Optical Advances in the Field of Selected Solar Technologies for Exploitation in Building Energy Efficiency.

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Abstract
Research findings in the scope of building science and building engineering are more frequently looking for a challenge related to current issues, recent progresses and future directions in the field of buildings, sustainability and creation of healthy built environment. One of the major factors contributing to this issue is also integration of new progressive materials and technologies on solar energy exploitation base. Those aspects in the area of renewable energy can contribute to the surveying of new building materials and innovative building envelope concepts based on interdisciplinary attributes of observation. It could be the one of the ways to improve thermal and energy performance of current building and including of new technologies, whose the aspects could potentially be implemented to improve energy efficiency of buildings. Recent advances in the field of solar technologies initiate fundamental strategy to apply the tools for improving the efficiency of all existing elements and concepts. Application of selective absorbent technologies may help us find new ways for optimization of energy consumption and mitigation of environmental impacts of buildings. In the building science for the field of renewable resources, the issues of solar energy, a progressive involvement is focused, among others, on the reflective, selective and solar cell technologies. Based on an optical analysis, the paper is focused on a spectral laboratory survey of those technologies to predominantly demonstrate its thermal aspects. The results of spectrophotometry and infrared spectroscopy represent an overview of indicators concerning with the optical efficiency of selected absorbent materials to be conceivably integrated in future energy efficient concepts.

Keywords: sustainable building, selective technologies, energy efficiency, optical survey, optical efficiency, solar absorbent features

Introduction

Due to expand new scientific knowledge, it is strongly recommendable to focus on current research and developments in the field of comprehensive building solutions and implementation of advanced material forms. Recently a wide range of progressive solutions has been described but they are yet to be not assessed from building physics (thermal and energy) point of view. Newly disseminated findings can be implemented to the field of Building Science. In the building science for the field of renewable resources, the issues of solar energy have also become of a crucial importance. Attention in this field is focused, among others, on the research, development and innovations of solar cells, collectors and various photovoltaic elements with interdisciplinary attributes of investigation. For the purpose of the near zero energy performance attributes and subsequent approaching of zero energy balance, the observation is also focused on the façade systems integrating passive or active heating and cooling solutions with aim to achieve the greatest rate of the energy self-sustainability of the whole building. From this point of view, basic requirement concerns on synergy between ensuring of improvements in thermal insulation functions for winter periods and on the other hand its elimination of overheating in periods of summer. Here we can additionally find the ways how to implement various solar technologies based on optical advances in applications of building integrated systems. Development and evaluation of different technical solutions and integration of new progressive materials are of a relevant interest of the ongoing research. Considering the most recent findings, it could be the one of the directions to improve thermal and/or energy performance of current building with direct relation of including the new technologies. Currently, numerous research activities deal with utilization of the recent technologies in the field of nanomaterials which, especially in the last few decades, have been undergoing steep progress. In the scope of research and development we frequently confront the application of tools for optimizing and improving the efficiency of existing elements and technologies. Potential way of development of solar technology includes even innovation of materials with solar technologies base, in particular reflective [1] [2], solar [3] [4] and selective [5] functions as those of the spectrally developed that may principally employ required parameters for specific cases of particular thermal radiation spectrum.

Thermal radiation spectrum in Building Exploitations

In general one of the most important roles in the mechanism of thermal radiation transfer is influenced by the optical properties of material depending, in an ideal case, upon the impact angle and the wavelength of radiation. The decisive range of the electromagnetic waves affecting the process of thermal radiation at the building surface is roughly within 0.40 to 40.00 µm. The characteristic regions are basically defined by boundaries in different cases of building applications (Tab. 1).
Each range of thermal radiation has a specific importance for building energy efficiency. An important aspect of thermal performance effect for the area of thermal radiation is depend on spectral irradiance of the sun with particular dependence on wavelength known as solar radiation spectrum (Fig 1a), whilst the spectral radiance intensity of temperatures typically related to buildings and build environment are demonstrated on Fig.1b as related to longwave radiation phenomena. Overall, the building envelope tends to be markedly chilled due to radiating heat exchange,

especially under clear and cloudless sky conditions. The marginal condition of thermal radiation shifts towards longer waves in the longwave region.

