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Opaque construction materials solar loads calculation: Dependence on directional reflectance

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Abstract

Generally the solar reflectance associated to construction material surfaces is considered perfectly diffuse, namely they reflect in every direction the incident irradiance. Therefore reflectance and absorptance are assumed to be constant and independent on the incidence angles. This assumption, generally used in the most of energy analysis simulation tools, has to be considered not valid for materials characterized by a regular reflection, 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 behavior, which includes regular and diffuse (or scattering) reflectance components. Moreover, the apparent roughness of the materials surface changes according to the angle of incidence of the solar irradiance. 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. In this work the dependence of opaque materials on the directional properties of their surfaces are investigated to assess the impact on solar loads and energy performances of the building envelope. The reflectance shape and the hemispherical values of two materials used for roofing are measured by means of a goniophotometer to characterize the directional reflectance. A numerical analysis was carried out to compute the differences in solar loads during cold and hot seasons between a reflectance angular dependent model and a constant reflectance model. Sensible discrepancies between the two models put in evidence that solar reflectance angular dependence should be included in the calculation tools to achieve more accurate results.

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Keywords: Solar Loads; Goniophotometer; Lambertian; Directional Reflectance;

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1. Introduction

Buildings are responsible of 40% of the total national and Europe energy consumption. The European Directive 31 [1] establishes the need to adopt criteria for assessing building energy performances aimed at reaching low energy consumption standards for new and existing structures. Several studies on UHI mitigation techniques [2,3] and on the influence of urban climate on the building energy demand have been performed by means of BES [4-9] and CFD tools [10-13]. Several methods were proposed during the last years for improving building energy performance through envelope retrofit [14], passive ventilation [15], innovative glazed components [16], shading systems [17,18]. Talking about technical systems, innovative cooling technology has been studied [19-21].

Solar reflectance is a construction materials surface property concerning the assess of the selective capability to reflect the irradiance as a function of the wavelength. Aside from the spectral properties the assessment of the reflectance variation with the beam irradiance incidence angle is investigated. Reflectance ranges between a minimum value corresponding to a normal light beam incidence to a maximum one corresponding to a 90° incidence angle with a trend depending on surface roughness. Smooth surfaces present a regular (or specular) component with a magnitude dependent on incidence angle while rough surfaces present a reflectance value less affected by the incidence variation. Solar irradiance depends on latitude and change in intensity during the day. It can be divided into two components: diffuse and direct. While the first one hits a surface uniformly in every direction, the second one changes with the incidence angle. The energy and geometrical distribution of solar irradiance is typically taken into account in the thermo-physical tools while they assume as lambertian the reflectance of materials surfaces (perfectly diffusive with a constant distribution of hemispherical radiance and thus incidence angle independent). This assumption may not be valid for some actual materials that present a mixed behavior. This issue induces an overestimation of solar gains in the calculation of energy performances of buildings.

Cool materials are a particular category of materials that have high reflectance in the solar spectrum. They are able to reduce the absorption of solar irradiance limiting the surface temperature. These property keep building cool during hot season improving thermal comfort and energy savings. Moreover a massive use of this solutions in urban scale may induce a mitigation of the urban heat island effect [22,23]. This technology is now well-established especially with regard of coatings for roof applications. The latter generally present smooth surfaces with a reflection that has a not negligible regular component. In this perspective the study of reflectance solar dependence on incidence angle increase in importance for a correct estimation of energy gains in buildings.

Nomenclature

G	Solar Irradiance	[$W \cdot m^{-2}$]
Q	Solar Load	[$W \cdot m^{-2}$]
ρ	Reflectance	[-]
θ	Incidence Angle	[°]

Superscript

b	Beam
diff	Diffuse
hem	Hemispherical

Subscript

b	Beam
d	Diffuse
e	Solar
g	Global
v	Light (in the visible spectrum)

2. Methodology

Optical measurements were carried out on two materials by means of a goniophotometer at different incident angles of a light beam. The reflectance shape was obtained in order to assess the directional properties of the samples surfaces (diffuse and regular reflectance components).

