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Using photocatalytic coating to maintain solar reflectance and lower cooling energy consumption of buildings

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Solar reflectance is one of the main parameters that affect the heat transfer through opaque building envelope and cooling energy consumption. Deposition of airborne black carbon (BC) darkens the building surfaces and increases the cooling energy consumption. The objective of this study is to experimentally demonstrate that photocatalytic coating with TiO_2 is able to maintain solar reflectance of opaque building envelope and lower the cooling energy consumption. Portland cement mortar specimens were coated with transparent silicate coating (TSC), white silicate coating (WSC), and white silicate coating incorporating photocatalyst (PWSC). The solar reflectance, color, heat gain, and surface temperatures of the specimens exposed to a sun simulator for 9 h were determined at three different time points: 1) before BC deposition; 2) after BC deposition; and 3) after 300 h exposure to simulated solar irradiation in an accelerated weathering chamber. The BC deposition reduces the solar reflectance of the specimens by 51 - 56% and increases the heat transfer through the specimens exposed to the sun simulator by 27% - 123%, depending on the solar reflectance before BC deposition. The photocatalytic TiO_2 is able to remove black carbon and restore the solar reflectance and color of the PWSC specimen after 300 h of exposure to simulated solar irradiation in a weathering chamber. With the removal of black carbon, the heat gain and inner surface temperature of the PWSC specimen exposed to the sun simulator for 9 h are comparable to those before the BC deposition but 53% and 7.2 °C lower than those after the BC deposition, respectively. The results indicate that photocatalytic coating with TiO_2 is able to maintain the solar reflectance of opaque building envelope and lower cooling energy consumption of buildings.

1. Introduction

Urban temperature is rising due to global warming and population increase, thus increasing the energy consumption for cooling the building interior in tropical countries and during the summer months of temperate countries. The increased energy consumption of cooling may be attributed significantly to the interior heat gain through building envelope (façade and roof) [1]. The heat transfer pathways through building envelope include windows, walls, and roofs etc. Although a lot of heat is transferred through windows, heat transferred through opaque surface is also significant especially for buildings of masonry and reinforced concrete structures with low window to wall ratio. It is, thus, desirable to reduce the interior heat gain through opaque building envelope, which is affected significantly by the solar reflectance of building surface for given design and material of the building envelope. With higher solar reflectance, less heat is absorbed by the building surfaces, leading to less heat gain of building interior [2,3] and lower cooling energy consumption [4–6].

As one of the most widely used materials for opaque building envelope, conventional concrete has a solar reflectance of 0.4 - 0.5, depending on the solar reflectance of ingredient materials used, their relative proportions, and exposure condition [7,8]. The solar reflectance of building surface can be increased up to 0.8 by various coatings [2,9–11]. In 2010, an initiative was taken in New York to apply white coatings to the rooftop of buildings to increase the solar reflectance and reduce cooling energy consumption of buildings [12]. Studies demonstrate that increasing the solar reflectance of rooftops from 0.1 - 0.2 to about 0.6 leads to more than 20% reduction of the cooling costs for buildings, which translates to more than one billion USD per year in the United States [13]. Further, increasing the solar reflectance of urban surface area by 0.1 is equivalent to reduce 44 Gt of CO_2 emission [13].

The solar reflectance of building surface may decrease with time when exposed to ambient environment [2,14,15] mainly due to soiling i.e. deposition of particulate matters and microbiological growth [16,17]. Relevant laboratory and field studies [5,15,18–21] summarized in Table 1 demonstrate the reduced solar

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Table 1
Effect of soiling on solar reflectance and thermal performance of various coatings.

Reference	Specimens	Color	Initial solar reflectance	Exposure environment	Exposure duration, years	Solar reflectance after exposure	Maintenance method	Solar reflectance after maintenance
Kelen et al. [18]	Ceramic plates with acrylic coating	Light color	0.54–0.90	Outdoor exposure in São Paulo, Brazil	1.5	0.46–0.63	NA	NA
Levinson et al. [15]	PVC membranes	Light color	0.63–0.80	Outdoor exposure in 10 US cities	5–8	0.32–0.70	Wiping, rinsing, washing, bleaching	0.63–0.82
Paolini et al. [5]	Roofing membranes of modified bitumen, PVC or polyolefin	Various color	0.23–0.85	Outdoor exposure in 2 Italian cities	2	0.23–0.75	NA	NA
Shi et al. [19]	Cement based board with coating of acrylic emulsion incorporating TiO_2 rutile and glass microspheres	White	0.87–0.88	Exposed to simulated soiling with graphite ash slurry	NA	0.80	Washing with soap	0.86–0.87
Takebayashi et al. [20]	Roofs with high reflectance paint, composition unknown	White	0.73–0.87	Outdoor exposure in 5 Japanese cities	0.2–7.0	0.60–0.79	Washing with wet cloth	0.67–0.88
Xue et al. [21]	Films with Styrene acrylate copolymer, white cement, and TiO_2 rutile. etc	White	0.82	Exposed to simulated soiling of graphite ash slurry	NA	0.62–0.63	NA	NA

