



A novel approach to measuring the solar reflectance of conventional and innovative building components



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ABSTRACT

A fast integrated method for the measurement of solar reflectance of building's envelope components was developed. The method is based on a solar simulator and two pyranometers setup in a wind tunnel of controllable environmental conditions. The geometry was calibrated by spectralon standards and its validity was tested by measurements comparison with two standard methods of solar reflectance determination (ASTM standards E903-96 and E1918-06). A very good agreement was found and the developed method was applied for typical building's envelope components like cements, marbles, plaster, reflective paint. The method was also implemented for the solar reflectance determination of a specific NIR reflective compound of the form of calcium carbonate. Coupling of the reflectometer with the monitoring of additional solar-matter interaction processes extends its applicability as a precise, integrated and less time consuming method towards the characterization of “cool” materials.

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1. Introduction

Globally, buildings are responsible for 40% of the total world annual energy consumption and one-third of greenhouse gas emissions. A significant portion of this energy is used for lighting, heating, cooling, and air conditioning purposes in buildings. Unfortunately, the growing trend of energy use is expected to increase in the future due to climate changes, population growth and increase in the living standard. However, increasing awareness of the environmental impact of gas emissions and CFCs triggered a renewed interest in environmentally friendly cooling and heating technologies for buildings. Therefore, the research for materials and coatings for passive cooling techniques (e.g. highly reflective building components) towards energy conservation for buildings and urban structures has been considerably increased in the last years due to the need of reducing the cooling loads [1–3]. In almost all the proposed strategies, “cool” materials with high solar reflectance possess an exceptional position in their effectiveness for reducing the cooling energy needs of buildings [4]. Cool materials work by reflecting solar radiation and emitting the absorbed energy back to the atmosphere, therefore reducing indoors heat transfer by conduction (e.g. reduced cooling loads up to 93% [1]). A variety of “cool” products have been developed for several climate

conditions as white or colored coatings of high reflectance in the entire solar energy spectrum [2]. Since the application of “cool” materials in building's envelope will be increased in the future, the development of integrated approaches for the characterization of their effectiveness is of urgent need. Furthermore, the parameter of solar reflectance is also required to calculate the solar heat gains in buildings. Since it depends on the wavelength and the environmental conditions, any new method for the characterization of “cool” materials should be distinguished for its accuracy and ease.

Currently, two standard methods for lab and field solar reflectance measurements are based on ASTM E903-06 [5] and ASTM E1918-06 [6]. Both methods have advantages and drawbacks. The latter is measured as a function of time and requires homogeneous and low-sloped, dry surfaces such as roofs, streets, and parking lots. Additionally, the surface to be measured has to be large enough so that all the reflected radiation can be collected by the pyranometer facing downward [7]. Therefore, the method can be applied for large surfaces like installed roofs and pavements but presents difficulties with new materials and prototypes. Moreover, solar reflectance depends on the spectral and angular distributions of the incident solar radiation which varies during the year. Therefore measurements have to be performed with incident sun angles of less than 45 degrees on clear sunny days [6]. Alternatively, Akbari et al. proposed the E1918A method for smaller samples, where the pyranometer sensor is faced directly toward the target surface for three sequential measurements of radiation intensity [8]. A similar in situ procedure was also proposed by Li et al. [9] with the use of two pyranometers facing upward and downward. Similar

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in-field measurements were also recently reported by Pisello et al. for the determination of solar reflectance of gravel samples [10]. However, the albedometer shading effects can lead to non-negligible error and underestimation of the solar reflectance [7]. Additionally, a portable solar reflectometer has been proposed to be used in field with the ASTM C1549-09 [11] but the method's beam spot is small and an averaging procedure is usually required (at least three non-overlapping spots on each sample [12,13]) for characterizing "cool" materials' solar reflectances, increasing the uncertainty for non-homogenous surfaces. In addition, the test method requires that the surface to be tested should be dry [9].

In ASTM E903, small samples can be used for the determination of solar reflectance spectrophotometrically with an integrated sphere as a function of the incident wavelength. Even in this method, there are several factors influencing its validity and limiting its applicability. First, the sample irradiation beam spot in the large and expensive spectrophotometer is usually small ($0.5 \times 1.4 \text{ cm}^2$ for the PerkinElmer Lambda 950 instrument used in this work) and requires homogenous samples or non-instantaneous multi-runs. In addition, a standard solar spectral irradiance spectrum such as that described in ASTM Standard G173-03, is required in order to weight the measured data. The NIR content of the solar spectrum used to calculate NIR radiation depends on the chosen spectrum (e.g. E891 beam normal instead of air mass 1.5 global horizontal). Therefore, the selection of the normalizing standard spectrum is not universal and can introduce non-negligible uncertainty when applied for horizontal surfaces exposed to both beam and diffuse sunlight [14].

