INFLUENCE OF THE IRRADIANCE SPECTRUM ON SOLAR REFLECTANCE MEASUREMENTS

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ABSTRACT

Solar reflectance is the key performance parameter of cool roof and cool pavement materials. For its assessment, the measured spectral reflectivity of the sample is weighted by a reference spectrum of solar irradiance. Several standard and non-standard spectra are however available, taking into account different climate conditions, angle of incidence of the solar beam, contribution of the diffuse radiation content.
This study is aimed at investigating the impact of using different solar irradiance spectra as specified by existing standards or suggested by qualified research institutions, and verifying if those spectra can yield equivalent solar reflectance values from the viewpoint of assessment of standard performance and comparison of commercial products. Several actual material are considered, either white or coloured ones and with assorted spectral behaviour.

KEYWORDS

Cool roof, cool pavements, cool colours, solar reflectance, solar irradiance spectrum

1 INTRODUCTION

Cool roof and cool pavement materials, characterized by high values of solar reflectance and thermal emittance, are probably the best solution to limit summer overheating of buildings and the urban heat island effect (Akbari, 2012; Santamouris, 2011, 2012). In particular, solar reflectance is the key parameter as it measures the ability of a material to immediately reflect the incident sunlight. In order to calculate this parameter, the measured spectral reflectivity of the samples is integrated with spectral values of the solar irradiance that try to reproduce the actual amount of solar radiation reaching a building or pavement surface. As it is generally easier to measure the reflected fraction of incident sunlight than the absorbed one (Levinson, 2010), solar reflectance is commonly specified for cool materials, whereas solar absorptance is more often found in standards for calculation of building performance such as ISO 13790. For an opaque surface, however, its solar absorptance is usually determined by subtracting the solar reflectance from unity.
Several standard spectra of solar irradiance are available, taking into account different climate conditions, angle of incidence of the solar beam, contribution of the diffuse radiation content, etc. A largely used hazy sky air mass 1.5 beam normal spectrum (E891BN) is provided by the ASTM E891 standard. In fact, while ASTM E891 was withdrawn in 1999, its E891BN spectrum is still employed via ASTM E903 and it is someway incorporated (see Levinson

2010, 2010a) also into ASTM C1549 – currently the most utilized standards for calculation of solar reflectance.
The E891BN spectrum takes into consideration bean normal solar radiation because it was intended for prediction of solar concentrator performance. For the same reason, air mass 1.5 is considered as it is close to the mean condition at which beam-normal solar energy is delivered in most relevant locations of the U.S.A. A hazy sky condition is also considered, with spectral optical depth of the atmospheric aerosol as large as 0.270 at 500 nm, since this was assumed to be an average condition for the U.S.A. Usage of the E891BN spectrum, however, is questioned by Levinson et Al. (Levinson, 2010) as it allows best predicting mean solar heat gain along the whole year, whereas it is a matter of fact that building overheating and the urban heat island phenomenon show up mostly in summer, that is for peak solar heat gain. Building air conditioning systems are typically sized to meet annual peak cooling load rather than annual mean cooling load. Moreover, most pavements and large roofs are approximately horizontal and, consequently, they tend to be most strongly irradiated when the sun is high and the sky is clear. On the other hand, a zenith sun (air mass 1) is shown to reasonably approximates the solar position of annual peak global horizontal solar irradiance in the mainland U.S.A. (Levinson, 2010), and the same can be shown to occur in Southern Europe, where air mass is always below 1.2 throughout the whole summer (Fig. 1: Athens, Rome).

