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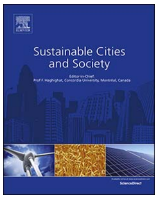

Optimized retro-reflective tiles for exterior building element

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ABSTRACT

Retro-reflective (RR) materials are innovative cool materials with the ability of reflecting most of the striking energy backwards and reducing the thermal energy kept inside the urban canopy.

The present work is aimed at introducing new optimized RR materials for building application by investigating and comparing their performance.

A base ceramic tile has been coated with glass beads: glass spheres (Glass) and clear solid barium titanate spheres (Barium). The experimental characterization showed that the base and the glass tile have a comparable global reflectance (30% and 32% respectively). The barium tile has a higher global reflectance, equal to 39%. Furthermore, the directional characterization showed that both the glass and the barium tiles have very strong retro-reflective properties. Moreover, the colorimetric analysis showed that the appearance of the base tile is kept almost unchanged when glass spheres are applied on it. A more evident change is observed when barium spheres are considered. Finally, the numerical simulations showed that the optimized RR materials applied on building envelope can increase the radiation energy reflected outwards the urban canyon up to 5% with respect to base materials, thus reducing the energy trapped within the urban canopy and thus the UHI effect at different latitudes.

1. Introduction

Data about urban population growing report that 66% of the world's population is expected to live in the cities by 2050 (Department of Economic and Social Affairs. United Nations, 2014). The urbanization process induces an increase of buildings density. In this way natural surfaces are replaced by artificial surfaces resulting in changes of thermal budget of cities (Douglas, Goode, Houck, & Wang, 2011; Kolokotroni, Davies, Croxford, Bhuyan, & Mavrogianni, 2010; Santamouris, Cartalis, Synnefa, & Kolokotsa, 2015; Stone, Hess, & Frumkin, 2010).

Urban Heat Island (UHI), that is typically an urban area characterized by warmer temperatures than its surrounding rural areas, affects the major cities worldwide (LBNL, 2017; Kolokotroni, Giannitsaris, & Watkins, 2006; O'Malley, Piroozfar, Farr, & Pomponi, 2015; O'Malley et al., 2015; Santamouris, 2007). The UHI affects building energy consumptions for cooling and peak electricity demand in summer, indoor and outdoor thermal comfort, pollution and the carbon footprint of urban facilities and utilities (Akbari, 1992; Kolokotroni et al., 2006; Rossi, Bonamente, Nicolini, Anderini, & Cotana, 2016). Its intensity is influenced by several factors, such as the canyon geometry, the building materials and the presence/lack of vegetation (Stathopoulou, Mihalakakou, Santamouris, & Bagiorgas, 2008; Santamouris, 2001; European Commission, 1996). Several mitigation strategies have been proposed to mitigate the UHI phenomenon. Among these, the impact "cool materials" and "green roofs" have been widely analyzed (Rossi, Anderini, Castellani, Nicolini, & Morini, 2015).

These techniques allow to mitigate the UHI phenomenon (Bonamente et al., 2013; Santamouris, 2014; Synnefa, Dandou, Santamouris, Tomborou, & Soulakellis, 2008; Taha, Hammer, & Akbari, 2002; Wang and Akbari, 2016; Yumino, Uchida, Sasaki, Kobayashi, & Mochida, 2015), to offset the CO2 emissions (Akbari, Menon, & Rosenfeld, 2009; Cotana et al., 2014) and to reduce the building energy consumption (Akbari, Levinson, Miller, & Berdahl, 2005; Synnefa, Santamouris, & Akbari, 2007; Santamouris et al., 2001).

Mesoscale modeling studies in (Morini, Touchaei, Castellani, Rossi, & Cotana, 2016; Morini, Touchaei, Rossi, Cotana, & Akbari, 2017a; Taha, 2008a; Taha, Konopacki, & Gabersek, 1999; Taha, 2008b) showed that increasing the urban albedo or vegetation can reduce the air temperature by 1–3 °C during the daylight hours. Rosenfeld et al. (Rosenfeld, Akbari, Romm, & Pomerantz, 1998) estimated that an increase of the urban albedo of 0.25 for 1250 km^2 of pavements in Los Angeles, induces a decrease of temperature equal to 1.5 K.

White and colored highly reflective materials, thermochromics

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materials, directionally reflective materials, and retro-reflective materials are the main technologies in the field of optimized cool materials (Akbari and Kolokotsa, 2016a). Among these, several typologies of cool materials are suitable and available on the market: white paints, white coatings, white pigments for tiles, concrete and shingles, cool-colored materials, thermo-chromic and retro-reflective materials (Anand et al., 2014; Akbari and Kolokotsa, 2016b; Ferrari, Libbra et al., 2016; Ferrari, Muscio, & Siligardi, 2016; Ferrari, Muscio, Siligardi, & Manfredini, 2015; Joваní, Sanz, Beltrán-Mir, & Cordoncillo, 2016; Levinson, Berdahl, & Akbari, 2005; Lei et al., 2017)

Typically, UHI generates when sun radiation energy is entrapped in urban canyon. Retro-reflective (RR) materials are particularly effective materials that can reduce the radiation energy in urban canyons. In fact the directionality of the reflected light would allow to reflect outwards the urban blocks, the urban canyons, and the urban canopy the incoming solar radiation, for different urban patterns. Multiple reflections between facing buildings or between neighbouring buildings with different heights, that typically happen when the vertical or horizontal surfaces are specular or multi-directional diffusive materials, might be avoided (Anting et al., 2017; Anting et al., 2015; Guntor, Mad Din, Ponraj, & Iwao, 2014; Li, Harvey, & Kendall, 2012; Morini, Castellani, Presciutti, Anderini et al., 2017; Narita, Tanabe, & Ozeki, 2001; Rossi, Morini et al., 2015; Rossi, Castellani et al., 2015; Rossi, Pisello, Nicolini, Filipponi, & Palombo, 2014; Yuan, Emura, & Farnham, 2014).

