Enhanced solar spectral reflectance of thermal coatings through inorganic additives

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Abstract

Space cooling of buildings is responsible for a substantial portion of energy consumption and greenhouse gas emission. In order to reduce the building energy consumption, reflective coatings have been adopted extensively since they can effectively minimize undesirable solar energy absorption. In this paper, functional additives (i.e., titanium dioxide and hollow glass beads) are used to improve the reflective and insulation properties of thermal coating materials. The thermal impact upon the application of different reflective coatings on concrete panels is experimentally examined. The experimental results have shown that the coating containing titanium dioxide and hollow glass beads leads to a drop in interior surface temperature, up to 3.5°C, implying that such coating can effectively reduce heat absorption and cooling load for buildings. The finite-difference time-domain simulation (FDTD) which can simulate the propagation of electromagnetic waves is used here to investigate the reflection of electromagnetic waves and to explore the working principles of additives. The numerical simulations demonstrate the reflective behavior in the coating material, showing that embedded TiO₂ nanoparticles can significantly improve the reflective performance of coating films. It is envisioned that a nontoxic coating with high level of reflectance and insulation can be characterized and the working principles of different additives can be revealed.

1. Introduction

Traditional buildings require a lot of energy for space heating and cooling, resulting in huge energy consumption accompanied with greenhouse gas emission. The indoor temperature increases when the exterior surfaces are exposed to solar radiation. A large amount of energy is consumed by air-conditioning system to maintain indoor thermal comfort. In the United States of America (USA), the air-conditioning system accounts for more than 40% of the building energy consumption according to the Department of Energy in the USA [1]. In order to reduce the cooling load and building energy consumption, actions should be taken to reduce undesirable absorption of solar radiation [2–7]. At present, three thermal insulation methods are commonly used, i.e., interior insulating materials, energy storage system with phase change materials and reflective coatings [8]. The interior insulating materials may cause a reduction in room size, loss of thermal mass and interstitial condensation problem. Some interior insulating materials can even pose health risks [9]. Implementation of energy storage system is relatively complicated. Phase change materials have to be encapsulated or stabilized in the building, and encapsulation may cause structural problems like leakage and corrosion. Furthermore, phase change materials may release toxic substances when exposed to fire [10,11]. In comparison with the two aforementioned methods, the reflective coating method is more convenient and reliable. Reflective coatings are generally non-combustible and can be conveniently applied to the surface of building envelope through roller or sprayer without affecting the properties of original building [12–14]. The reflective coatings should be featured with high reflectance throughout the entire solar spectrum and minimal heat transfer to the coated object. A schematic diagram exhibiting a comparison of buildings with and without reflective coatings is shown in Fig. 1(a). During hot seasons, the reflective coatings on building envelopes protect the building from being heated by solar radiation, preserving a relatively low indoor temperature. As a result, the cooling load is decreased and the additional energy consumed by air-conditioning system can be reduced [15–19]. Furthermore, reflective coatings can also contribute to the decrease of outdoor air temperature and therefore reduce the heat island effect [20].
The indoor temperature difference between coated and uncoated buildings has been observed up to 12 °C in hot and humid zones [21,22]. Such distinct indoor temperature difference can achieve an energy saving of 1.3 W/m² according to a comparison study between medium-grey reflective coating and traditional painting [23]. In another study, an electricity saving of 0.5 kWh/day has been observed after applying a reflective coating to a building envelope and improving its reflectance from 0.26 to 0.72 [24]. Due to the high reflectance of coating, a concern that it may result in a higher heating load of building in winter arises. A continuous two-year study has been conducted in the subtropical area to investigate the dynamic effect of reflective coatings on building thermal performance in summer and winter conditions. The results show that the reflective coatings could reduce the external surface temperature more than 10 °C in summer, while in winter, the temperature of external surface covered with reflective coatings was only about 1 °C lower than that of uncovered surface [25]. This study has demonstrated that the summer cooling saving is able to counteract the winter heating penalty and the application of reflective coating can still yield an energy saving effect.

Although the existing reflective coatings are effective in reducing heat absorption, they show some limitations that impede their extensive applications [26]. Firstly, organic pigments in the existing reflective coatings are easily aged when exposed to ultraviolet and the long-term durability is poor. Secondly, most inorganic pigments for reflective coatings contain hazardous metal elements (e.g., cobalt, chromium, cadmium), which are restricted by environmental regulations, for example, EU guideline No. 91/338/EEC [27]. In order to overcome these limitations and promote the reflective coatings, it is necessary to characterize the thermal performance of coatings with various inorganic additives which do not contain hazardous metal elements and explore their working principles.

