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Using lightweight cement composite and photocatalytic coating to reduce cooling energy consumption of buildings

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HIGHLIGHTS

- Lightweight cement composite (LCC) has 80% lower thermal conductivity than concrete.
- Photocatalytic coating increases the solar reflectance of the LCC from 0.41 to 0.78.
- Heat gain through LCC is 33% lower than concrete after 9-h exposure to simulated sunlight.
- Heat gain through LCC with photocatalytic coating is 54% lower than that without coating.
- The combination of the LCC and photocatalytic coating reduces the heat gain by 69%.

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ABSTRACT

Solar reflectance and thermal conductivity are two main factors which affect the heat transfer through opaque building envelope and cooling energy consumption of buildings in tropical countries and other regions in summer season. Effects of a lightweight cement composite (LCC) with hollow cenospheres and a photocatalytic coating with titanium dioxide (TiO_2) on the thermal conductivity and solar reflectance were investigated. Individual and combined effects of the LCC and photocatalytic coating on the heat gain and surface temperatures of panel specimens exposed to simulated sunlight were evaluated under controlled experimental conditions in comparison to a conventional concrete of similar 28-day compressive strength.

The LCC has a thermal conductivity of 0.39 W/m.K, 80% lower than that of the concrete (1.98 W/m.K). The photocatalytic coating increases the solar reflectance of the LCC specimen from 0.41 to 0.78 without significant effect on the thermal conductivity. The LCC and photocatalytic coating reduce the heat gain in 9 h exposure to simulated sunlight by 33% and 54%, respectively, while their combination reduces the heat gain by 69%. The inner surface temperature of the specimens is reduced by 3.7 °C, 4.3 °C, and 8.0 °C after 9 h exposure to simulated sunlight due to the use of LCC, photocatalytic coating, and their combination. The results indicate that the energy consumption for cooling building interior can be reduced significantly by the use of the LCC, photocatalytic coating, or a combination of these.

1. Introduction

Buildings consume more than 40% of total primary energy (from natural sources, such as energy from coal and natural gas) in the world, and more than 70% of the building energy consumption occurs during operation by lighting, cooling, and heating [1]. Among the energy consumed during operation, a large amount is due to cooling the building interior, especially in tropical countries. In Singapore, for example, approximately 40–50% of the building electricity consumption is due to air-conditioning [2]. A significant part of cooling energy consumption is attributed to the heat gain through building envelope [3]. Although substantial amount of the heat gain is through windows, the heat gain through opaque building envelope is also responsible for a significant amount of cooling energy consumption of buildings in tropical regions [3]. Various approaches have been proposed to reduce heat gain through opaque building envelope such as reducing thermal conductivity, increasing solar reflectance, and increasing thermal mass of building envelope. Among various strategies, reducing thermal conductivity and increasing solar reflectance are most effective and economical for tropical countries [4].

Reducing thermal conductivity can be achieved by incorporating materials with low thermal conductivity such as mineral wool

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and polyurethane foam in walls and roofs of buildings [5–8]. For example, Huang et al. [7] investigated cooling energy consumption of buildings with and without insulation layers and found that the installation of a 50-mm extruded polystyrene board (0.035 W/m.K) in walls reduced annual cooling energy consumption by more than 80% in both Hong Kong and Singapore. However, the application of traditional insulation materials is limited mainly due to low fire resistance of organic insulation materials such as extruded polystyrene and polyurethane foam and concerns about human health (e.g. carcinogenicity) of inorganic insulation materials such as fiber glass and rock wool [9,10]. Additionally, low resistance to water absorption of some insulation materials such as perlite and mineral wool boards leads to significant increase in thermal conductivity during operation [11]. To ensure satisfactory insulation, a building envelope often includes multiple layers, e.g. a structural layer, an insulation layer, a fire protection layer, and a waterproofing layer. This complicates the construction process and increases the thickness of building envelope and duration and cost for the installation [12]. To simplify the construction process and reduce the duration and cost of installation, it is desirable to incorporate insulation materials into the structural layer and achieve insulation performance with a single layer building envelope.