In view of the previous discussion, the primary objective of this work was to develop a time and wavelength integrated reflectometric method for the characterization of the solar reflectance properties of materials used in building applications. In this context, an integrated weather-independent solar reflectometer was developed in a bench top wind tunnel of controllable conditions by combining a vertical solar simulator and an inclined pyranometer on the top of the tunnel. The reflectometer was calibrated by spectralon standards and validated by measuring solar reflectance values of conventional building materials that were initially determined by the two ASTM standard methods with outdoors and lab measurements. Moreover, innovative "cool" materials of paints composites with cenospheres collected from fly ash were prepared and characterized by spectrophotometric measurements. Cenospheres are aluminosilicate-rich low density hollow particles generated as abundant and cheap by-products in coal firing powder plants [15]. They are extensively used as fillers in several products for reducing the weight of the composites and strengthen their mechanical, chemical and thermal properties while recently are studied as support materials for TiO_2 photocatalysis and heterojunction composites for water splitting [16–18]. In this work, we have mixed the cenospheres with blue paints in an attempt to create highly reflective coatings. This was confirmed by measuring the reflectance properties of the composites with the developed integrated reflectometric method.

2. Bench integrated solar reflectometer theory

Solar reflectance can be defined as the ratio of reflected light to total incident light on the surface. Due to the time and wavelength light variability, a double integration is required to determine the reflectance as

$$R_{\text{sur}} = \frac{\int_{T_{\text{day}}} \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} R_g(\lambda, t) \times I_g(\lambda, t) d\lambda dt}{\int_{T_{\text{day}}} \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} I_g(\lambda, t) d\lambda dt} \quad (1)$$

where R_g is the global solar reflectance, and I_g the global solar irradiance. T_{day} is the portion of the interval for which $I_g(t) > 0$ while the second integration is over the entire solar spectrum.

In the definition of Eq. (1), two cases should be considered. In smooth polished surfaces, specular reflection (or reflection) is observed where the angle of the reflected light is equal to the angle of incident light. When the surface is rough, diffuse reflection occurs and the reflected light is scattered in all directions (Fig. 1).

As it have been extensively analyzed by Akbari, Levinson and their colleagues in outdoors measurements [14], solar reflectance depends on the spectral and angular distributions of the incident solar radiation which varies during the year. However, a mean solar reflectance from pyranometer measurements at specific conditions can be calculated as

$$\bar{R} = \frac{\int_{T_{\text{day}}} R_g(t) \times I_g(t) \times dt}{\int_{T_{\text{day}}} I_g(t) \times dt} \quad (2)$$

where \bar{R} is the daytime mean solar reflectance. It has been shown by Levinson et al. [14] that the overall effect of the variable solar reflectance substitution with a fixed value R_j will be negligible in the estimation of cooling energy loads. In this context, we can assume that the fixed value can be determined by substituting the real outdoor conditions with a predefined benchtop solar simulated geometry with two pyranometers.

Moreover, solar reflectance in the spectrophotometric ASTM E903-96 method is considered constant in time but varies as a function of the incident wavelength. In this context, the mean value can be calculated as

$$\bar{R} = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} R_g(\lambda) \times P(\lambda) \times d\lambda \quad (3)$$

where

$$P(\lambda) = \frac{I(\lambda)}{I_{\text{tot}}} \quad (4)$$

is the intensity probability of a specific wavelength, $I(\lambda)$ is the spectral hemispherical total irradiance calculated from ASTM G173-03 [19], and I_{tot} is the integrated intensity from λ_{min} to λ_{max} . The accuracy of the reflectance calculation from Eq. (3) is more pronounced for increased surface roughness since both specular and diffuse reflections are detected with an integrated sphere.

However, light or radiation reflects (diffuse reflection) equally in all directions in a Lambertian surface which is almost valid in all the cases for building components. Therefore, the two integrations of Eq. (1) can be experimentally determined by keeping constant the vertical incident beam of solar simulation and pyranometrically integrate the reflected in a geometry of constant solid angle which has been a priori calibrated by Lambertian surfaces of standard reflectances. The unknown surface should be Lambertian which it is expected to be valid for surface measurements of polished or very fine reflective powder of building materials. In this context, the mean reflectance \bar{R} of an unknown Lambertian surface can be calculated as

$$\bar{R} = \frac{I_{\text{pyran}}}{I_{\text{solsim}}} \quad (5)$$

where I_{pyran} is the pyranometer response at a constant reflection angle and I_{solsim} is the simulated incident beam. It should be noted that the developed method is similar to the solar portal reflectometer method (ASTM C1549-09) but the used beam spot is much larger than the latter and comparable to the sample dimensions, which reduces the associated uncertainties with the averaging procedure of the combination of four detectors' responses. Additionally, ASTM C1549-09 requires the surface to be dry [9] since reflectance is

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