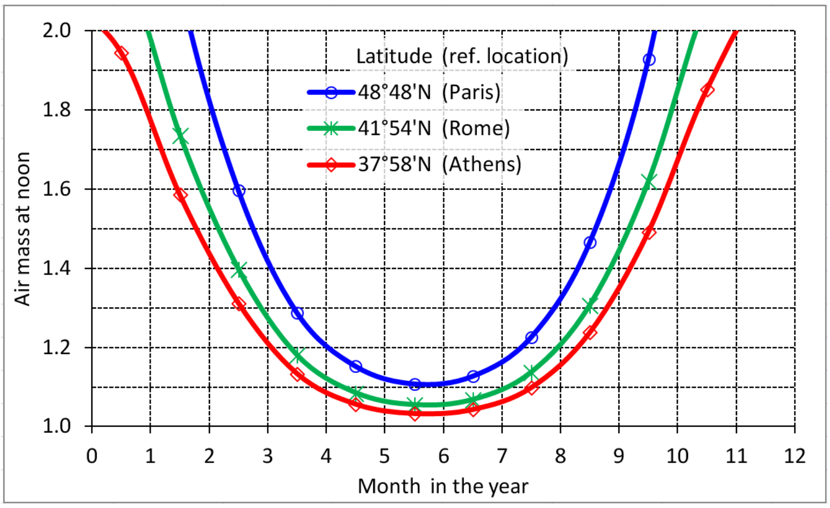

Figure 1: Minimum air mass for reference locations
in Southern and Central Europe

In view of the results of their above mentioned theoretical analysis, Levinson et Al. recommend using a clear sky air mass 1 global horizontal solar spectrum (AM1GH) for calculation of the solar reflectance value, and they show that solar heat gain computed from that value approximates the instantaneous annual peak solar heat gain of a horizontal surface in the U.S.A. to within 2 W m^{-2}. Nonetheless, AM1GH is not a standard spectrum such as EN891BN or another widely used one (EN410) provided by the European standard EN 410, which is similar to AM1GH but is available with a relatively coarse wavelength step size (20 nm in the range 300-800 nm, 50 nm in the range 800-2100 nm, and 100 nm in the range 2100-2500 nm). Two other interesting standard spectra provided by ASTM G173 for clear sky but air mass 1.5 are the spectral global irradiance (*i.e.* from the solar disk plus sky diffuse and diffuse reflected from ground) on a south facing surface tilted 37° from the horizontal (G173GT), and the spectral direct + circumsolar irradiance (*i.e.* in a field of view centred on the solar disk and with 5° diameter) on a surface pointing to the sun (G173DC).
AM1GH and the other above mentioned standard spectra E891BN, EN410, G173GT, and G173DC are summarized in Tab. 1. A dimensionless spectral irradiance is also represented in

Fig. 2 in terms of percentage of the total solar irradiance that falls in the unit wavelength, evaluated by the formula

$$100 \cdot S_\lambda \delta\lambda / S_{tot} \quad (\%) \tag{1}$$

where S_λ (W $m^{-2}nm^{-1}$) is the spectral irradiance, $\delta\lambda$ (nm) is the wavelength step size, and S_{tot} (W m^{-2}) is the total irradiance in the range 300-2500 nm, which includes about 99% of total solar irradiance at the earth surface and can be estimated from spectral data as follows:

$$S_{tot} = \int_{300}^{2500} S_\lambda d\lambda \cong \left(\sum S_\lambda \delta\lambda\right)_{\lambda=300..2500} \tag{2}$$

Linear interpolation of available data was generally applied to obtain a common wavelength step size or to match that of the measured reflectivity spectrum. In Fig. 3 the discrepancy of the dimensionless spectral irradiance with respect to E891BN is also presented for all spectra.