Table 1 Characteristic regions of thermal radiation in building exploitations

character:	spectral range	building application
VIS	0.38 – 0.78 µm	especially concerning the reflective features of the surface finish color character
NIR	0.78 – 2.50 µm	predominantly on outdoor surfaces, the source of radiation being the Sun (T = 6000 K), or heat sources with thermodynamic temperature exceeding 800 K
LW	2.50 – 40.00 µm	predominantly on indoor surfaces, the source of this type of radiation being, e.g., current heating systems achieving thermodynamic temperatures around 350 K, as well as the sky as a source of cooling

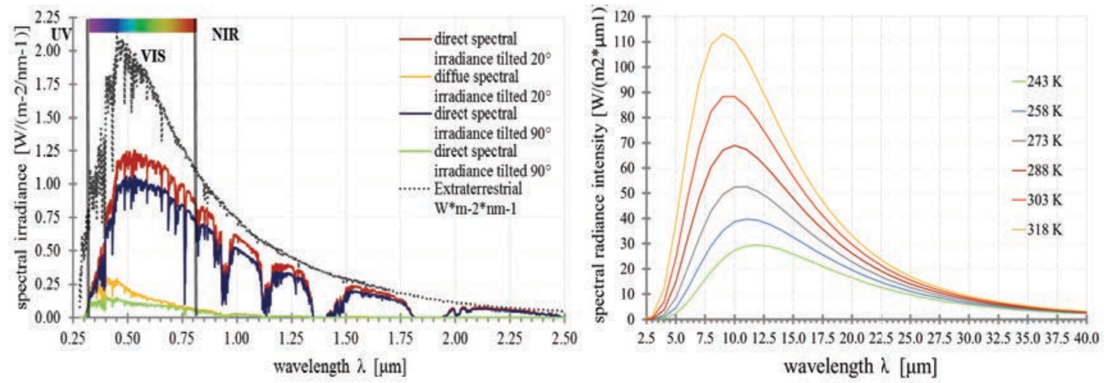


Figure 1 (a) Standard direct and diffuse spectral solar irradiance for 20º and 90° sun-facing tilted surfaces [6]; (b) spectral radiance intensity of temperatures typically related to buildings and build environment from -30°C to +45°C

Methodology of observation

As one of the aims of this study is to utilize potential technologies for building energy efficiency based on solar exploitation can be applied, the paper deals, basically, with the optical efficiency and its advances of selected solar technologies. For the purpose of this study, we use three groups of coatings representing solar technologies, the solar reflective and both of the absorbent of cell as well as selective bases. From the view of thermal aspects of building performance, it additionally introduces other evaluation indicators such as emissivity and Solar Reflectance Index (SRI). Since the production of recent solar technologies which can be applied in the progressive envelope constructions of buildings in both their active and passive forms, the objective of the study is to analyze reflectance parameters in the whole range of thermal radiation applying spectral analysis. Laboratory methods for estimation of solar reflectance and thermal emissivity were used for this study.

For the purposes of quantifying the solar reflectance, an UV/VIS/NIR spectrophotometer Perkin Elmer Lambda 1050 with 150 mm Spectralon integrating sphere (Fig. 2a) was used. This apparatus can register the spectral reflectance properties from 200 nm to 3 300 nm. Spectral curves and finally integrated values over 280 to 2 500 nanometers of Total Solar Reflectance (TSR) (Eq. 1) and of each specific region are presented, where R is percent reflectance, I is Solar Irradiance and dλ is the wavelength interval of integration. The solar reflectance of the analyzed surface is calculated by means of ASTM Standard G173 [6] for the hemispherical global tilt irradiance.

$$\%TSR = \frac{\int (\%R \times I d\lambda)}{\int I d\lambda} \times 100 \qquad (1)$$

The Solar Reflectance Index (SRI) is exploratory calculated due to demonstrate material proper with respect to energy efficiency especially in building practice. The calculation of the SRI is performed according to ASTM E1980-11 [7] and based on quadratic formula (Eq. 2, 3). The standard conditions for this calculation are defined as the convective coefficient of 12 $W/(m^2*K)$, solar flux of 1000 W/m^2, ambient air temperature of 310 Kelvin (K), and sky temperature of 300 K.