The ability to reflect radiation in infrared region is quantified by scattering rate, which is an important factor for the design of thermal coatings because the radiation in infrared region (i.e. wavelength longer than 720 nm) accounts for 49% of solar energy received by the Earth [28]. The scattering rate depends on the difference in dielectric constants between additive and base material. Distinct dielectric constants between additive and base material give rise to a high scattering rate of coating. Thus, choosing an additive with a high dielectric constant or a base material with a low dielectric constant is feasible to obtain a high scattering rate. Normal base materials for thermal coating feature a dielectric constant around 3 (relative to vacuum), which is adequately low and has little room for further reduction. Therefore, the selection of additives plays an important role in improving the scattering rate of thermal coating. The titanium dioxide that exhibits a high dielectric constant makes an ideal candidate for thermal coating additive. In addition, heat insulation aggregates with low thermal conductivity can be used to improve the insulation capabilities of coatings. Because hollow glass beads possess a low thermal conductivity coefficient and a low density, they can act as an effective thermal barrier at the outer surface of coating. With the above considerations, titanium dioxide and hollow glass beads are chosen as the functional additives for reflective coating materials, which are then evaluated in terms of their reflective and thermal insulation performance.

The objective of this study is to characterize the reflective and insulation performance of coatings with different additives and to explore the working principles of different additives. In this research, two kinds of additives, i.e. titanium dioxide and hollow glass beads, are used. The thermal performances of pure acrylic coating, acrylic with titanium dioxide coating and acrylic with titanium dioxide plus hollow glass beads coating are measured and compared. The surface temperature and reflectance of various coatings are obtained from the experiment.

To explore the working principles, Finite-difference time-domain (FDTD) approach that can simulate the propagation of electromagnetic (EM) waves is employed for different coating materials (i.e. pure acrylic, acrylic with titanium dioxide), demonstrating how titanium dioxide particles enhance the reflection. It is envisioned that a coating material with high level of reflectance and insulation can be characterized and the working principles of different additives can be revealed, providing guiding instructions for picking suitable materials and giving insightful implications to novel design of reflective coating materials.

2. Experimental program

2.1. Materials

As one of most extensively used building materials, precast concrete was adopted as substrate material in this experimental program according to following advantages. Firstly, the shape and dimensions of precast concrete can be standardized, eliminating the requirement of supporting formwork in situ. Secondly, the quality of precast concrete can be standardized and is more reliable than that of concrete cast in situ.
In this study, two functional additives were used, i.e. titanium dioxide and hollow glass beads. Three types of coatings were prepared with different components. Coating A was an ordinary white acrylic emulsion; coating B was acrylic with titanium dioxide and coating C was acrylic with titanium dioxide and hollow glass beads. The preparation process for coating B is as follows. The acrylic emulsion and titanium dioxide were added into the mixing tank with a portion of water. The appropriate dispersing agent, wetting agent and anti-foaming agent were also used to promote the coating performance. The mixture was stirred at high speed to disperse evenly. Then, water was added to adjust the viscosity of coating and the reflective coating B with titanium dioxide was produced. The preparation process for coating C was similar to that of coating B. The only difference was that the hollow glass beads were added to the mixture after pigment dispersion, then the entire mixture was stirred at low speed before adding water. All coatings possess the potential to reflect solar radiation, reduce heat absorption, and thus reduce the cooling load.

2.2. Specimens

Four concrete panels were used in this experiment, namely panel N (reference uncoated concrete panel), panel A (covered with white acrylic emulsion), panel B (covered with acrylic emulsion and titanium dioxide) and panel C (covered with acrylic emulsion, titanium dioxide and hollow glass beads). Before the application of coatings, the surfaces of concrete panels were cleaned using detergent and water so that no grease and ash exists on the surfaces. The coatings were applied to the concrete panels through brushing. The panel samples were then put into laboratory environment for 7 days curing. The photos of panels covered with different coatings are shown in Fig. 1(b) and (c). It should be noted that the dimensions of the concrete panel are 450 mm × 200 mm × 60 mm (Length × Width × Height) and all concrete panels are identical.

