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Application of glass beads as retro-reflective facades for urban heat island mitigation: Experimental investigation and simulation analysis

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ABSTRACT

Glass beads are the common main component of retro-reflective (RR) material applied to building envelopes for urban heat island (UHI) mitigation. In order to evaluate the influence of glass bead RR materials on the UHI mitigation, two glass bead RR samples with refractive index of 1.9 and 1.5 in white reflective layer, one prism RR sample and one white diffusive sample for comparison were produced for this study. Their RR angular distributions of reflection intensity were investigated by an emitting-receiving optical fiber system developed in our laboratory. Their solar reflectance at different incident angles was measured by thermal balance theory in the outdoor environment. Furthermore, the influence of these developed samples on UHI mitigation potential was evaluated at an example location of Osaka, Japan using a 2-D analytic model. It showed that the glass bead RR sample with refractive index of 1.9 is more effective for mitigating the UHI phenomenon, both increasing the urban albedo and reducing the proportion of solar radiation absorbed by urban canyons.

1. Introduction

Urban heat island (UHI) effect is a well known phenomenon that has been documented in hundreds of cities worldwide [1,2]. The temperature of cities continues to increase because of the UHI phenomenon and climate change [3], and leads to a rise in energy consumption for cooling [4,5]. Hence, to mitigate the UHI effect has become an important global issue. Many countermeasures of reducing the UHI effect are being implemented. Santamouris et al. [6] reviewed many articles relating to the UHI mitigation strategies, and showed that the mitigation strategies such as; highly reflective (HR) and emissive light colored materials, cool colored materials, phase change materials (PCMs) and dynamic cool materials used for building roofs or facades, increasing urban albedo, green roofs, etc. can significantly contribute to UHI mitigation and the improvement of urban environmental quality. Akbari et al. [7] showed existing UHI mitigation strategies in detail; such as development of HR materials, development of cool and green roof technologies, development of cool pavement technologies and urban trees that can decrease ambient and surface temperatures in cities. Furthermore, UHI mitigation leads to energy savings, improves urban air quality and ambient conditions, and helps to counter global warming (GW). Among these mitigation technologies for UHI mitigation, HR envelopes are still being researched by scholars globally. Gobakis et al. [8] developed a number of inorganic coatings both for buildings and the urban environment. The materials were characterized using X-ray diffraction (XRD) and differential thermal analysis (DTA) to verify their composition, and the optical properties of these materials were analyzed by measuring the surface temperature while exposed to the outdoor environment. Pisello et al. [9] implemented an experimental characterization and optimization of a new membrane for building roofs with the aim of contributing to the reduction of the peak ambient temperatures and improvement of the intense UHI phenomenon during summer. Cozza et al. [10] produced smart paints applied to building facades for UHI mitigation and energy conservation. A total of five different black colorants produced in laboratory have been mixed with commercial paints and have been compared to the standard black colorant usually used for building paints. It showed that the surface temperature on the back of a painted support is lower as the total solar reflectance is higher, thus can be used for building energy conservation. HR materials for practical application on building envelopes have been investigated by many researchers. Saber [11] investigated the R-value of reflective insulations using the hygrothermal model, hygIRC-C. The results showed that a horizontal specimen with downward heat flow results in the highest R-value, and the same specimen with upward heat flow results in the lowest R-

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List of symbols

$\rho_{ret\text{-}ang}$	the angular retro-reflectance of samples
$\rho_{ret\text{-}base}$	the retro-reflectance with incident angle of 7° of the base RR prism sample
$S(\lambda)$	the reflection intensity of these samples at different incident angles
$S_{base}(\lambda)$	the reflection intensity of the base prism RR sample at incident angle of 7°
$E(\lambda)$	the spectral distribution of hemispherical solar irradiance specified in ISO 9845-1 of International Organization for Standardization
ρ_{tp}	the overall solar reflectance of samples measured by thermal balance in the outdoor environments at different incident angles
q_r	the amount of short wave irradiance on sample surface
E_i	the global irradiance on the inclined reflecting plate
N	the refractive index of glass beads
H	the height of the urban canyons
D	the width of the urban canyon (or distance between buildings)
H_s	the height of façade's area hit by solar radiation
B	the solar elevation angle
φ	the solar azimuth angle
φ_s	the azimuth angle of building surface
λ	the latitude of simulation location
d	the sun declination
ω	the hour angle in the local solar time
x	the angle of inclination with the horizontal plane
θ_i	the angle of incident solar radiation on a vertical wall of building
E_d	the direct normal irradiance
A	the apparent extraterrestrial irradiance which takes into account the variations in the sun-earth distance
B	a dimensionless, represents an overall broadband value of the atmospheric attenuation coefficient for the basic atmosphere
G	the day of the year from 1 to 364
γ	an angle represents the angle under which the reflected solar radiation remains inside the canyon and hits the opposite façade and the pavement
P_{ot}	the proportion of the incident solar radiation reflected toward to the sky over the angle range from γ to +90°
P_{in}	the proportion of the incident solar radiation reflected toward to the opposite building and pavement over the angle range from −90° to γ
R_{alb}	the albedo of the 2-D urban canyon
P_t	the total reflection distribution of facades over the angle range from −90° to +90°