$$SRI = 123.71 - 141.35 \times x + 9.655 \times x^2 \qquad (2)$$

$$x = \frac{(\boldsymbol{\alpha} - 0.029 \times \boldsymbol{\varepsilon}) \times (8.797 + h_c)}{9.5205 \times \boldsymbol{\varepsilon} + h_c} \qquad (3)$$

For the purposes of quantifying the thermal emissivity, an infrared spectrometer Nicolet 380 from the Thermo Electron Corporation equipped with an integrating sphere Mid-IR ™ IntegratIR (Fig. 2b) from PIKE Technologies was used. The results were obtained by the DRIFT method and authenticated by repetitive measurements of each sample. Spectral curves of the reflectance as a function of the wavelength are presented for spectral range from 2.5 to 20.0 μm. As a result from the law of the conservation of energy and Kirchhoff's laws (Eq. 4), emissivity can be derived and consequently used for determination of the measurement results in terms of emissivity values.

$$\varepsilon = \alpha = 1 - \rho \text{ ,or } \varepsilon_\lambda = \alpha_\lambda = 1 - \rho_\lambda \qquad (4)$$

As a consequence, Plank´s formula (Eq. 5) of spectral radiance intensity of 273 K black body $M_{0,\lambda}$ is used as the weighted function for determination of emissivity values.

$$M_{0,\lambda}(\lambda, T) = C_1 \times \lambda^{5} \times (e^{\frac{C_2}{kT}} - 1)^{1} \qquad (5)$$

Figure 2 (a) UV/VIS/NIR Spectrophotometer Perkin Elmer Lambda 1050 with 150 mm Spectralon integrating spheres; (b) FT-IR infrared spectrometer Nicolet 380 and integrated sphere Mid-IR ™ IntegratIR

As is well known, the significant region lies somewhere between 8.0 and 15.0 μm in building applications (as demonstrated in accordance with the maximum of spectral radiance intensity on Fig. 2b), where all the standard bodies radiate the maximum of its energy. It also represents an area of atmospheric windows where the outdoor conditions are transmissive to thermal radiation.

Solar reflective coatings

In general, coatings mainly create thin surface layers. Their character does not have much of an influence on the thermal resistance of building envelopes. However, they can markedly influence transfer effects on building surfaces and can therefore be relevant to the thermal performance of buildings as well as many others benefits. These benefits can contribute to reduction of heating and cooling loads of building environment, decreasing of surface temperatures of building envelopes, contribute to the reduction of the air temperature due to the heat-transfer phenomena therefore improve outdoor thermal comfort and finally reduce the heat-island effect [8] [9]. One of the assumptions of their improved thermal properties is based on the optical properties of the building surfaces that can be considered as significant for this area. Therefore, this issue can be quantified in terms of energy efficiency of buildings at two problem fields of the electromagnetic radiation spectrum in the optics. The first on the solar reflectance properties, while the second are further specified in the longwave radiation field of building surfaces and thermal emissivity parameters.
For spectral analysis purpose: The samples were collected and divided into two groups of coatings: standard facing coatings of acrylic base (group A) and based on hollow microspheres (group B). The table (Tab. 2) shows all the measured samples, their description, color and material base.

Table 2 Table of studied coatings on reflective base

Symbol:	Expression and description:	color
A1	Disperse acrylate facing coating, reference	white
A2	Disperse acrylate facing coating, reference	orange
A3	Disperse acrylate facing coating, reference	5% gray
B1	Facing coating of hollow ceramic microsphere base	white
B2	Facing coating of hollow ceramic microsphere base	orange
B3	Flexible coating consisting of hollow borosilicate microspheres	white
B4	Coating of hollow ceramic microsphere base	white
B5	Coating consisted of hollow ceramic and silicone microspheres	white

Table 3 Total solar reflectance values ρ_λ, *SRI* parameters, and total spectral emissivity ε_λ and reflectance ρ_λ as weighted values in measured infrared spectrum