2.3. Instrumentation and data collection

Halogen lamp was used as heat radiation source to model solar radiation, irradiating the panels consistently in the experiment. According to the standard solar spectrum from ASTM G 173, 5% of solar energy is distributed in the ultraviolet range (300–400 nm), 46% of solar energy is distributed in the visible range (400–720 nm) and 49% of solar energy is distributed in the near infrared range (720–2500 nm) [29]. The spectrum of the halogen lamp used in the experiment ranges from 380 to 3000 nm, covering the visible and near infrared regions, which are the major part of the solar spectrum in terms of energy constitution. Meanwhile, the functional additives mainly improve the reflectance of coating in the visible and the near infrared range. Based on above reasons, the halogen lamp can be used to simulate the solar radiation for studying the thermal performance and the relative cooling effect of the coatings containing different additives. The test environment for all specimens was set to be identical for mimicking similar weather and solar radiation condition in order to achieve a fair comparison. The schematic diagram and photo of test instrumentation are shown in Fig. 2 and the halogen lamp is placed above the tested specimens. The illuminated surface of panels in this experiment represents exterior surface of building (outdoor) and unilluminated surface stands for interior surface of building (indoor). During test, the radiation was kept on for 12 h continuously. The ambient temperature was kept the same as 25.6 °C throughout the test and it was consistent during the experiment for different samples. The temperature of both illuminated surface and unilluminated surface was measured at one-minute interval by thermocouples connected to data logger system. The range of temperature measurement is from −10 °C to 200 °C and the accuracy is ±0.5% or ±0.5 °C (whichever is greater). After radiation, the halogen lamp was turned off and the panel was cooled down until ambient air temperature. Then the panel was replaced by another one for next test. The surface condition and surrounding environment were the same for all panels, and the heat transfer at the side surfaces of different panels was consistent for all measurements. The thickness of samples was thin enough so that the area of side surfaces was relatively small compared to that of the front surface. The heat transfer at the sides would not affect the experimental findings. Through monitoring the variation of illuminated and unilluminated surface temperature, the thermal performance of panels covered with different coatings can be evaluated.

3. Experimental results and discussions

3.1. Surface temperature

The heat transfer of insulated surface under solar radiation can be described by the following equation:

\[
(1 - \alpha)l = \varepsilon\sigma(T_s^4 - T_{sky}^4) + h(T_s - T_a)
\]

where \(\alpha\) is reflectance of surface; \(l\) is total radiation on the surface; \(\varepsilon\) is emissivity; \(\sigma\) is Stefan-Boltzmann constant; \(T_s\) is the equilibrium surface temperature; \(T_{sky}\) is radiant sky temperature; \(h\) is convective coefficient; \(T_a\) is the ambient air temperature [30]. When the surface is under radiation, the surface reflectance of the objective is the governing parameter that affects the thermal performance of specimens.

The recorded temperature of illuminated surface and unilluminated surface of specimens covered with different coatings is shown in Fig. 3 and Fig. 4, respectively. In the first 200 min, both the illuminated and unilluminated surface temperature rose quickly. After that, the increasing rate slowed down, implying that the thermal equilibrium between specimen and environment was approached gradually. Meanwhile, the illuminated surface temperature of uncoated panel N and panel A was close to each other, which is far higher than the temperature of panel B and panel C specimen. These results demonstrate that the ordinary acrylic painting has little effect on reflecting radiation and reducing exterior surface temperature, while the coating B and C containing titanium dioxide can reflect more radiation, reducing energy absorption and the surface temperature of exterior wall significantly. The illuminated surface temperature difference between panel B and panel C is only 0.4 °C, implying that the effect of hollow glass beads on reflective performance is not significant. When it comes to the unilluminated surface temperature, an obvious temperature difference between panel B and panel C can be observed from Fig. 4. Due to the low density of hollow glass beads, it can be concluded that the hollow glass beads can effectively retard the
Fig. 3. The temperature variation against time (T-t curve) of illuminated surface in different samples.

Fig. 4. The unilluminated surface temperature variation against time (T-t curve) of different specimens.

heat transfer from the coating surface to concrete surface, forming a thermal barrier for the exterior surface.