reflectance when exposed to ambient environment and simulated soiling processes. For example, Levinson et al. [15] studied the effect of soiling on the solar reflectance of 15 roof membranes from 10 cities in the United States and found 11 - 59% reduction of solar reflectance after 5 - 8 years of outdoor exposure. Thus, “aged solar reflectance”, which is defined as the solar reflectance after exposure to ambient environment, has become a criterion to evaluate the energy efficiency of building envelopes and products used. For example, the “2016 Building Energy Efficiency Standards for Residential and Nonresidential Buildings” from California Energy Commission [22] requires that the 3-year “aged solar reflectance” be higher than 0.63 for roofing products on low sloped roofs of nonresidential buildings. However, a lot of current coatings reported in literature and available on market may not be able to meet the requirement of the “aged solar reflectance” without regular and frequent maintenance, e.g. washing or bleaching (Table 1).

Research has been conducted to develop dirt resistant coatings with high “aged solar reflectance” for energy efficient buildings [19,23–25]. For example, white elastomeric roof coatings with high “dirt pickup resistance” have been developed by incorporating solid or hollow beads and chemical additives [25]. However, approximately 20% reduction of the solar reflectance was observed on these roofing products after exposure to a simulated soiling process [25]. As washing the building surface may not be cost effective [26], it is necessary to develop coatings with not only high initial solar reflectance (solar reflectance before exposure to ambient environment) but also with persistent solar reflectance and long term durability which require little maintenance.

Among various soiling pollutants, black carbon plays a major role in the darkening and decreasing in the solar reflectance of building surface because it absorbs solar radiation strongly in the wavelengths from 280 nm to 2500 nm [16,17,27]. Black carbon, refers to light-absorbing refractory carbonaceous matter, is released during the combustion of fossil fuels and biomass from various industrial and residential sources [28]. Favez et al. [16] studied the composition of soiling pollutants on glass surfaces exposed to climate conditions of six cities in Europe and found that 4 - 12% of the deposited pollutants by total weight were black carbon. Experimental results reported in literature [15] revealed that rinsing was not able to completely remove the black carbon deposited on roofing surfaces. Further, several buildings bear testimony that the BC deposited on building surfaces cannot be completely removed by rain considering that darkening and reduction of solar reflectance are widely observed on building surfaces in various cities around the world [5,15,18].

Self-cleaning coatings with photocatalysts (e.g. TiO_2, ZnO, and ZrO_2) have been developed in recent decades which can remove particulate pollutants deposited on the building surfaces [29,30]. Among various photocatalysts, TiO_2 is the most widely used due to its high photocatalytic reactivity, stability, and low cost [31]. It has also been observed and reported that photocatalytic coating with TiO_2 is able to degrade black carbon deposited on Portland cement mortar surface [30]. Hence, it is reasonable to hypothesize that photocatalytic coating with TiO_2 is able to maintain solar reflectance of opaque building envelope. The objective of this study is to quantitatively evaluate how the photocatalytic coating with TiO_2 can maintain the solar reflectance of opaque building envelope and lower the cooling energy consumption by removing black carbon from opaque surface. The correlation between the solar reflectance and heat transfer through specimens in a controlled experimental environment is investigated and discussed. Quantitative information on the effect of black carbon on the heat transfer through opaque building envelope is also provided.

2. Experimental details

Experiments were designed and conducted with three types of coatings applied on mortar specimens which represent typical wall and roof surfaces: (1) transparent silicate coating, (2) white silicate coating, and (3) white silicate coating incorporating photocatalyst. The specimens with these coatings have comparable surface texture and porosity. The black carbon was used as surrogate of atmospheric black carbon in particulate pollutants deposited on building surface and the photocatalytic removal of the black carbon was achieved through simulated solar irradiation.

2.1. Materials, specimens, and coatings

Mortar specimens were made by ASTM Type I normal Portland cement (also EN ‘CEM I 52.5N’) and natural sand with a fineness modulus of 2.66 and a density of 2630 kg/m^3. The materials were mixed in a Hobart mixer and filled into plastic moulds of 300 × 300 × 50 -mm vertically to obtain specimens with uniform thickness. After about 24h curing in the molds, the specimens were demolded and cured in a fog room at temperatures of 28–30 °C