In recent years, lightweight aggregates with low thermal conductivities such as perlite and expanded polystyrene beads have been incorporated into concretes to achieve lower densities and thermal conductivities for insulation purposes [13–15]. Since the mechanical properties of concrete are compromised with the decrease of density, many of these lightweight concretes are not able to meet the modern day requirement for structural applications due to low compressive strengths [16]. For example, Sengul et al. [13] developed lightweight concrete with a thermal conductivity lower than 0.6 W/m.K by using expanded perlite. Yu et al. [15] developed ultra lightweight concrete with a thermal conductivity approximately 0.1–0.2 W/m.K by incorporating synthesized porous aggregate from recycled glass. However, the 28 days compressive strength of these lightweight concrete were below 20 MPa. Huang et al. [17] developed lightweight cement composites with a thermal conductivity of 0.3–0.4 W/m.K and compressive strength of 44–48 MPa by incorporating cenospheres. Wu et al. [16] developed structural lightweight cement composites with compressive strength up to 70 MPa and thermal conductivity of less than 0.4 W/m.K using hollow cenospheres which is a by-product from coal combustion in thermal power plant. The specific strength of such cement composites is up to 0.047 MPa/kg/m^3, equivalent to normal weight concrete with a compressive strength of 110 MPa [16]. While these studies demonstrated the low thermal conductivity of the lightweight concretes or cement composites, more systematic studies on the direct implications on the thermal performance of opaque building envelope are needed.

Another approach to reduce the heat gain through building envelope is to increase the solar reflectance of building surfaces [18–21]. As one of the most widely used building envelope materials, conventional concrete has a solar reflectance of about 0.4–0.5 [22,23], which can be increased to 0.8 with various coatings [24–26]. For example, a 90-μm thick white acrylic coating on a cement board has a solar reflectance of more than 0.8 [26]. Studies demonstrate that increasing the solar reflectance of the rooftops from 0.1 to 0.2 to about 0.6 leads to more than 20% reduction of the cooling cost for buildings in California and Florida, which translates to savings of more than one billion USD per year in the United States [27]. However, the solar reflectance of building envelope is significantly reduced due to soiling by pollutants [24,28–30] such as black carbon (or soot). For example, Takebayashi et al. [30] studied the effect of soiling on the solar reflectance of rooftops with coatings from different cities in Japan, and found up to 30% reduction of solar reflectance after four years of exposure. Such reduction in the solar reflectance due to soiling increases the cooling energy consumption of buildings [31].

To overcome the negative effect of soiling on the solar reflectance of building surfaces and cooling energy consumption, coatings with high resistance to soiling have been developed based on various principles such as increasing hydrophobicity and incorporation of photocatalysts [32–34]. Although high hydrophobicity increases the resistance to the deposition of pollutants on building surfaces, substantial reduction of solar reflectance is still observed [32]. In contrast, experimental results indicate that coatings with photocatalyst can maintain the solar reflectance of building surfaces by removing pollutants such as black carbon and organics [33,34]. However, no information is available on the effect of such photocatalytic coating on thermal performance of buildings.

From the information above, structural lightweight concrete with low thermal conductivity in combination with photocatalytic coating can meet structural requirements and maintain the solar reflectance of building envelope. However, their effects on the heat transfer through building envelope need to be studied systematically to determine their individual and combined contributions to thermal performance of buildings. The objective of this study is to experimentally evaluate the contributions of lower thermal conductivity of a lightweight cement composite (LCC) and higher solar reflectance of a photocatalytic coating on the heat transfer of panel specimens exposed to simulated sunlight. The low thermal conductivity of LCC was achieved by incorporation of hollow cenospheres, while the high solar reflectance of photocatalytic coating was achieved by having a multi-layer coating consisting of a white base layer, a separation layer and a photocatalytic top layer.

2. Experimental details

To achieve the objective, a normal weight concrete and a LCC with comparable compressive strength and solar reflectance but significantly different thermal conductivities were prepared. A photocatalytic coating was applied on the LCC specimen to increase its solar reflectance. The heat gain and surface temperatures of specimens of the concrete and LCC with and without coating exposed to simulated sunlight for 9 h were compared and analyzed.

2.1. Concrete and lightweight cement composite specimens

ASTM Type I ordinary Portland cement was used for both mixtures and undensified microsilica (Grade 920E, Elkem Materials) was used in the LCC. The microsilica used in this study was whitish with lower carbon content compared to typical silica fume. The pozzolanic activity of microsilica mainly correlates to its amorphous SiO_2 content and specific surface area. According to the manufacturer, this microsilica contains about 88% amorphous SiO_2 and has a specific surface area of 15–35 m^2/g which meet the requirements of BS EN 13263-1-2005 [35] and ASTM C1240-15 [36].

Crushed granites with a density of 2650 kg/m^3 and a nominal maximum size of 10 mm and natural sand with a density of 2630 kg/m^3 and a fineness modulus of 2.66 were used in the concrete mixture. For the LCC, hollow cenospheres (QK300, Sun Microspheres, China) from fly ash generated by coal combustion in a thermal power plant were used as micro aggregate. According to the manufacturer, the cenospheres are extracted from fly ash by flotation method during which particles with densities lower than water were collected. Most of the cenospheres used in this study had particle sizes ranged from 10 to 300 μm with an average particle density of approximately 908 kg/m^3. The cenospheres are commercially available.