Table 1: Summary of the considered solar irradiance spectra

Initialism	Description	Aerosol optical depth at 500nm	UV/Vis/NIR (%)	Source
AM1GH	Clear sky AM1 global horizontal irradiance	0.084	6.5/45.0/48.5	NREL SMARTS 2.9.5
EN410	Clear sky AM1 global horizontal irradiance	0.1	6.2/44.3/49.5	EN ISO 410:2011
G173GT	Clear sky AM1.5 global irradiance on a south facing surface tilted 37°	0.084	4.5/43.5/52.0	ASTM G173-03
G173DC	Clear sky AM1.5 direct irradiance on a surface normal tracking the sun	0.084	3.3/42.2/54.5	ASTM G173-03
EN891BN	Hazy sky AM1.5 beam-normal irradiance	0.270	2.8/39.2/58.0	ASTM E891-87(1992)

As pointed out by Levinson et Al. (Levinson, 2010), direct solar irradiance has a higher NIR content than diffuse solar irradiance. As a result, E891BN and also G173DC have a significantly higher NIR content than all other spectra (see Tab. 1 and Figs. 2-3). In principle, since vertical and/or north facing surfaces mostly collect diffuse irradiance, whereas horizontal or south facing surfaces mostly collect direct irradiance, different spectra should be used to integrate the spectral reflectivity for surfaces having different orientation and inclination, thus obtaining different solar reflectance values even if the material is the same. On the other hand, unique values are surely preferred by either material manufacturers or building designers, in order to more easily define the product specification or calculate the building performance. A spectrum selected for integration of spectral reflectivity data should therefore realize a compromise between ease of operation and correctness of performance prediction. The NIR content of solar irradiance spectra is also affected the by the air mass, which depends on the location and the time in the year, as well as by the sky clearness, which can be quite variegated throughout the U.S.A., and at an even greater extent throughout Europe due to higher population and industry concentration and the existence of heavily polluted areas with permanent low wind condition.

While the impact of the spectrum selection on the calculated values of solar reflectance can be expected to be small for cool white materials with flat spectral reflectivity, it can become significant with cool coloured materials having selective reflective properties (Levinson, 2010). A non-negligible impact may even arise for cool white surfaces, since white ceramic materials can show an almost flat spectral reflectivity, whereas organic materials often show a strong absorption in the range above 1500-1700 nm (Libbra, 2011). Generally speaking, the spectrum selection may affect competition between manufacturers of cool solutions because it may arbitrarily induce differences in the solar reflectance estimate up to a few percentage points, almost negligible in terms of solar heat gain but evident enough to influence the choice of an inexperienced designer or end user.

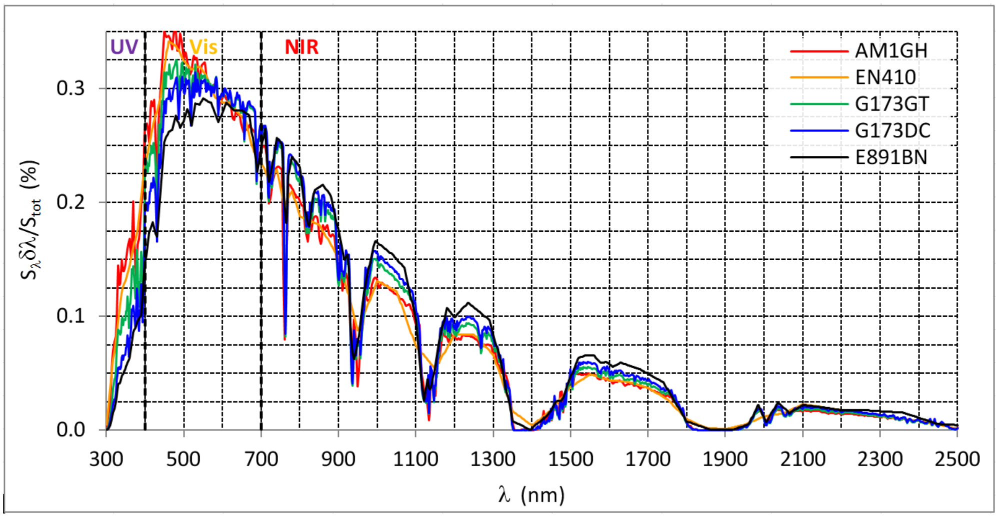

Figure 2: Dimensionless spectral irradiance expressed in terms of percentage of the total solar irradiance falling in the unit wavelength

