi, M.; Siligardi, C.; Muscio, A. A composite cool colored tile for sloped roofs with high 'equivalent' solar reflectance. *Energy Build.* **2016**, *114*, 221–226. [CrossRef]
- 9. Guo, X.; Wang, J.; Wu, Y.; Ao, Y.; Liu, X. Experimental study of the thermal performance of a new type of building reflective coating in hot summer and cold winter zone of China. *Procedia Eng.* **2017**, *205*, 603–608. [CrossRef]
- 10. Qiu, T.; Wang, G.; Xu, Q.; Ni, G. Study on the thermal performance and design method of solar reflective–thermal insulation hybrid system for wall and roof in Shanghai. *Sol. Energy* **2018**, *171*, 851–862. [CrossRef]
- 11. Cheng, V.; Ng, E.Y.Y.; Givoni, B. Effect of envelope colour and thermal mass on indoor temperatures in hot humid climate. *Sol. Energy* **2005**, *78*, 528–534. [CrossRef]
- 12. Uemoto, K.L.; Sato, N.M.; John, V.M. Estimating thermal performance of cool colored paints. *Energy Build.* 2010, 42, 17–22. [CrossRef]
- 13. Del Carpio, J.A.V.; Marinoski, D.L.; Trichês, G.; Lambert, R. Urban pavements used in Brazil: Characterization of solar reflectance and temperature verification in the field. *Sol. Energy* **2016**, *134*, 72–81. [CrossRef]
- 14. Roman, K.K.; O'Brien, T.; Alvey, J.; Woo, O. Simulating the effects of cool roof and PCM (phase change materials) based roof to mitigate UHI (urban heat island) in prominent US cities. *Energy* **2016**, *96*, 103–117. [CrossRef]
- 15. Synnefa, A.; Santamouris, M.; Livada, I. A study of the thermal performance of reflective coatings for the urban environment. *Sol. Energy* **2006**, *80*, 968–981. [CrossRef]
- 16. Carnielo, E.; Fanchiotti, A.; Zinzi, M. Energy and Comfort Benefits of a Cool Roof Application in a Non-Residential Building Belonging to Roma Tre University. *World Renew. Energy Congr.* **2011**, *57*, 1970–1977.
- 17. Shen, H.; Tan, H.; Tzempelikos, A. The effect of reflective coatings on building surface temperatures, indoor environment and energy consumption—An experimental study. *Energy Build.* **2011**, *43*, 573–580. [CrossRef]
- 18. Santamouris, M.; Synnefa, A.; Karlessi, T. Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions. *Sol. Energy* **2011**, *85*, 3085–3102. [CrossRef]
- 19. Parker, D.S.; Barkaszi, S.F. Roof solar reflectance and cooling energy use: Field research results from Florida. *Energy Build.* **1997**, 25, 105–115. [CrossRef]
- 20. Takebayashi, H.; Masakazu, M. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. *Build. Environ.* **2007**, *42*, 2971–2979. [CrossRef]
- 21. Costanzo, V.; Evola, G.; Marletta, L. Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. *Energy Build*. 2016, 114, 247–255. [CrossRef]
- 22. Algarni, S.; Nutter, D. Influence of dust accumulation on building roof thermal performance and radiant heat gain in hot-dry climates. *Energy Build.* 2015, 104, 181–190. [CrossRef]
- 23. Shariah, A.; Shalabi, B.; Rousan, A.; Tashtoush, B. Effects of absorptance of external surfaces on heating and cooling loads of residential buildings in Jordan. *Energy Convers. Manag.* **1998**, *39*, 273–284. [CrossRef]
- 24. Ruivo, C.; Ferreira, P.; Vaz, D. On the error of calculation of heat gains through walls by methods using constant decrement factor and time lag values. *Energy Build.* 2013, 60, 252–261. [CrossRef]
- 25. ASTM G173-03. Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface; American Society for Testing and Materials: West Conshohocken, PA, USA, 2020. [CrossRef]
- Pomianowski, M.; Heiselberg, P.; Jensen, R.L.; Cheng, R.; Zhang, Y. A new experimental method to determine specific heat capacity of inhomogeneous concrete material with incorporated microencapsulated-PCM. *Cem. Concr. Res.* 2014, 55, 22–34. [CrossRef]
- 27. Shafigh, P.; Asadi, I.; Mahyuddin, N.B. Concrete as a thermal mass material for building applications—A review. *J. Build. Eng.* **2018**, *19*, 14–25. [CrossRef]
- 28. Sarbu, I.; Sebarchievici, C. A Comprehensive Review of Thermal Energy Storage. Sustainability 2018, 10, 191. [CrossRef]
- 29. Smith, E.R.; Daivis, P.J.; Todd, B.D. Measuring heat flux beyond Fourier's law. J. Chem. Physics 2019, 150, 064103. [CrossRef] [PubMed]

- 30. Childs, P.R.N.; Greenwood, J.R.; Long, C.A. Heat flux measurement techniques. *Proc. Inst. Me Chanical Eng. Part C J. Mech. Eng. Sci.* **1999**, 213, 655–677. [CrossRef]
- 31. Misra, K.; Shrotriya, A.K.; Singhvi, N.; Singh, R.; Chaudhary, D.R. Prediction of heat storage coefficient of two-phase systems with spherical inclusions. *J. Phys. D Appl. Phys.* **1994**, 27, 1823. [CrossRef]
- 32. Li, M.; Wu, Z.; Tan, J. Heat storage properties of the cement mortar incorporated with composite phase change material. *Appl. Energy* **2013**, *103*, 393–399. [CrossRef]