value. Solar reflectance of building envelopes and urban pavement represents an important optic-energetic property for the characterization of building energy performance for cooling and mitigating the summer UHI effect. Hence, to improve the solar reflectance of building envelopes is an effective method for UHI mitigation and energy saving of buildings in summer. Therefore, with the aim of improving the solar reflectance of roofs to help to mitigate UHI effects, many countermeasures of UHI mitigation strategies have also been carried out widely in Japan [12,13]. From 2010, HR roofing sheets were installed on the roofs of 70 schools in Osaka to mitigate the UHI effect and reduce building energy consumption. Yuan et al. [12] evaluated the long-term change in the solar reflectance of HR roofing sheets installed on the roofs of schools in Osaka over approximately 780 days to evaluate the durability of HR materials applied to actual building rooftops. Inoue [13] proposed and developed a thermal shielding film for UHI mitigation, and implemented field measurements of the developed thermal shielding film applied to the office building. The result showed that it could reduce adverse effects on the outdoor environments. HR materials can reduce cooling loads of buildings, especially in early afternoon during the summer. On the other hand, HR materials can increase heating loads in winter due to their high albedo [14,15]. HR materials are often combined with thermal insulation of building exterior walls to reduce the annual thermal loads together with the heating loads [16].

Most of these HR materials are applied to building roofs. HR roofs can reflect solar radiation to the sky if there are no high buildings around it. However, if there are high buildings nearby, part of the reflection will be absorbed by those neighboring buildings. In addition, HR materials applied to vertical surfaces can also reflect onto roads, causing them to become hotter, thus the total effect against the UHI is limited [17]. To solve this problem of HR materials used for vertical outer walls, a variety of retro-reflective (RR) materials began to appear on the market which can reflect the incident solar radiation backward to the incoming direction of sunlight. At present, several types of RR materials are commercially available in Japan. However, they are employed for various safety and decorative purposes and useful at night time when visibility is important under low light conditions. As for application to building envelopes, they are not in used practice.

In order to encourage the application of RR materials to building envelopes more widely, the RR performance of these materials are being studied. Nishioka et al. [18] evaluated the directional reflective performance of RR materials configured by a three-mirror and a four-mirror type of corner, using geometrical optical principles. The RR effective area of three-mirror or four-mirror type of corner reflectors was defined, and the relationship between the incident angle and the RR effective area was also examined. Rossi et al. [19,20] have tested reflection directivity characteristics of five RR samples and one diffusive sample using an optical apparatus, and evaluated the mitigation effects of RR materials in UHI scenarios by experimental campaign and a novel analytical model. As discussed by Rossi's studies, all RR samples show RR behavior only for low incident angles of sunlight. For higher incident angles, the solar radiation is mainly reflected specularly. The potentiality of RR materials for mitigating UHI was estimated in terms of "cooling potential". Comparing the cooling potential of a RR envelope to a diffusive reflective envelope, it showed that the cooling potential of a high-intensity prismatic RR sample with south-facing is about 1.5% better than the diffusive envelope at a latitude of 30°, as evaluated by the analytical model. Yuan et al. [17] have developed a type of RR material and investigated its durability and RR performance by evaluating changes in retro-reflectance for a long time period (about 485 days) exposed to the outdoor environment, showing no significant change in retro-reflectance. The influence of different reflective characteristics on the albedo of urban canyons was simulated and analyzed. The results showed the albedo of simulated urban canyons at a latitude of 31° with RR envelopes is the largest, about 6.1% larger than those with diffusive reflective envelopes and about 9.4% larger than those with mirror reflective envelope. Han et al. [21] have used EnergyPlus software to analyze the thermal-energy impact of RR envelopes and diffusive reflective envelopes in neighboring buildings in an urban context where