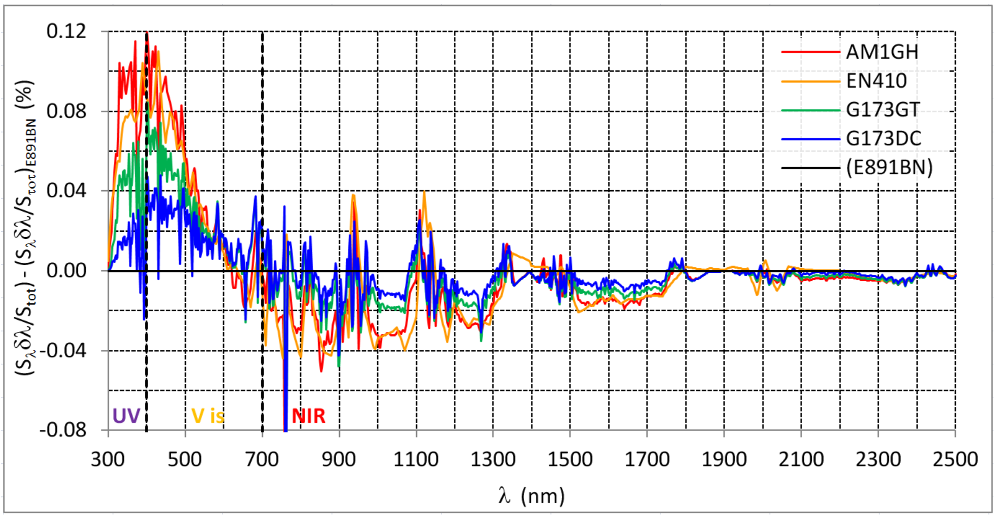

Figure 3: Discrepancy of dimensionless spectral irradiance of the considered spectra with respect to E891BN

This study is part of an investigation campaign on cool roofing solutions (Libbra, 2011, 2011a, 2013; Ferrari, 2013) and it is aimed at investigating the use of the solar irradiance spectra as specified by common existing standards or proposed by Levinson at Al. (Levinson, 2010), summarized in Tab. 1, and verifying if those spectra can yield equivalent solar reflectance values from the viewpoint of standard performance assessment, in order to enable the comparison of commercial products within the framework of a certification program like that of the Coor Roof Council of the U.S.A. (CRRC, 2013) or that under development by the European Cool Roof Council (ECRC, 2013). Actual materials are considered, either white or coloured ones and with assorted spectral behaviour, most of them commercially available.

2 EXPERIMENTAL ANALYSIS AND TESTED MATERIALS

Samples of several different materials were analysed in this study, representative of commercial products of the same type tested at the Energy Efficiency Laboratory (EELab) at Modena in terms of qualitative spectral behaviour. Those samples can be divided into three sets, identified in the following as 'cool white samples', 'white samples', and 'coloured samples'. The first sample set consists of five different 'cool' white samples (SR>65%): a glazed tile, an unglazed tile, a single ply membrane, painted bitumen shingle, and a thin organic coating applied onto a metallic substrate. The second sample set consists of three (non-bright) white samples with relatively low solar reflectance: white concrete, coated basalt grit, and slate shingle. The third sample set consists of mass coloured concrete samples with six different colours: yellow, orange, brick, ocra, brown, and red. These colours are representative of common surfaces of the Mediterranean architectures and the selected samples show a NIR reflectivity spectrum significantly higher than that in the visible range, thus approaching the concept of cool colour surface with selective behaviour. If fact, the coloured sample set is not representative of all possible cool coloured materials and coatings, nonetheless cool colours are a product category still under development and with marginal commercial impact.