Symbol:	ρ_λ	*SRI*	$\rho_{\lambda\ SRS}$ 0.3 – 2.5 μm	$\rho_{\lambda\ SRS}$ *VIS* 0.3 – 0.8 μm	$\rho_{\lambda\ SRS}$ *NIR* 0.8 – 2.5 μm	ε_λ 2.5 – 18.0 μm	ρ_λ 2.5 – 18.0 μm
A1	0.83	105	0.81	0.78	0.86	0.92	0.08
A2	0.54	65	0.53	0.45	0.63	0.94	0.06
A3	0.69	85	0.68	0.67	0.69	0.94	0.06
B1	0.85	108	0.83	0.81	0.86	0.94	0.06
B2	0.63	77	0.61	0.51	0.77	0.94	0.06
B3	0.83	105	0.81	0.79	0.84	0.94	0.06
B4	0.83	105	0.81	0.79	0.84	0.94	0.06
B5	0.79	99	0.78	0.75	0.82	0.93	0.07

The evaluated final results were authenticated by repetitive measurements of each sample (Table 3). The comparison of multiple measurements of each specimen enabled us to achieve results with negligible deviation and to simplify diagrams in showing only one single spectral curve representing one sample. The diagrams (Fig. 3a,c) show the spectral curves of reflectance in the solar radiation spectrum (200 nm to 2500 nm) and Spectral curves of the reflectance as a function of the wavelength (in spectral range from 2.5 to 20.0 μm) are shown in the figures (Fig. 3b,d).

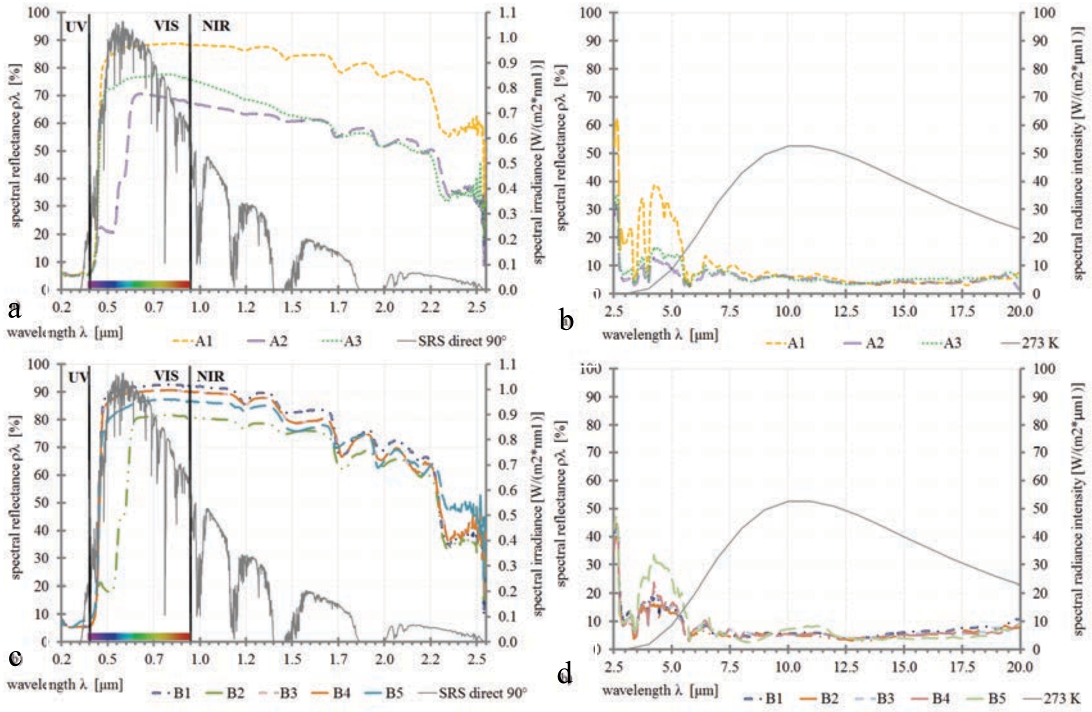


Figure 3 (a) Solar reflectance measurements gr. A (b) thermal emissivity measurements gr. A (c) Solar reflectance measurements gr. B (d) thermal emissivity measurements gr. B (c)