3.2. Reflectance

The physicochemical and optical properties of the coatings with inorganic additions were tested following the China National Standard (GB/T25261-2010) [31]. The physicochemical properties of coatings containing titanium dioxide and hollow glass beads are listed in Table 1. The spectral reflectance of the coating B and C which ranges from around 250–2500 nm was measured through spectrophotometric. The calculated spectral reflectance of coating B and C is shown in Table 2. It can be seen that in the ultraviolet range, the reflectance variation is small and coatings show high absorption. In the visible and the near infrared range, the spectrum reflectance of reflective coatings is much higher than that of pure acrylic emulsion, leading to an improved solar reflectance behavior.

According to the US standard MIL-E-46136, the reflectance of different coating materials can be calculated. A panel painted with black enamel coating was used as a reference specimen. The reference specimen was tested under the same instrumen-

<table>
<thead>
<tr>
<th>Item</th>
<th>Qualification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition in container</td>
<td>No agglomeration, uniformity after stirring</td>
</tr>
<tr>
<td>Application property</td>
<td>Brush twice barrier-free</td>
</tr>
<tr>
<td>Film appearance</td>
<td>Normal</td>
</tr>
<tr>
<td>Stability of low-temperature storage</td>
<td>No lumps, gel and separation</td>
</tr>
<tr>
<td>Temperature change resistance</td>
<td>No change</td>
</tr>
<tr>
<td>Water resistance (96 h)</td>
<td>No blister, crack, flake</td>
</tr>
<tr>
<td>Scratch resistance (2000 times)</td>
<td>No grinning effect</td>
</tr>
<tr>
<td>Tack-free time/h</td>
<td>1</td>
</tr>
<tr>
<td>Alkali resistance (48 h)</td>
<td>No blister, crack, flake</td>
</tr>
<tr>
<td>Artificial weathering resistance (400 h)</td>
<td>No blister, crack, flake Color change ≤ class 1</td>
</tr>
</tbody>
</table>

Table 2 The spectral reflectance of coatings containing inorganic additives.

<table>
<thead>
<tr>
<th>Reflectance</th>
<th>Ultraviolet</th>
<th>Visible</th>
<th>Near infrared</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coating B</td>
<td>0.06</td>
<td>0.91</td>
<td>0.88</td>
</tr>
<tr>
<td>Coating C</td>
<td>0.06</td>
<td>0.95</td>
<td>0.87</td>
</tr>
</tbody>
</table>

Table 3 The temperature of specimens after 12 h radiation.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>Temperature (°C)</th>
<th>Reflectance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Illuminated layer</td>
<td>Unilluminated layer</td>
</tr>
<tr>
<td>N</td>
<td>48.5</td>
<td>40.1</td>
</tr>
<tr>
<td>A</td>
<td>47.6</td>
<td>37.5</td>
</tr>
<tr>
<td>B</td>
<td>41.3</td>
<td>34.5</td>
</tr>
<tr>
<td>C</td>
<td>40.9</td>
<td>34.0</td>
</tr>
</tbody>
</table>

The ambient air temperature during testing is 25.6°C. Based on this formula, the reflectance of different panels can be calculated. The measured surface temperatures and the reflectance of different coatings are summarized in Table 3. The illuminated surface temperature after 12 h radiation could reach up to 48.5°C for uncoated concrete panel N. The C specimen shows the lowest illuminated surface temperature, which is 7.6°C lower than that of N specimen. Through observing these temperatures, the reflection performance of different specimens can be evaluated. The illuminated surface temperature of panel A is only 0.9°C lower than that of N panel, meaning that the ordinary white acrylic painting is not effective in reflecting the solar radiation. Through adding titanium dioxide, the illuminated surface temperature decreases 6.7°C and reflectance increases from 0.21 to 0.76, which is observed in panel B, implying that coating titanium dioxide can reduce heat gain from radiation and improve the thermal reflection capability efficiently. The unilluminated surface temperature difference between panel B and C is 0.5°C, implying that the hollow glass beads are efficient in impeding heat transfer from coating surface to concrete surface.