Table 2: Summary of the measured values of solar reflectance

Sample	**AM1GH SR (%)** (UV/Vis/NIR)[a]	**EN410 SR (%)** (UV/Vis/NIR)[a]	**G173GT SR (%)** (UV/Vis/NIR)[a]	**G173DC SR (%)** (UV/Vis/NIR)[a]	**EN891BN SR (%)** (UV/Vis/NIR)[a]
Cool white samples					
Glazed tile	82.8	83.0	83.6	84.0	84.2
	(51.4/85.4/84.6)	(52.5/85.4/84.6)	(52.8/85.5/84.6)	(54.4/85.6/84.6)	(56.1/85.6/84.5)
Unglazed tile	79.9	80.0	80.6	81.0	81.2
	(53.5/81.1/82.2)	(54.3/81.2/82.2)	(54.5/81.2/82.3)	(55.7/81.3/82.2)	(57.0/81.4/82.2)
Single ply	76.4	76.5	77.8	78.5	78.4
	(9.7/84.9/77.5)	(10.1/85.0/77.2)	(9.7/85.1/77.6)	(10.2/85.4/77.4)	(11.0/85.6/76.8)
Painted bit. shingle	74.7	74.9	76.2	77.0	77.1
	(8.8/81.0/77.7)	(9.1/81.2/77.5)	(8.8/81.3/77.9)	(9.2/81.6/77.7)	(9.9/81.8/77.2)
Metallic substrate	66.7	66.9	67.8	68.5	68.6
	(11.2/74.2/67.2)	(11.5/74.3/67.2)	(11.2/74.5/67.2)	(11.7/74.7/67.1)	(12.5/74.9/67.0)
White samples					
White concrete	56.1	56.1	56.6	56.8	56.7
	(42.8/56.7/57.4)	(43.1/56.7/57.2)	(43.1/56.9/57.6)	(43.5/57.0/57.4)	(44.0/57.1/57.1)
Basalt grit	42.4	42.5	43.1	43.5	43.6
	(14.4/44.6/44.1)	(14.6/44.7/44.0)	(14.4/44.8/44.1)	(14.6/45.0/44.1)	(15.0/45.1/43.9)
Slate shingle	42.4	42.5	43.1	43.5	43.6
	(14.4/44.6/44.1)	(14.6/44.7/44.0)	(14.4/44.8/44.1)	(14.6/45.0/44.1)	(15.0/45.1/43.9)
Coloured samples					
Yellow	33.5	33.7	34.6	35.2	35.8
	(11.5/29.0/40.7)	(11.5/29.1/40.6)	(11.5/29.7/40.7)	(11.5/30.1/40.7)	(11.5/30.5/40.6)
Orange	25.4	25.7	26.4	27.0	27.6
	(9.0/19.5/33.1)	(9.0/19.6/33.2)	(9.0/20.1/33.2)	(9.0/20.4/33.2)	(9.0/20.7/33.2)
Brick	22.3	22.5	22.9	23.3	23.7
	(12.2/18.8/26.9)	(12.2/18.9/27.0)	(12.2/19.2/26.9)	(12.2/19.4/27.0)	(12.2/19.6/27.0)
Ocra	20.6	20.7	21.0	21.3	21.6
	(9.7/19.1/23.4)	(9.7/19.1/23.4)	(9.7/19.4/23.4)	(9.7/19.6/23.4)	(9.7/19.8/23.4)
Brown	18.8	18.9	19.3	19.7	20.0
	(8.5/15.7/23.0)	(8.5/15.7/23.0)	(8.5/16.0/23.0)	(8.5/16.2/23.0)	(8.5/16.4/23.0)
Red	16.5	16.7	17.2	17.6	18.1
	(6.4/11.4/22.6)	(6.4/11.5/22.7)	(6.4/11.8/22.6)	(6.3/12.0/22.7)	(6.3/12.1/22.8)

[a] The UV, Vis, and NIR solar reflectance values reported between brackets are calculated by means of Eq. (3) but applied to the UV (<400 nm), Vis (400-700nm), and NIR (>700 nm) ranges

