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Optical analysis of glass bead retro-reflective materials for urban heat island mitigation

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Abstract

Retro-reflective (RR) envelopes can reduce the urban heat island (UHI) effect. To develop a lower cost method for imparting RR properties to external wall surfaces, this research measures RR performance of RR surfaces made with glass beads. 8 glass bead RR samples were created, as well as 1 prism and 1 capsule type for comparison. Their angular retro-reflectance and angular distribution were measured by an emitting–receiving optical fiber system developed in our laboratory. It shows that the retro-reflectance of all RR samples at low incident angle with respect to the perpendicular is better than at high angles. The RR capacity of glass bead samples with a refractive index of 1.9 is better than those of 1.5. The retro-reflectance of prism sample is much larger than the all glass bead samples at incident angles up to about 60–70°. The performance decreased sharply at incident angles of 70° and above. At high incident angles, the glass beads are slightly better than prisms. This could make them better suited to apply to outer walls with the goal of reducing reflection of midday sunlight onto streets and buildings. Also, considering their simple construction, glass beads may be more cost-effective the prism in reducing UHI.

Keywords: Glass bead coatings; Retro-reflective (RR) capacity; Angular distribution; Optical analysis

1. Introduction

The urban heat island (UHI) effect is currently becoming very serious in urban canyons over the summer period. Therefore, many countermeasures to mitigate the UHI effect are being enacted globally (Wang et al., 2015; Cozza et al., 2015; Yang et al., 2015; Dabaieh et al., 2015; Pisello et al., 2014b; Bozonnet et al., 2013; Synnefa et al., 2006; Doulos et al., 2004). Solar reflectance of building coatings and urban pavement represents an important optic-energetic property for the characterization of building energy performance for cooling and to mitigate the summer UHI effect (Mari et al., 2013; Pisello et al., 2013; Rossi et al., 2014; Saber, 2012; Pisello et al., 2014a). Highly reflective (HR) materials applied as building outer walls have been investigated worldwide (Santamouris et al., 2011; Synnefa and Santamouris, 2012; Zou et al., 2014) including in Japan (Inoue, 2007; Nishioka et al., 2008; Sakai et al., 2009; Yuan et al., 2012). HR material is an acknowledged solution for energy savings and mitigation of the UHI effect. HR roofs have similarly been studied widely (Akbari and Gholizadeh Touchaei, 2014; Akbari and Matthews, 2012). HR roofs can reflect solar radiation to the sky if there are

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no high buildings around it. However, if there are high buildings nearby, part of the reflection will be absorbed by those neighboring buildings. HR materials applied to vertical surfaces can also reflect onto roads, causing them to become hotter, so the total effect against the UHI is limited. 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 back towards to the incoming direction.

In order to encourage use of RR materials more widely, the RR properties of these materials are being studied internationally (Rossi et al., 2014, 2015; Yuan et al., 2015b; Han et al., 2015). Rossi et al. (2014, 2015) have evaluated the mitigation effects of RR materials in UHI scenarios by experimental campaign and a novel analytical model. Five RR samples and one diffusive sample were chosen and their reflection directivity characteristics were tested by an optical apparatus. As discussed by Rossi's studies, all RR samples show an RR behavior only for low incident angles of sunlight. Then for higher incident angles, the radiation is mainly specularly reflected. 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 at a latitude of 30°, as evaluated by the analytical model. Yuan et al. (2015b) have developed a type of RR materials 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°N 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. (2015) 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 buildings are in close proximity. It revealed that reductions of cooling energy consumption under the RR context for both total energy consumption and cooling energy consumption of HVAC, by up to 8.2% and 9.8% in different metropolitan areas of the U.S. The result showed that a RR façade can reduce the energy required for cooling loads of buildings, and lessen the reflected heat of solar radiation in spatially-proximal buildings, thus reducing the UHI effects.

Glass beads and prism-arrays are the common main component of RR materials. Although those RR materials are employed for various safety and decorative purposes and useful at night time when visibility is important under low light conditions, for application to building envelopes, they are not commercially available in Japan at present. Thus, the development of RR materials suitable to apply to external walls of buildings has become an important issue. Our previous research on the geometrical-optics analysis of reflective glass beads (Yuan et al., 2015a) was an analytical study. In this contribution, for the purpose of exploring the value of a simple construction method of applying glass beads to external wall surface as a RR envelope on the wide scale, we produced several types of RR samples made with glass beads and paints, and measured their RR properties using optical apparatus. As glass beads are easier to manufacture or apply and expected to be less expensive and more convenient than prism or capsule RR materials, the RR performance comparison is essential for any future cost-benefit analysis.

2. Optical analysis experiment

2.1. RR samples

In this research, we made 8 types of RR samples coated with glass beads of either refractive index of 1.5 or 1.9, added at either $0.15\,\text{kg/m}^2$ or $0.30\,\text{kg/m}^2$, on top of a reflective surface of either white or silver paint. For comparison, 2 types of commercial RR sheet (capsule and prism) samples (KICTEC Corporation) were also used. All samples were 120 mm square plates. Additionally, because the glass covering could improve the durability of RR material as found in our previous research (Yuan et al., 2015b), the surface of samples were designed with a glass covering with high transmittance (visible transmittance 91.3%, UV transmittance 92.5%), a reflectivity of 2% and high strength.

As an example of the glass bead RR samples, Fig. 1 shows the surface appearance of glass bead RR sample, capsule RR sample and prism RR sample, taken with microscope (30 × magnification). Detailed characteristics of the 10 RR samples are in Table 1. Structures of those RR samples (glass bead sample, capsule RR sample and prism RR sample) are shown in Fig. 2a–c, respectively.

The evaluation on RR directional characteristics of those RR samples was carried out by spectrophotometer measurement in the laboratory.

For comparison of RR materials with diffusive reflection, white and black diffusive reflection samples with the same size as RR samples, were also created without glass covering, and their RR directional characteristics were also analyzed using the optical apparatus.

2.2. An emitting–receiving optical fiber system

As stated in the research of Yuan et al. (2014) and Rossi et al. (2015), the lab spectrophotometer measurement with an integrating sphere and pyranometer, could not be used to measure the optical characteristics of RR materials over different directions.

For this reason, we designed an emitting and receiving optical fiber apparatus as shown in Fig. 3, consisting of a