3.3. Energy saving effect

The unilluminated surface temperature is used to represent the indoor temperature in order to evaluate the thermal impact of different coating materials on the indoor environment. The results demonstrate that application of the reflective coating containing
titanium oxide and hollow glass beads can decrease the indoor temperature and indoor temperature fluctuation significantly. The average unilluminated temperature of panel A is 3.5 °C higher than that of panel C. Based on experimental results, the energy saving effect through replacing the ordinary white acrylic painting by reflective coating containing titanium dioxide and hollow glass beads can be roughly estimated. The reflectance is now integrated with Transient Systems Simulation (TRNSYS) program to evaluate the cooling energy demand under annual weather condition at Hong Kong. A representative building is constructed. Simulations with and without reflective coatings are performed. It is a 3-story building with 10 × 15 m² area and 3.5 m layer height. Whole-year cooling demand for the entire building is calculated under the weather condition of Hong Kong. According to the results, the reflectance of solar radiation is set to 0.8 and 0.2 corresponding to the buildings with and without reflective coating, respectively. The cooling demand is defined as the energy required by air-conditioning system to maintain an internal temperature below 24 °C. As Hong Kong is located in the subtropical area, space heating is not needed so the heating requirement is not considered here. The whole-year cooling demand for the building model with and without reflective coating is 16694 kwh and 15750 kwh respectively. The saved energy is 944 kwh, occupying around 5.7% of the total cooling energy demand. The result shows an approximately 5% energy save in terms of cooling demand.

4. FDTD simulation

In order to figure out the working principles of TiO₂, FDTD (finite-difference time-domain) method is adopted to simulate the propagation of EM waves at the surface of reflective coating materials.

4.1. Model construction and simulation setting

Finite-difference time-domain (FDTD) method is implemented using Meep [33]. Two models are constructed for representing the pure acrylic paint and the TiO₂-embedded coating, as shown by schematic drawings in Fig. 5. The acrylic paint is represented by block area with relative dielectric constant equal to 2.5. The TiO₂ particles are represented by spheres with relative dielectric constant equal to 9 and 200-nm diameter. Referring to the typical TiO₂ concentration from existing experiments, the number of TiO₂ particles in a 40 × 40 μm² is calculated as 3373 [32]. These 3373 particles are randomly distributed inside the acrylic block. A dot source is placed 3 μm above the acrylic block. The top and bottom boundaries of the simulation box are set to be a perfect matching layer (PML) that can absorb electromagnetic (EM) waves. The left and right boundaries are set to be periodic, so the EM wave passing through the boundary from one side can re-enter the simulation box from the other side. A flux counter is placed on the top surface of the block, recording the flux with a wavelength ranging from 300 nm to 2500 nm. The reflectance of each model is calculated by dividing the reflected flux over the incident flux. The simulation keeps running until the flux intensity decays by 1/1000 of its peak, permitting a convergent calculation.

4.2. Reflectance of acrylic paint embedded with TiO₂ particles

In the simulation, the acrylic film is treated as an ideal dielectric, non-magnetic material with dielectric constant equal to 2.5. In this case, the reflectance of the plain surface can be calculated analytically by Fresnel equations, which link the reflectance to the refractive index and incident angle

\[
\frac{\Delta}{\Delta'} = \frac{n_1 \cos \theta_1 - n_2 \sqrt{1 - \left(\frac{\rho}{\kappa} \sin \theta_1\right)^2}}{n_1 \cos \theta_1 + n_2 \sqrt{1 - \left(\frac{\rho}{\kappa} \sin \theta_1\right)^2}}, \quad \frac{\Delta}{\Delta'} = \frac{n_1 \sqrt{1 - \left(\frac{\rho}{\kappa} \sin \theta_1\right)^2} - n_2 \cos \theta_1}{n_1 \sqrt{1 - \left(\frac{\rho}{\kappa} \sin \theta_1\right)^2} + n_2 \cos \theta_1}.
\]

Eq. (3) calculates the reflectance of s- and p-polarization incident from substance 1–2, with refractive index \( n_1 \) and \( n_2 \), respectively. Because solar radiation contains an equal mix of s- and p-polarizations and the incident angle ranges from 0 to 90°, the total reflectance can be calculated by Eq. (4).

\[
R = \frac{1}{2} (R_s + R_p), \quad R_{total} = \int \frac{R}{R}
\]

With \( n_1 = 1 \) (air) and \( n_2 = 1.5811 \) (square root of the dielectric constant of acrylic), a reflectance of 0.1634 is obtained. This result is in agreement with the result from numerical simulations (the average reflectance is 0.1584) shown by Fig. 6, justifying the validity of the simulation. It is also showed that the reflectance of acrylic coating is significantly improved with embedded TiO₂ particles. The reflectance of the TiO₂-embedded acrylic system shows fluctuated values at different wavelengths. Such fluctuations could be related to the dispersive nature of the TiO₂-particle system. With detailed simulation, we would further reveal how the TiO₂ particles reflect...
EM waves and demonstrate that the interval between particles is a critical parameter of the reflection.