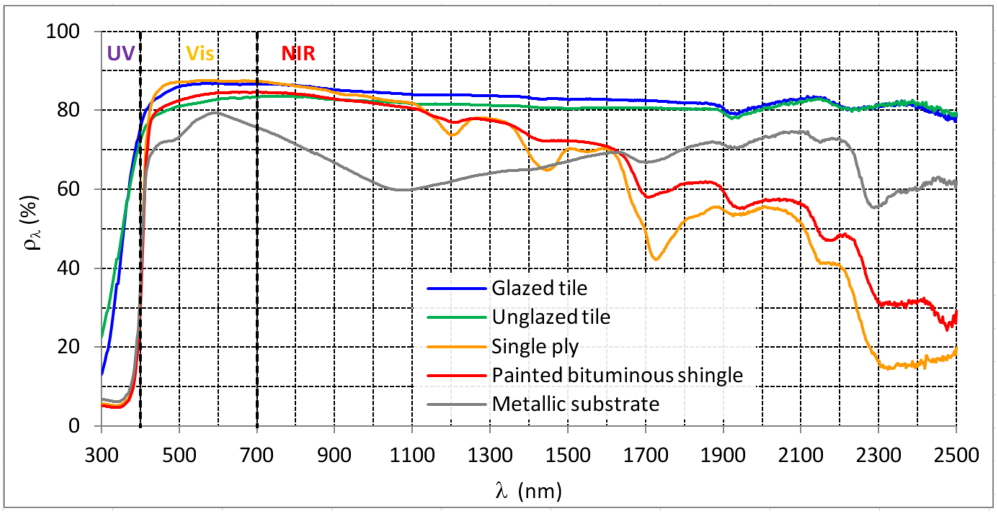

Figure 4: Reflectivity spectra of the ‘cool’ white samples

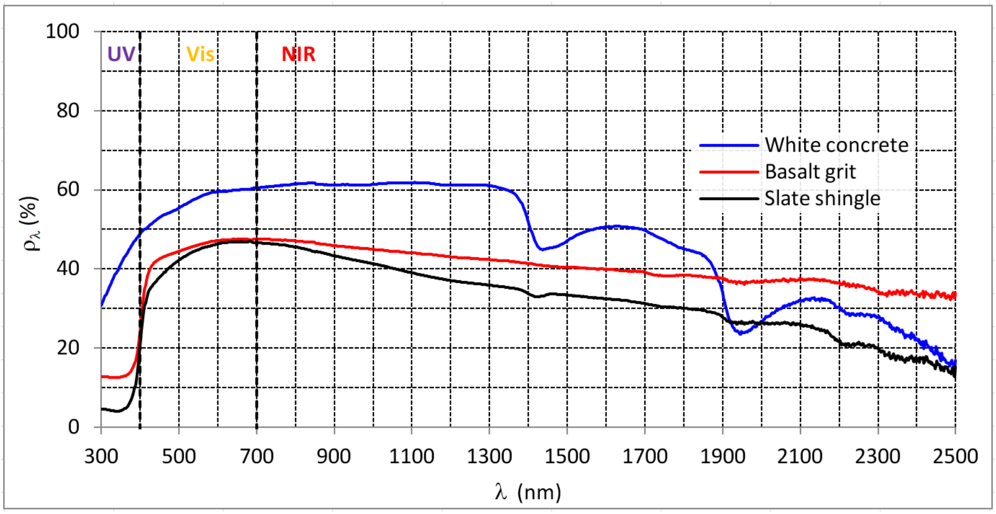

Figure 5: Reflectivity spectra of the white samples

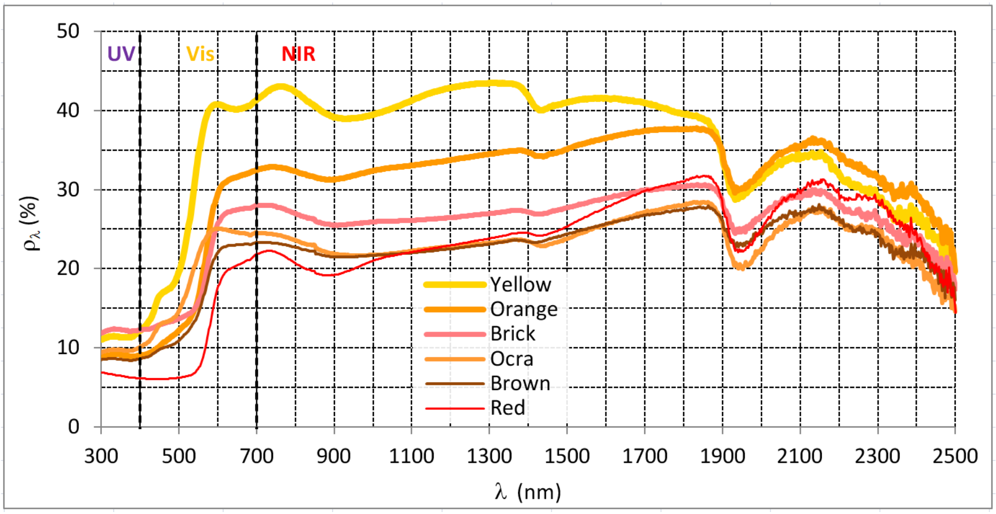

Figure 6: Reflectivity spectra of the coloured samples

The solar reflectance of each sample was calculated according to ASTM E903, using a Jasco V-670 UV/Vis/NIR spectrometer with 150 mm integrating sphere to measure the reflectivity spectrum. In order to compute the solar reflectance value SR, the reflectivity spectrum is then integrated with the five considered spectra of solar irradiance (AM1GH, EN410, G173GT, G173DC, and E981BN):