A surface subjected to a diffuse irradiance generate a constant reflectance hereinafter indicated with $\rho_e^{diff-hem}$, where the first apex indicates the irradiance modality and the second apex the reflection modality, while the reflectance generated by an incident beam irradiance is angular dependent, hereinafter indicated with ρ_e^{b-hem}. Considering these assumptions and the conservation equation for opaque surfaces, $\alpha + \rho = 1$, the following equation for the solar loads can be written:

$$Q = G_b(\theta) \cdot [1 - \rho_e^{b-hem}(\theta)] + G_d \cdot (1 - \rho_e^{diff-hem}) \tag{1}$$

Most of building energy simulation tools assume as perfectly diffuse the opaque surfaces reflectance neglecting the dependence on the incidence angle. In such cases $\rho_e = \rho_e^{b-hem} = \rho_e^{diff-hem}$ and equation (1) is simplified as follow:

$$Q = [G_b(\theta) + G_d] \cdot (1 - \rho_e) = G_g \cdot (1 - \rho_e) \tag{2}$$

By means of a tested procedure the hemispherical reflectance values were extrapolated starting from the directional results.

The aforementioned values were used to find a correlation between incidence angle in the form of equation (1). The correlation was used as input in a numerical analysis to compare the solar loads obtained with a incident angle dependent reflectance method and with the constant reflectance method preset in most of software.

3. Tested Materials

Two materials generally used as roofs external coatings with different surface finishing were selected for the experimental campaign:

- Polished polyvinylic membrane, Fig. 1(a);
- Bituminous shingle, Fig. 1(b).

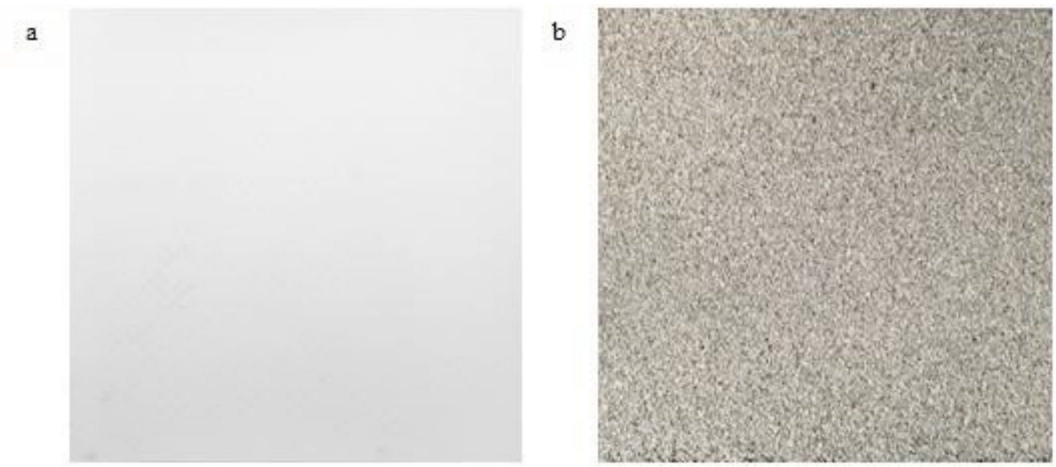

Fig. 1. Selected samples.

4. Experimental

The luminance, expressed in nit (cd/m^2), is the luminous intensity per unit area reflected by a surface hit by a light beam. The luminance distribution on a plane normal to the sample surface and passing from the center of it was measured by means of an experimental goniophotometer [24]. The two samples were tested at four incidence angles of the light beam: near normal (8°), 30°, 45° and 60°. The incidence angle is considered 0° when the light beam hits a surface normally, while is 90° when the light beam is parallel to it. The used optical bench is composed by the following elements:

