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Geometrical-optics analysis of reflective glass beads applied to building coatings

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Abstract

Replacing highly reflective envelope materials, retro-reflective materials (RRMs) used as building coatings can help to fight the urban heat island effect. The common component of RRMs are mainly glass beads and prisms. The use of glass beads is relatively wider. This paper presents a study on the reflective principle of a single glass bead. Retro-reflective directional characteristics of a glass bead were evaluated by simulation. It showed that the reflective directional characteristics of glass beads are different for different refractive index of glass beads. Among the 3 refractive indexes evaluated, the retro-reflective directional characteristics of glass beads are the most remarkable when the index is 1.93. Compared to the refractive index of 1.93, both a lower refractive index and a higher refractive index have a much wider reflective distribution on the glass bead surface. The reflective directional properties are affected by the refractive index of the glass bead, but almost unaffected by the angle and direction of the incident light.

Keywords: Retro-reflective material (RRM); Glass bead; Refractive index; Simulation

1. Introduction

Recently, the urban heat island (UHI) is becoming very serious in urban canyons, and therefore many countermeasures to mitigate the UHI effect are being enacted globally (Cozza et al., 2015; Yang et al., 2015; Synnefa et al., 2006; Doulos et al., 2004; Dabaieh et al., 2015; Pisello et al., 2014a; Bozonnet et al., 2013). 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 reduce the urban heat island effect (Pisello et al., 2013; Rossi et al., 2014; Akbari et al., 1999; Pisello et al., 2014b). Highly reflective materials (HRMs) applied as building coatings have been researched internationally (Santamouris et al., 2011; Synnefa and Santamouris, 2012; Zou et al., 2014) and in Japan (Sakai et al., 2009; Yuan et al., 2013; Inoue, 2007). HRMs are an acknowledged solution for energy savings and mitigation of the UHI effect. Highly reflective roofs (often called “cool 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. HRMs applied to vertical surfaces can also reflect onto roads, causing them to become hotter, so the total effect against the UHI is limited. Retro-reflective materials (RRMs) can reflect light back along the incident direction,

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thus it can counter the above problem by reducing the reflected sunlight reaching neighboring buildings and roads. Urban architecture coated with RRMs has the potential to reduce the UHI (Yuan et al., 2015). Although RRMs are employed for various safety and decorative purposes, they are not commercially available for use as building coatings in Japan. RRMs are useful at night time when visibility is important under low light conditions. In order to encourage use of RRMs more widely, the retro-reflective properties of these RRMs are being studied internationally. Nishioka et al. (2008) have evaluated the retro-reflective performance of retro-reflectors with three-mirror and four-mirror types by using optical principles, and Rossi et al. (2015) use an experimental and analytical study for the assessment of the angular reflectance of RRM samples.

2. Motivation

At present, most RRMs are often used in road signs, work clothes and the traffic safety field in Japan. The structure of existing RRMs is roughly classified into two types, one with glass beads and the other with prisms. Glass beads have been used in the form of an addition to road partition lines. In order to make these RRMs of reflective glass beads useful as building coatings to fight the UHI effect, their retro-reflective performance must be better understood. In this paper, a geometrical-optics analysis of the reflective properties of glass beads is carried out. The principle of reflective glass beads is described, and influence of the refractive index of glass beads and the angle of incident light on the position and outgoing direction of emitted light from the bead is evaluated by simulation.

3. The principle of reflective glass beads

When light strikes a glass bead, a part of the incident light is reflected by the glass air interface, and a part of the incident light is refracted by the glass air interface into the glass bead. The refracted light is reflected by the inner spherical surface of the opposite side (the reflective layer), back to the surface, where it is refracted again, and returned to the incident direction. The principle of reflection by glass beads is shown in Fig. 1.

3.1. Reflection and refraction of light ray

As shown in Fig. 2, when the light ray is incident on the interface of two media from media 1 with refractive index (n_1) to the media 2 with refractive index (n_2), part of the light ray is reflected by the surface of bead, the remainder is refracted at the interface into media 2. The formula of Snell's law is the following,

$$\frac{\sin\theta_i}{\sin\theta_t}=\frac{n_2}{n_1} \tag{1}$$

$$\theta_i=\theta_r \tag{2}$$

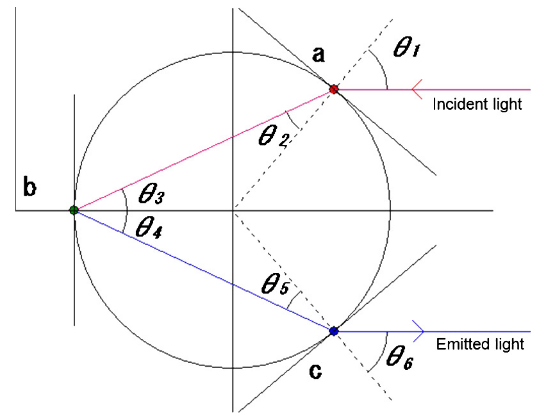

Fig. 1. Reflective principle of a glass bead.

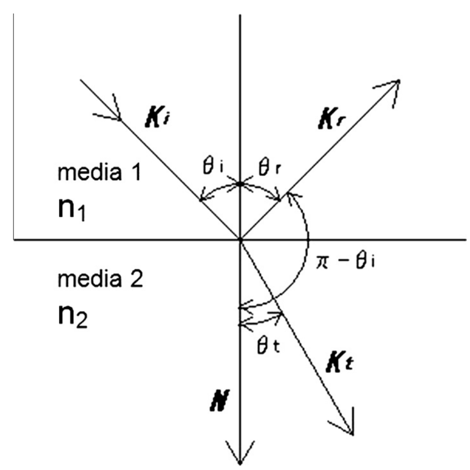

Fig. 2. State of reflection and refraction of light ray at the interface of two media.

where θ_i is the incident angle of light (°), θ_t is the refractive angle of light (°), θ_r is the reflective angle on the interface (°), n_1 is refractive index of media 1 (–) and n_2 is refractive index of media 2 (–).

3.2. Reflectance and transmittance

The reflection of light at the material surface varies greatly depending on polarization and incident angle. Polarization in natural light can be divided into two types, one is P-polarization and the other is S-polarization. The reflectance and transmittance of P-polarization and S-polarization are derived by the following formulas,

$$R_p=\left(\frac{\cos\theta_t-n\cdot\cos\theta_i}{\cos\theta_t+n\cdot\cos\theta_i}\right)^2 \tag{3}$$

$$R_s=\left(\frac{\cos\theta_i-n\cdot\cos\theta_t}{\cos\theta_i+n\cdot\cos\theta_t}\right)^2 \tag{4}$$

$$T_p=1-R_p \tag{5}$$

$$T_s=1-R_s \tag{6}$$