Solar cell technologies

Here the primary intention relies on the solar cells´ applications. The basic aspects of their efficiency also include involvement of the optical properties of materials making up cells integrated, to major extent, into solar and photovoltaic panels. Apart from others, there are efforts to implement all those progressive elements in various active and passive forms also as a part of building envelopes [10, 11] (BIPV – Building Integrated Photovoltaics). It also offers the way of their applications, in which the field of solar energy has recently indicated a significant expansion [12, 13, 14]. In particular, the continuously developed technologies and advances [15] of creating these elements can be used also in applications of progressive building envelopes or additionally in the innovative concepts of solar facades integrating the latest advanced material solutions. In these concepts they can actively contribute, to large extent, as part of the top envelope. On the other hand, their thermal properties may be used for secondary functions where, apart from the decisive indicators of their efficiency, observation must be also conducted to other thermal and optical parameters. In general, the overall efficiency of solar cells is quantified by the ratio of the electrical output of a solar cell to the incident energy in the form of sunlight. Several factors enter this indicator and affect the final efficiency value [16] including its reflectance efficiency, thermodynamic efficiency, charge carrier separation efficiency, and conduction efficiency values. Mainly the darks colored cells (dark blue, violet to black, or their mutual combination at refraction of light) are currently among the most frequently used solar cells. While dark colors approach the highest solar absorption values, from the view of optical efficiency they are still the most typical colors in all kinds of the industry. At present, there are also frequent requirements for the colorfulness, particularly in building envelopes, and they can contribute, to large extent, to a better variety and additional architectural measure in the final formation of buildings. The consequence of this is that solar cells with various color variations appear to have a relevant interest.

One of the key aspects in the production of solar cells is to minimize losses with the aim to achieve the highest possible efficiency [17]. In general, we distinguish the losses as optical and electrical. Optical losses are caused by the fact that a large part of solar radiation reflects back to space after falling on the surface of semi-conductors. From the solar radiation point of view, the color and glossiness of the surface are the decisive factors for the visible region, whilst the material composition and the texture of the surface are the leading ones for the near infrared. An important aspect is that their surface will adapt in such a way that its reflectance is reduced as much as possible. Various antireflective layers can be applied on the surface or a textured surface can be made by etching, which will erode the smooth and glossy surface to reduce its solar reflectance. These methods are able to reduce the rate of reflectance down to below 10%. In addition, the current technologies of antireflective layers cause properties which may thermally contribute to selective effects. Table 4 presents all values for individual regions and then it compares them numerically in bar graphs for selected colored crystalline solar cell technologies. Spectrally there are presented in terms of curves by following figures (Figs. 4 and 5)