- A tungsten halogen lamp with adjustable power, ranging from 100 to 400 Watt and covering the visible spectrum emission. A system composed by three lens with different focal distance assures the focus and the collimation of the beam on the sample surface, see Fig. 2(a);
- A mechanical system of two rotational axes equipped with a luxmeter able to scan the space around the sample drawing a sphere centered on the sample-holder, see Fig. 2(b). The luxmeter measuring range is confined between 0 and 5000 Lux with 1 Lux of resolution.
- The sample-holder can rotate in order to vary the beam incidence angle, see Fig. 2(b);

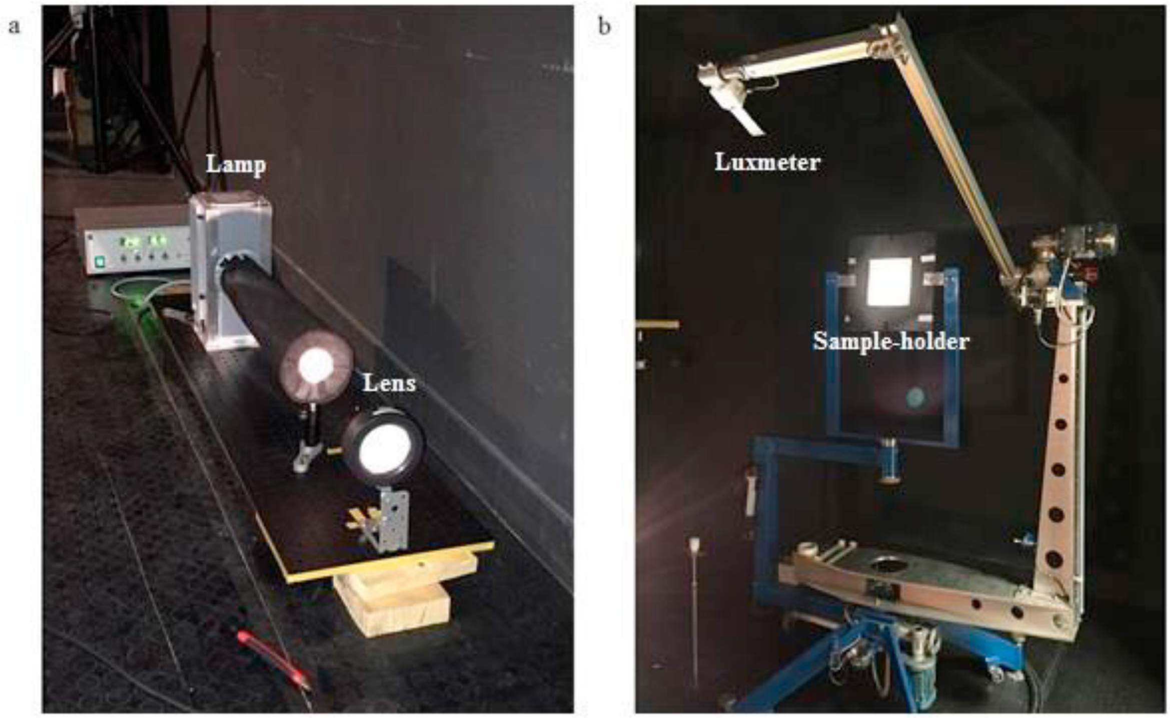

Fig. 2. (a) Light source; (b) Optical bench in measuring configuration.

5. Numerical Analysis

Solar irradiance data extracted from the World Meteorological Organization (WMO) database were used to calculate solar loads on five orientations (the four cardinal points and the horizontal) of a reference building composed by a unique thermal zone with a plant area of 100 m^2. Two calculation model were considered to obtain solar loads: A solar reflectance incidence angle dependent model obtained using the experimental results and following the equation (1), hereinafter called ADR and a constant reflectance model, hereinafter called CR. Three Italian localities were considered: Turin, Rome and Palermo.

6. Results

6.1. Experimental

The luminance distribution of the selected samples carried out with the goniophotometer is presented in Fig. 3 and Fig. 4.