$$SR = \frac{\int_{300}^{2500} \rho_\lambda S_\lambda d\lambda}{\int_{300}^{2500} \rho_\lambda S_\lambda d\lambda} \cong \left(\frac{\sum \rho_\lambda S_\lambda \delta\lambda}{\sum S_\lambda \delta\lambda} \right)_{\lambda=300..2500} \tag{3}$$

where ρ_λ is the spectral reflectivity. The measured solar reflectance (SR) values are summarized in Tab. 2, while the measured reflectivity spectra are shown in Figs. 4-5-6.

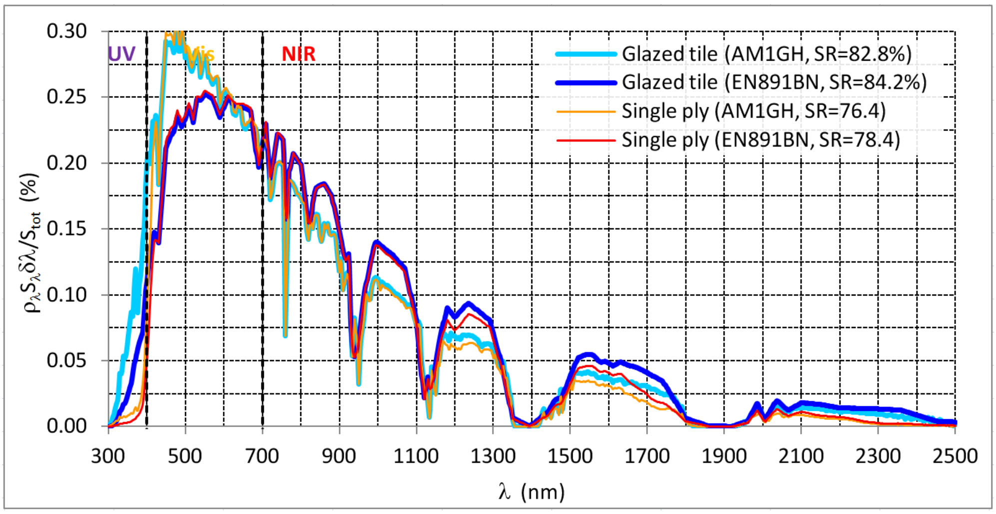

Figure 7: Comparison of dimensionless spectral reflection (dimensionless reflectivity x irradiance) for a ceramic and an organic 'cool' white solutions

