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A study on the durability of a glass bead retro-reflective material applied to building facades

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ABSTRACT

Heat from buildings contributes about 1/2 of the city's anthropogenic heat to the urban heat island (UHI). The ratio of heat emitted from building external walls occupies about 1/3 of the anthropogenic waste heat total in Japan. Retro-reflective (RR) materials applied to building facades instead of highly reflective (HR) materials for UHI mitigation are being studied. Glass bead RR material is one of the main RR material types. In this study, several glass bead RR materials with different refractive indices and different color reflective layers were developed. The long-term change in solar reflectivity and angular distribution of reflection intensity for these glass bead RR materials was evaluated for purpose of durability verification. The result showed that both the solar reflectivity and angular distribution of reflection intensity for these developed glass bead RR materials almost have no significant change after 368 days of exposure in the outdoor environment. Moreover, it is shown that the glass bead RR material with a refractive index of 1.9 has much better RR performance, compared to that with a refractive index of 1.5.

1. Introduction

1.1. Highly reflective materials for building envelopes

The urban heat island (UHI) phenomenon is a well-documented climatic change phenomenon in lots of large cities worldwide [1,2]. Especially in the summer period, the urban temperature is continuing to rise due to the UHI phenomenon and climate change [3], and leads to a vast increase in building energy consumption for cooling demand and affects quality of human life [4,5]. Thus, many strategies of mitigating UHI are carried out globally.

A research has shown that the surface temperature of buildings could be reduced by approximately 10 °C when the highly reflective (HR) coating materials were used [6]. HR envelope materials are still being researched as one solution to mitigate UHI effect. For the purpose of lowering the outdoor environment high temperatures and reducing the UHI effect in hot summer period, a new type of building rooftop membrane was selected and an experiment of surface features and optimization on the membrane were carried out by Pisello et al. [7]. Gobakis et al. [8] have developed several inorganic materials used in building envelopes for improvement of built environments. In order to verify the composition of these developed materials, X-ray diffraction and differential thermal analysis were used. In addition, the optical characteristics of developed materials were evaluated through surface temperature measurement in the outdoor environment. Several HR paints were developed for application to building external walls to mitigate UHI effect and save energy in buildings. The experimental verification of these HR paints was also carried out by Cozza et al. [9].

1.2. Retro-reflective materials for building facades

Most of the HR envelope materials noted above are applied to rooftops of buildings. However, some scholars have suggested that it is possible to replace the HR envelope materials with retro-reflective (RR) materials as building envelope materials to fight the UHI effect, since the RR materials can reflect the incident sunlight back towards sky and will not affect the surrounding buildings and roads [10–12]. However, currently these RR materials are usually only employed for various safety and decorative purposes. They are not used as building envelope materials, because the durability of these RR materials is still unknown and their costs for construction are relatively expensive. Thus, there is interest in research on RR materials for application to building facades.

RR materials are commonly made with one of two reflective components, glass beads or prisms. For glass bead RR materials, Rossi et al. [13,14] investigated the RR capacities of five selected RR materials using an optical apparatus, and showed that the RR capacity of these RR

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materials is strong when the incident angle is low, however the mirror reflection becomes stronger as the incident angle of light is varied from low to high values. It indicated that the glass bead RR materials are more effective when the incident angle of sunlight is low. Yuan et al. [15] implemented a simulation analysis of glass beads with different refractive indices of 1.5, 1.7, 1.9 and 2.2. The result of simulation analysis showed that the glass bead with refractive index of 1.9 is the most effective to mitigate UHI effect as RR envelope materials, compared to those with refractive indices of 1.5, 1.7 and 2.2. Yuan et al. [16] also developed several RR materials using glass beads with refractive indices of 1.5 and 1.9 and investigated the reflective directional characteristics of these developed glass bead RR materials using optical apparatus in the laboratory. The optical analysis showed that the RR material with a refractive index of 1.9 has the best RR capacity in terms of mitigating UHI effect and saving building energy. In addition, the difference between building envelope samples using glass microspheres and the same sample without the glass microspheres was compared in terms of retro-reflectivity at different incident angles of light. It showed that the envelope samples without glass microspheres have almost the same overall solar reflectivity, but the retro-reflectivity at different incident angles is very small, compared to the envelope samples with glass microspheres. Castellani et al. [17] developed new ceramic colored (light grey and dark brown) tiles with RR microspheres and showed the industrial continuous process of producing the new RR tiles in an economic and sustainable way. The optical performance of these RR ceramic colored tiles was evaluated by spectrophotometric, angular reflectance and colorimetric analysis. Morini et al. [18] investigated and compared the performance of three materials used for external wall surfaces, including a common ceramic commercial tile, a glass tile obtained by covering the ceramic tile with a transparent paint on which glass spheres are spread, and a barium tile obtained by spreading treated barium microspheres on the wet transparent paint on the ceramic tile. The spectrophotometric analysis indicated that the barium tile has the highest overall solar reflectivity (39%), compared to common ceramic tile (30%) and glass tile (32%). The angular reflectance analysis showed that both the glass tile and the barium tile have stronger RR behavior for most of the incident directions, compared to the common ceramic tile. The analysis on a potential in UHI reduction showed that both glass tile and barium tile are more effective to mitigate the UHI effect, compared to the common ceramic tile.