The polyvinylic membrane sample in Fig. 3 present a relevant regular reflectance component. It becomes progressively very pronounced with the incidence angle following almost directly the Fresnel Law. Considering an incidence angle of 8° the regular component is comparable with the diffuse one, the same does not apply for the other angles. At 60° the regular component is almost 8 times higher than the one at 8°.

The bituminous shingle luminance distribution in Fig. 4 does not present precise regular components, but shows reflection in the same semi-plane which contains the incident light beam. This phenomenon is due to the presence of small sized gravel granules. The specularity of their surfaces reflects back the light beam especially at high incidence angles.

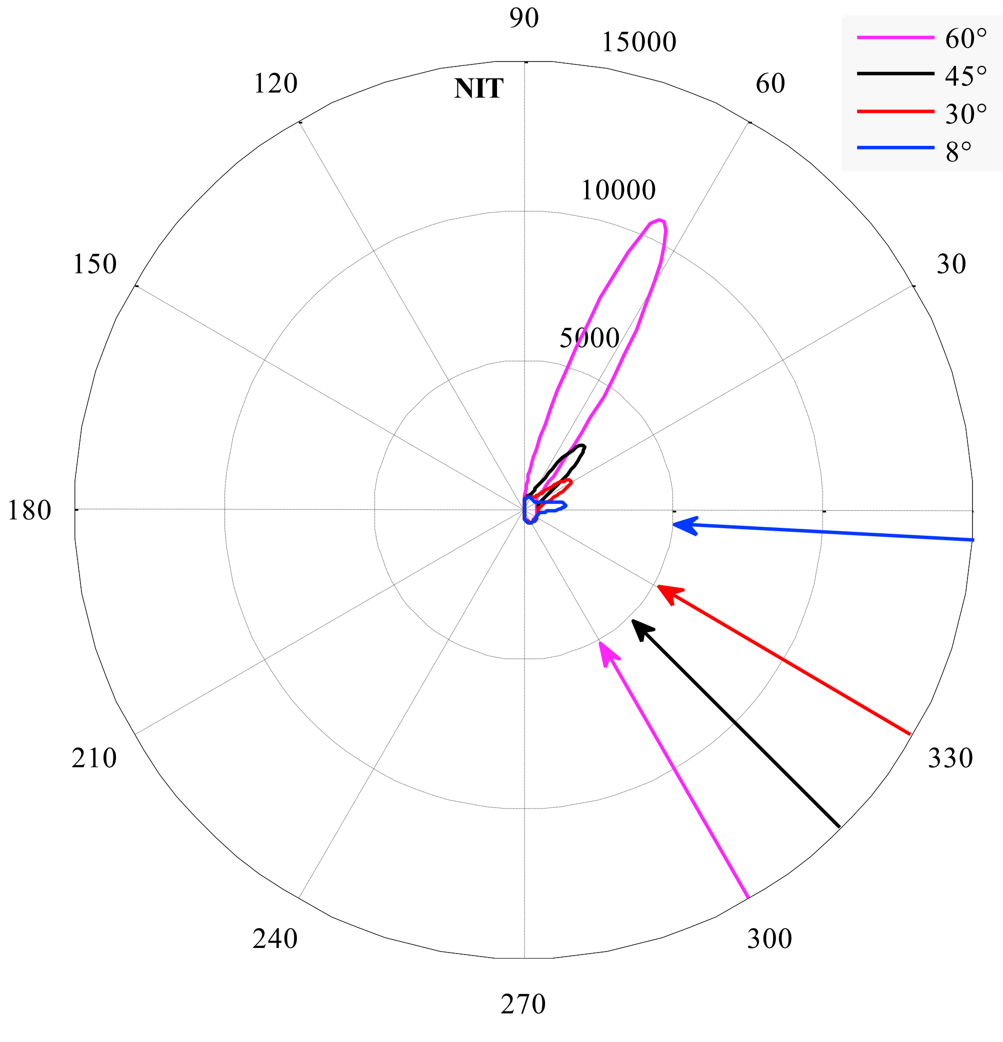

Fig. 3. Polyvinylic membrane: Luminance distribution on a plane normal to the sample.

