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Directional and angular response of construction materials solar properties: Characterisation and assessment

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Abstract

Construction and building materials are generally considered Lambertian, namely they reflect as perfectly diffusive the radiation incident onto their surface. Thus, reflectance and absorptance are assumed to be constant and independent on the incidence and view angles. This assumption is not valid for specular materials, like glass or polished surfaces, where an angular dependence of their optical–radiative properties is observed. However, many opaque construction materials often show a mixed behaviour, which includes specular and diffuse (or scattering) reflectance components. Moreover, the apparent roughness of the materials surface changes according to the angle of incidence of the solar radiation. This issue is relevant for some cool materials, which are polished or treated with other methods to offer a very smooth surface, to increase the solar reflectance.

Herein, the angular dependent solar reflectance of the opaque materials and the impact on the solar gains and energy balance of the building envelope is investigated. The off-normal solar spectral reflectance of four typical construction material for roofing and façade systems is measured with a spectrophotometer, equipped with a large integrating sphere, and with a goniophotometer to characterise the directional reflectance. The comparison between reflectance values in the visible band obtained with both devices shows relative variations lower than 2% for materials with prevalent diffusing behaviour. Discrepancies up to 6% are observed for the samples with a perceivable specular component. Solar reflectance angular dependent curves are calculated, starting from measurements, to compare different models to compute the solar gains. A building energy simulation tools is then used to compute the differences between heat fluxes and energy needs obtained with reflectance angular dependent models and with constant solar reflectance. Discrepancies of the thermal fluxes up 0.7 kW h/m^2 in summer and 0.5 kW h/m^2 in winter are calculated, with relative variations exceeding 7%. Discrepancies of 1.7 kW h/m^2 in winter and 1.2 kW h/m^2 in summer are calculated for the heating and cooling energy uses of a reference building.

Keywords: Building envelope components; Directional solar reflectance measurements; Building thermal response

1. Introduction

The optical–radiative response of construction and building materials is important to assess the thermal behaviour of the built environments. This is crucial during the hot season, since the building energy need is ruled by solar gains (Coch and Serra, 1996). Obviously, most of the solar gains occur through the transparent components of the building envelope. However, the whole building balance is affected also by the thermal load due to the solar radiation absorbed by façades and roofs. The phenomenon is well known since hundreds years, as witnessed by the vernacular architecture in the Mediterranean region, where houses painted in white and light colours to modulate the

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Nomenclature

E	illuminance or irradiance [cd sr m^{-2} (or W m^{-2})]
I	solar radiation (W m^{-2})
L	luminance (or radiance) [cd m^{-2} (or W m^{-2} sr^{-1})]
D	relative spectral distribution of illuminant D65 (–)
S	relative spectral distribution of solar spectrum (–)
T	temperature (°C)
V	spectral luminous efficiency of photopic vision (–)
α	absorptance (–)
φ	azimuthal angle (°)
Φ	radiant flux (W)
λ	wavelength (nm)
θ	polar angle (°)
ρ	reflectance (–)
q	bi-directional Reflectance Distribution Function (BRDF) (sr^{-1})

Subscript

SG	solar gains
b	direct (beam)
cp	correlated colour
e	solar
g	global
i	incident
r	reflected (view)
v	visible

Superscript

b	direct (beam)
diff	diffuse
hem	hemispherical
nn	near normal

solar gains still populate villages and towns in the area. In recent years, solar control of the opaque building envelope emerged as a new strategy with two objectives:

- To reduce the cooling energy needs and consumption in buildings, which are in rapid increase according to actual data and forecast. The main causes of this increase are: the poor energy performance of actual building envelope and energy systems; climate change; increase of cooling appliance in emerging economy countries [IEA (International Energy Agency) 2013 Transition to Sustainable Buildings: Strategies and Opportunities to 2050]; and
- to mitigate the urban heat islands, namely the phenomenon because higher air temperatures are recorded within urban areas compared to those in an adjacent non-urban environment. This is due to many factors among which the reduction of air circulation in the urban fabric, the heat released by anthropogenic sources, the lack of vegetation, and the deployment of man-made materials with high thermal inertia and high solar absorbance. The urban heat island was monitored for the first time in the 19th century (Howard, 1833). Now it is registered for all climatic conditions, because of the global warming and urban sprawl that are taking place whatever are climatic, economic and social conditions. Thermal discomfort and health risks are correlated to this phenomenon (Perrin et al., 2006), as well as energy consumption in buildings (Santamouris, 2014). Several studies were aimed to propose mitigation strategies in order to improve urban microclimate (Synnefa et al., 2011; Akbari et al., 2001; Carnielo and Zinzi, 2013; Santamouris, 2015).

White, light coloured and cool coloured materials, being the latter produced using near infrared reflective technologies, result to be an efficient solution, since they reduce the absorption of the solar radiation incident on the envelope, by increasing the solar reflectance. These products include coatings, paints, membranes often manufactured as smooth as possible, in the attempt of reducing the absorption due to the surface (optical) roughness. This is the main difference between traditional materials, usually characterised by rough finishing and diffuse behaviour, and new solutions, with smoother and partly specular surfaces. The impact on the building performance is proved by several monitoring campaigns in real buildings (Bozonnet et al., 2011; Carnielo et al., 2011; Kolokotroni et al., 2011; Kolokotsa et al., 2011; Paolini et al., 2014; Parker et al., 1998; Romeo and Zinzi, 2013; Synnefa et al., 2012; Zinzi et al., 2012), and by software simulations of thermal comfort and energy needs in various climatic conditions (Akbari et al., 1997; Christen and Vogt, 2004; Suehrcke et al., 2008; Synnefa et al., 2007; Zinzi, 2010).

The solar reflectance is defined as the ratio of the global solar radiation reflected by a surface to the global solar radiation incident on it. It is independent of the incidence angle for diffuse reflectors, while for mirror-like materials it increases with the angle of incidence, according to the Fresnel equation. Levinson et al. (2010) computed the impact of the angular dependency of the solar reflectance on the solar heat gains of selective and non-selective, glossy and matte surfaces. However, some materials exhibit an intermediate behaviour, with direct and diffuse components, which can vary as a function of the angle of incidence.

The directional response of the reflectance is determined through the BRDF (Bi-directional Reflectance Distribution