So far, traditional RR sheets for street sign application or early samples of RR reflective materials for building application have been investigated. In this paper, samples of tiles for exterior building application have been provided with microspheres that give them the property of retro-reflection.

Three samples have been investigated: a traditional ceramic tile, and two RR tiles. The ceramic tile has been chosen among the commercial ones commonly used for exterior application. It is a light brown colored tile and is characterized by a rough surface.

The aim of the paper is to propose the above mentioned new materials as an effective strategy to reduce the energy trapped inside the urban canyon and as an innovative solution to be introduced on the market of RR materials. As already said, in fact, RR materials available on the market are mainly related to street sign, automotive and high visibility clothes application. In the present work the main objective is to assess the optical properties of new RR tiles, obtained by commonly used materials for buildings and promote them as suitable exterior building elements for UHI mitigation.

2. Methodology

2.1. Samples preparation

For the purpose of this research, three samples have been investigated in order to compare their different behaviors in terms of reflectivity, directional properties and colorimetry. The selected samples (Fig. 1) have the following characteristics:

- Base tile: it is a common ceramic commercial tile. This type of tile is generally used for exterior applications. The base tile color is light brown.
- Glass tile: it is a RR material obtained by covering the Base tile with a transparent paint (for exterior application, UV resistant) on which glass spheres have been spread. The diameter of the spheres is 0.1–0.2 mm.
- Barium tile: it is an advanced RR material. It is obtained by spreading treated barium microspheres on the wet paint (transparent paint for exterior application, UV resistant) on the base tile. The microspheres dimension is in the order of 0.044–0.053 mm, with certified roundness of 91% and index of refraction 1.9.

The view of samples stricken by camera flash allows to notice the texture of the surfaces.

Residual dusts have been removed by the tiles in the preparation process. New and clean equipment has been used to spread the paint and the spheres. In this experimental campaign, all samples have been tested in a clean, dry condition.

2.2. Experimental work

In terms of RR materials characterization, the hemispherical reflectance of surfaces, the directional properties, colorimetric properties have been evaluated according to three main steps: spectrophotometric, directional and colorimetric analysis.

The spectrophotometric analysis allowed to assess the reflectivity of samples at different wavelength (300 nm to 2500 nm). By means of the directional properties analysis, the spatial distribution of reflected light has been investigated. The colorimetric analysis evaluated at what extent the application of the spheres makes the appearance of samples changing.

2.2.1. Spectrophotometric analysis of samples

Reflectance of the RR samples in the solar spectrum is measured by Shimatzu SolidSpec 3700 spectrophotometer equipped with 60 mm integrating sphere (https://www.ssi.shimadzu.com/products/literature/Spectroscopy/C101-E101D.pdf) as reported in Fig. 2. The spectrophotometer measurement range is 240–2600 nm, which include the 99% of the solar energy (Libbra, Muscio, Siligardi, & Tartarini, 2011). The value of solar reflectance RR is calculated as described in ASTM Standard G173-03 (ASTM E903-12, 2017;ASTM G 173-03, 2012). The purpose of these measurements is the evaluation of the global hemispherical solar reflectance even in terms of spectral distribution.

2.2.2. Directional characterization of samples

The investigation of directional reflectivity of samples has been performed using the ad-hoc experimental apparatus introduced in (Rossi, Castellani et al., 2015) (Fig. 3). In (Morini, Castellani, Presciutti, Filipponi et al., 2017) it has been demonstrated that the retro-reflectivity is kept at different wavelengths, therefore, the red wavelength (between 620 and 780) has been chosen to test the samples, since it is the closest to the highest value of sensitivity of the photodiodes (Fig. 4).

2.2.3. Colorimetric analysis of samples

A Portable Spectrophotometer CM-2500c Konica Minolta was used to carry out the colorimetric analysis (Website: https://www.konicaminolta.com/instruments/download/catalog/color/pdf/cm2500c_catalog_eng.pdf). Two colors might look the same to one person while having slight differences, that can be evaluated with a color measurement instrument. The used methodology follows the specifications of the International Commission on Illumination (French Commission Internationale de l'Éclairage, hence its CIE initialism) (Website: http://www.cie.co.at/index.php/Publications). The differences are indicated in absolute color coordinates and is referred to as Delta (Δ). CIE provides the formulas to calculate the difference between two colors to identify inconsistencies and help users control the color of their products more effectively (Website: http://sensing.konicaminolta.us/2014/04/identifying-color-differences-using-L-a-b-or-L-c-h-coordinates/?utm_campaign=Color+Differences+Blog&utm_medium=Email&utm_source=April+%2214+Color+Newslette). In the L*a*b* coordinates, L* indicates lightness ($\Delta L^* = L^*$ sample $-$ L^* standard; + = lighter, − = darker), a* is the red/green coordinate ($\Delta a^* = a^*$ sample $-$ a^* standard; + = redder, − = greener), and b* is the yellow/blue coordinate ($\Delta b^* = b^*$ sample $-$ b^* standard; + = yellower, − = bluer). ΔE* (positive) is the total color difference calculated as Eq. (1):

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (1)$$