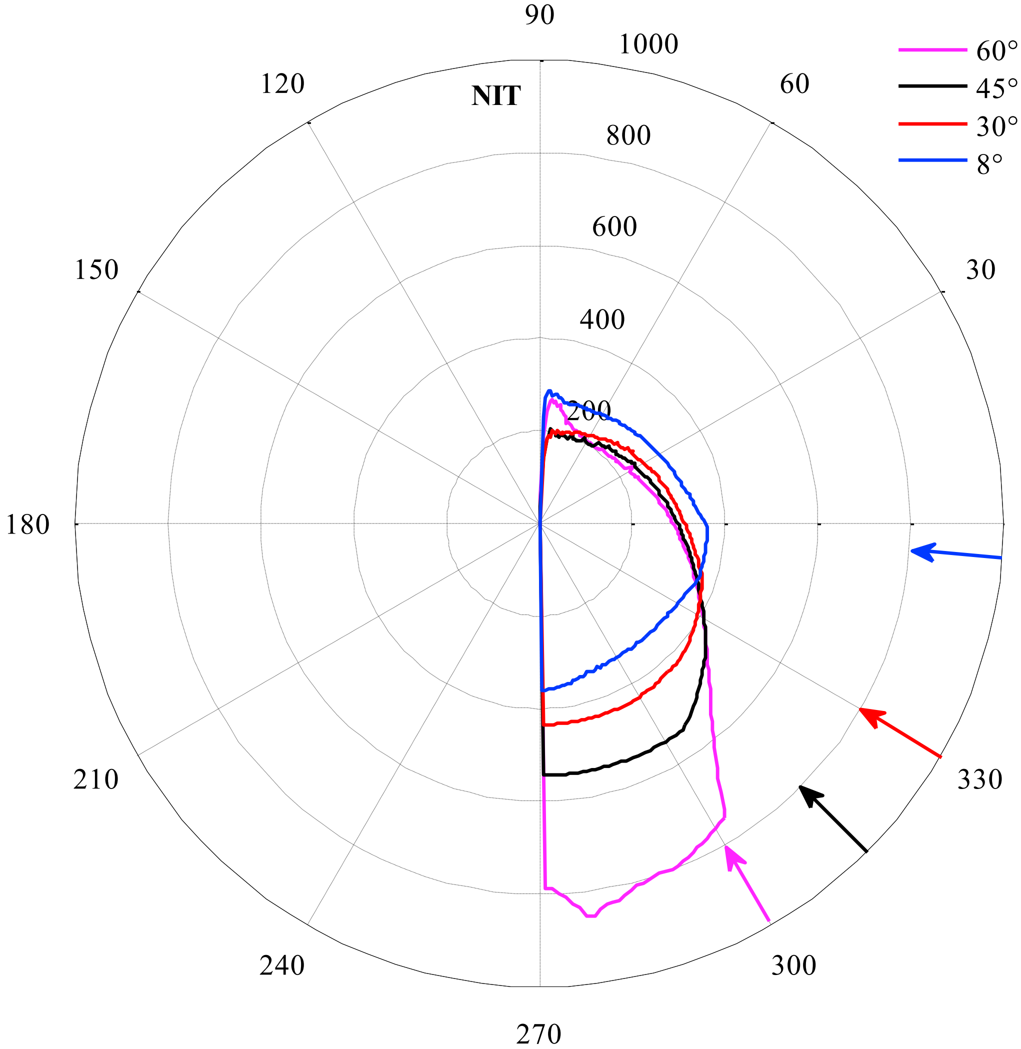

Fig. 4. Bituminous shingle: Luminance distribution on a plane normal to the sample.