4.3. Light propagation in a dispersive system of TiO₂ particles

Physical processes including reflection, refraction (at the macroscopic scale) and diffraction (at the microscopic scale) occur when EM wave meets the surface of a TiO₂ particle. Depending on particle size and wavelength, either the macroscopic or microscopic optics are applicable. When the size of the TiO₂ particle is larger than half of the wavelength, reflection and refraction would be the major physical processes occurring. Light propagation can be described by Snell’s Law. As shown in the schematic diagram in Fig. 7, the propagation path can be guided back to the outside. Following this mechanism, the radiation energy is partially reflected. However, since the light has already traveled for a distance inside the coating film and the energy is attenuated, the coating film is still heated. As a result, this process only provides limited improvement on thermal insulating capabilities of coating materials.

The microscopic optical process, diffraction, occurs when the size of the TiO₂ particle is comparable to one-half the wavelength. In this case, light behaves more like a wave and the propagation can be predicted by solving Maxwell’s equations in time domain over the space. The diffracted lights interfere with each other, leading to constructive or destructive interferences and redistributing the energy unevenly. Such microscopic optical process can be simulated by the FDTD method. In this study, an emissive dot source is employed to stimulate three systems including a free space, the air-acrylic interface and the dispersive particle matrix. The responses of these systems are shown in Fig. 8.

From Fig. 8(b) it is noticed that the interface between two dissimilar materials causes a one-time reflection, corresponding to the case of pure acrylic coating subjected to incident EM wave. On the other hand, multiple reflections are observed in the dispersive particle system shown in Fig. 8(c), corresponding to the case of TiO₂-embedded acrylic coating. The multiple reflections result from the dissimilar material property (dielectric constant) between the acrylic and the TiO₂. Lots of interfaces are generated between the acrylic base and the TiO₂ particles, leading to an enhanced reflectance. Such microscopic reflection patterns could explain how the incorporated TiO₂ particles improve the reflectance of the entire thermal coating film.

4.4. Absorbance of infrared radiation by glass

In addition to optics, microscale mechanics can also be involved in the interaction between solar radiation and substances. The vibration of molecules can be a temporary storage for radiation energy, which would later dissipate to ambient environment in the form of heat. Thus, the molecule acts as a barrier blocking the radiation. For example, water can absorb solar radiation specifically with
around 900-nm, 1100-nm, 1300-nm and 1800-nm wavelengths, corresponding to the frequencies of different vibration modes of water molecules. Such radiation absorbance can be observed and validated by comparing the solar spectrum with and without atmospheric absorption [34]. Under cloudless skies, solar radiation should be stronger than that under cloudy skies due to radiation absorbance by water. Similarly, in hollow glass beads O–H bond as well as other molecular bonds exist and can absorb near infrared radiation, making a storage of solar radiation energy. Because hollow glass beads are lighter than other components and they often concentrate near the upper surface of the coating, the energy gained from infrared radiation could dissipate through heat convection or radiation process to the air. The floating hollow glass beads can also act as a barrier blocking the heat conduction from ambient environment to internal layer of the coated wall. These two effects from the hollow glass beads additive contribute to the improved thermal insulating performance.

5. Conclusion

In this work, experimental studies on thermal properties of various coatings and numerical simulations that can simulate the EM wave propagation have been conducted. The coating material containing titanium dioxide and hollow glass beads leads to a drop in interior surface temperature, up to 3.5 °C, implying the prepared coating can effectively reduce heat absorption and cooling load for buildings, and hence the energy consumed by air-conditioning system can be saved significantly when the prepared coating material is applied to building envelope. Via numerical calculations, the propagation of EM wave in dispersive TiO₂-particle system at the macroscopic scale, as well as the microscopic scale, has been successfully examined. By investigating the propagation of EM wave at the interface between the coating material and air, it is found that the embedded TiO₂ nanoparticles can significantly improve the reflective performance of coating films. This work shows that the FDTD method is capable of predicting the optical properties of coatings and can provide insightful information for the design of novel thermal coating materials.

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References