3 DISCUSSION AND CONCLUSIVE REMARKS

The spectral reflectivity data in Figs. 4-5 illustrate the almost flat spectrum that white ceramic materials can have, as well as the strong absorption in the range above 1500-1700 nm (Libbra, 2011) often shown by organic materials. Intermediate results are generally obtained when an organic coating is applied onto a metallic or inorganic substrate with very different behaviour and the coating is not thick enough to mask the substrate. Close values of solar reflectance can thus be provided by materials with quite dissimilar spectral behaviours and reflective properties in the UV, Vis and NIR ranges (Tab. 2). As a result, the choice of the reference spectrum with which the spectral reflectivity data are integrated, with its peculiar distribution of radiant energy in the different spectral ranges, may affect the returned SR value. The problem was already extensively investigated by Levinson et Al. (Levinson, 2010) from the viewpoint of theoretical prediction of mean and peak solar heat gain in function of all most relevant parameters. Therefore, this study is focused on the solar reflectance values returned by the use of selected solar spectra when actual materials are tested, in order to verify if the emerging discrepancies are large enough to influence product comparison and competition.
A main result of this analysis is that the UV, Vis, and NIR solar reflectance values, calculated by means of Eq. (3) applied to the UV (<400 nm), Vis (400-700nm), or NIR (>700 nm) ranges, are almost the same with all solar spectra (Tab. 2). Discrepancies for a same material and a same spectral range are generally well below one percentage point. Larger discrepancies, however, arise in the values of total solar reflectance. These discrepancies can be as high as a couple of percentage points and are basically due to the different fractions of total radiant energy that fall in the UV, Vis, and NIR ranges: for instance, the NIR range includes as much as 58% of total radiant energy in the EN891BN spectrum, but only 48.5% and 49.5% in the AM1GH and EN410 spectra, respectively (Tab. 1). As easily predictable, ceramic surfaces with a relatively flat reflectivity spectrum show the smallest discrepancies,

nonetheless these can be as high as a percentage point due to the relatively low solar reflectance in the UV range, which includes as much as 6.5% and 6.2 of total radiant energy in AM1GH and EN410, respectively, but only 2.8% in EN891BN. Over evidence of the consideration above can be provided by the reflection spectra in Fig. 7, where the dimensionless spectral reflectivity of a ceramic surface and that of an organic coating, which show very different spectral behaviour, are multiplied by the dimensionless spectral irradiance from the E891BN and AM1GH spectra, the two ones showing the largest differences.
While passing from one solar spectrum to the other, the arising discrepancies always show the same sign and, for a same sample set, the same magnitude. Therefore a fair product comparison is likely to be allowed if a same reference spectrum is always used. In fact, the maximum discrepancies evidenced here are scarcely significant in terms of solar heat gain and, moreover, below the accuracy of commonly used measurement methods such as those based on spectrometers or reflectometers, nevertheless situations can be envisaged in which the choice of an inexperienced designer or end user can be influenced.
In conclusion, EN891BN is the most widely used standard spectrum for solar reflectance measurement and, therefore, it is the current reference, but AM1GH or EN410 may provide more accurate predictions in terms of peak solar heat gain of horizontal or low-sloped surfaces in regions like mainland U.S.A. or Southern Europe. Other standard spectra like G173DC and G173GT generally return intermediate results. Any one among them can probably be chosen for assessment of standard performance and product comparison, at least for white products, but a unique choice can be recommended.

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