Once the luminance measurements were performed, the reflectance values in the visible spectrum were calculated as the ratio between the sample luminance and the reference luminance obtained from a high reflective and calibrated sample in Spectralon. The results obtained for a normal plane were extended in the whole space by means of a tested procedure reported in a previous work [24] obtaining the hemispherical reflectance in the visible range. The following Table 1 shows the light reflectance results of the two samples at the four incidence angles of the light source.

Table 1. Hemispherical light reflectance of the selected samples.

	ρ_v			
Sample	8°	30°	45°	60°
Polyvinylic Membrane	0.51	0.52	0.53	0.57
Bituminous Shingle	0.30	0.30	0.32	0.37

6.2. Numerical Analysis

Starting from the experimental results contained in the previous Table 1 it was possible to extract a correlation between the incidence angle and the hemispherical light reflectance values of polyvinylic membrane sample. The light reflectance values were extended to the whole solar spectrum being the sample not spectrally selective as reported in a previous work [25]. The correlation $\rho_e^{b-hem}(\theta)$ was inputted in the equation (1) to obtain the solar loads with an angular dependent reflectance method (ADR). Table 2 presents the solar loads in MJ/year·m^2, obtained with the two considered assessment methods of solar reflectance: the aforementioned angular dependent (ADR) and constant one (CR). The percentage variation between the two methods is also reported. Solar loads calculated with ADR are lower than the ones calculated with CR for every orientation and latitude.

Table 2. Solar loads calculated with reflectance angular dependent method (ADR) and constant reflectance method (CR).

		Solar Loads [MJ/year·m^2]				Variation [%]	
		ADR Method ρ(θ)		CR Method ρ=const			
		Winter	Summer	Winter	Summer	Winter	Summer
Turin	Hor	281.5	798.0	314.2	832.9	10.4	4.2
	North	96.7	245.7	96.7	253.3	0.0	3.0
	South	431.6	436.8	448.7	480.1	3.8	9.0
	East	194.2	441.3	206.6	456.6	6.0	3.4
	West	192.6	473.3	205.2	491.0	6.1	3.6
Rome	Hor	346.2	960.7	385.3	1010.3	10.2	4.9
	North	110.2	250.3	110.2	260.6	0.0	4.0
	South	498.7	472.4	522.2	537.8	4.5	12.2
	East	226.7	540.6	241.4	567.0	6.1	4.7
	West	240.1	539.6	255.8	565.9	6.1	4.6
Palermo	Hor	409.8	987.8	450.3	1034.4	9.0	4.5
	North	123.6	254.5	123.6	266.3	0.0	4.4
	South	524.9	429.3	553.2	492.5	5.1	12.8
	East	253.5	532.9	269.8	558.7	6.0	4.6
	West	260.5	549.2	278.1	576.4	6.3	4.7

Sensible solar loads variation, higher than 9%, were found for the horizontal during winter and for south orientation during summer for all the three latitudes. The maximum variation was 12.8%, registered for Palermo south orientation, during summer season.

7. Conclusions

Solar reflectance is incidence angle dependent as demonstrated from the experimental campaign reported in this study. Two roofing materials samples were tested showing the extent of this dependence as a function of surface roughness. A procedure was applied on the reflectance shape to obtain the hemispherical values in the visible band. The function that links the reflectance to incidence angle was used to find an accurate method of calculation of solar loads. This method was compared to the constant reflectance method typically used in the thermo-physic models.

The results show an underestimation of reflective power of materials in the constant reflectance method leading to an overestimation of solar absorptance and thus of solar loads. The percentage difference between the two methods reaches not negligible values especially for horizontal and south orientations respectively in winter and summer [26, 27]. The calculation method for reflectance proposed in this paper demonstrated the limits of the thermo-physic models generally used to perform energy analyzes. Further developments will concern a more detailed thermal analysis on building scale in order to assess this different approach in the reflectance evaluation on space heating and cooling energy demands, considering the influence of different levels of thermal insulation for the building envelope. Another future study will concern the impact of these materials on outdoor urban microclimate conditions and their effects on energy demands when they interact with other buildings and city structures in an urban context.

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