For prism RR materials, Nishioka et al. [10] used geometrical optical principles to analyze the RR characteristics of a three-mirror and a four-mirror type of corner RR samples. Yuan et al. [12] developed a type of prism RR material covered with a type of glass sheet. The durability of the developed prism RR materials was investigated by thermal measurement for a long-term exposure (about 1.5 years) in the outdoor environments. It was found that both the solar reflectivity and retro-reflectivity of the prism RR material showed no significant decrease. Additionally, a simulation analysis of different reflective characteristics on the urban albedo was implemented. It showed that the prism RR envelope applied to simulated buildings in an urban canyon has the largest potential in term of mitigating the UHI effect, compared to diffuse reflective (DR) and mirror reflective (MR) envelopes. Han et al. [11] analyzed the thermal-energy influence of RR and DR building coatings with inter-building effect (IBE) using EnergyPlus. The analysis results showed the RR building coatings are more effective for reductions of cooling energy consumption and total energy consumption of Heating, Ventilation and Air Conditioning (HVAC) in different metropolitan areas of the U.S.

1.3. Objective of this study

Previous studies on the geometrical-optics analysis of reflective glass beads [15] and development of glass bead RR samples as building envelope materials for UHI mitigation [16,19], and for possible application to building facades to fight the UHI phenomenon show great promise, however the durability of these developed glass bead RR materials must be ensured. Thus, this study aims to evaluate the long-term durability of developed glass bead RR samples through investigating the long-term change in solar reflectivity and angular distribution of reflection intensity for the developed glass bead RR samples when exposed to the outdoor environment.

Table 1
Characteristics of four developed glass bead RR samples.

Sample	Reflective layer color	Refractive index of glass bead (n)	Diameter of glass bead (μm)	Density of glass beads (kg/m^2)
Sample-1	White	1.5	106–850	0.30
Sample-2	White	1.9	106–850	0.30
Sample-3	Silver	1.5	106–850	0.30
Sample-4	Silver	1.9	106–850	0.30

2. Materials and methodology

2.1. Glass bead RR samples

As detailed in Table 1, a total of four glass bead RR samples (120 mm square plates) with a refractive index of 1.5 or 1.9 and a reflective layer of white or silver paint were made in this research. In addition, the surface of glass bead RR samples were coated with glass sheet with high strength, high transmittance (visible transmittance 91.3%; UV transmittance 92.5%), and a reflectivity of 2%, since it was found that the glass sheet covering could improve the durability of RR material in a previous study [12]. The surface appearance of these four glass bead RR samples are shown in Fig. 1. The structure of these glass bead RR samples is shown in Fig. 2.

2.2. Methodology of evaluating the durability of RR samples

In order to verify the durability of these glass bead RR samples under long-term exposure in the outdoor environment, the long-term change in solar reflectivity and angular distribution of reflection intensity for these glass bead RR samples was measured. In addition, a microscope was used to confirm the surface condition of the glass bead RR samples after about one year of exposure to the outdoor environment.

2.2.1. Thermal measurement in the outdoor environment

To evaluate the overall solar reflectivity of the four glass bead RR samples, thermal measurement was implemented in the outdoor environment. An experimental stand was set up on a roof at Osaka City University, Osaka, Japan (Longitude: 135.29°E; Latitude: 34.41°N), with no obstructions to the sky. The glass bead RR samples were attached to the upper surface of insulating material with thickness of 30 mm and square size of 120 mm using glue. T-type thermocouples were mounted at the center of the under-surface of the samples (under the steel plate, see Fig. 2) and the center of the bottom surface of the insulating material, providing a temperature profile over the thickness of the insulation. The appearance of experimental stand is shown in Fig. 3.

For the method to derive the overall solar reflectivity of developed glass bead RR samples, the total thermal balance of these samples' surface is considered (see Fig. 4). The method to obtain the overall solar reflectivity of each developed sample is detailed in Appendix A [20].

2.2.2. Optical analysis in the laboratory

The optical analysis of angular distribution of reflection intensity for these glass bead RR samples was investigated by an emitting-receiving optical fiber system, which was developed by our laboratory and detailed in previous research [16,19]. The emitting-receiving optical fiber