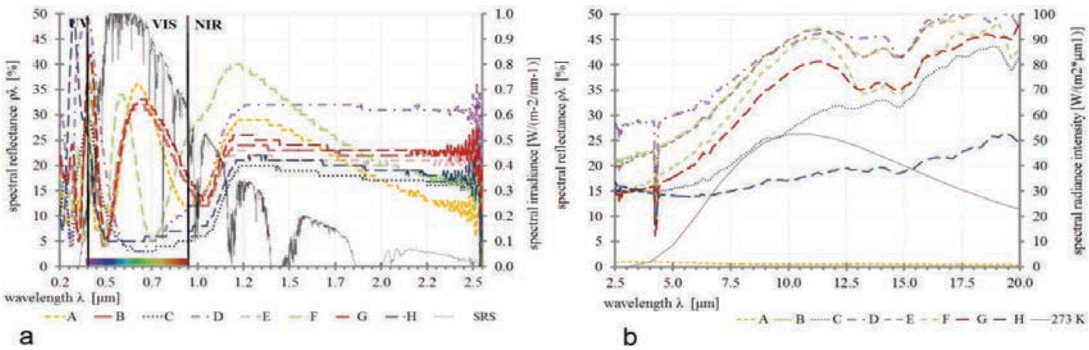


Figure 4 (a) Solar reflectance measurements (b) thermal emissivity measurements

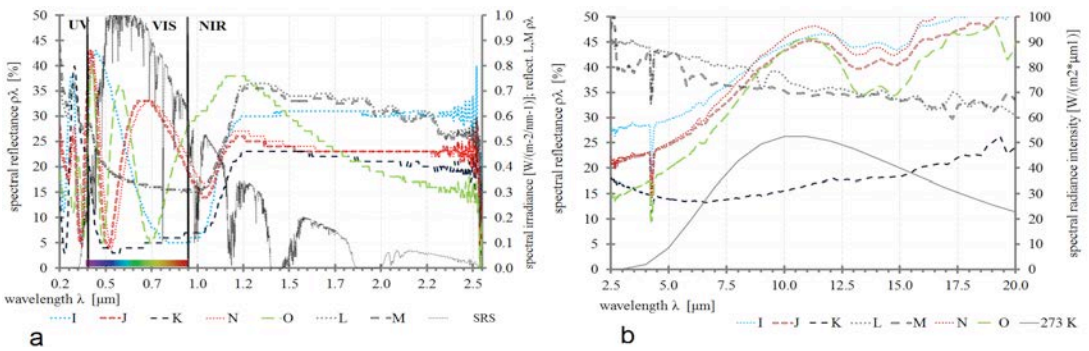
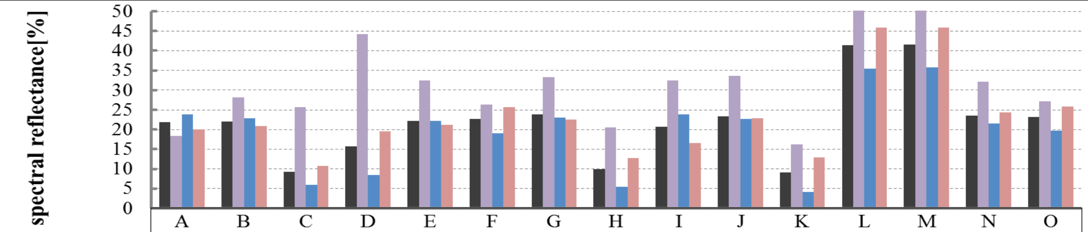


Figure 5 (a) Solar reflectance measurements (b) thermal emissivity measurements

Table 4 Reflectance ρ_λ, emissivity ε_λ and solar reflectance index SRI in particular spectrums

	A [%]	B [%]	C [%]	D [%]	E [%]	F [%]	G [%]	H [%]	I [%]	J [%]	K [%]	L [%]	M [%]	N [%]	O [%]
Colors															
ρ_λ: TSR	21.8	22.1	9.3	15.8	22.2	22.6	23.8	9.9	20.7	23.3	9.1	41.4	41.6	23.5	23.1
ρ_λ: UV reg.	18.3	28.1	25.6	44.2	32.5	26.4	33.3	20.6	32.4	33.6	16.2	51.8	53.2	32.2	27.1
ρ_λ: VIS reg.	23.9	22.8	5.9	8.5	22.2	19.1	23	5.5	23.8	22.6	4.2	35.4	35.8	21.5	19.7
ρ_λ: NIR reg.	20.1	20.8	10.7	19.5	21.2	25.6	22.5	12.8	16.5	22.9	12.9	45.9	45.9	24.4	25.8
ε_λ: IR reg.	83.3	62.8	76.2	61.0	63.0	67.0	62.8	83.6	61.1	64.2	84.7	61.2	63.5	62.4	66.7
SRI	6	7	0	0	7	11	10	3	4	9	2	34	36	9	11
Surf. Temp	80.0	79.8	77.0	83.5	79.8	78.3	78.7	81.3	80.8	79.0	81.6	69.6	68.7	79.1	78.3



Solar selective technologies

Finally, our recent knowledge can contribute to integration of selective absorbent technologies, as key absorbing factors that from thermal aspect point of view may be used to prevent heat loss in winter, decrease an overheating in summer and finally allow for the conversion of incident solar energy into thermal energy. Table 5 represents selected spectrally selective materials as compared with standard paints, whilst Figure 6 presents its spectral nature.

Table 5 Table of studied selective and standard technologies

S:	Material:	Surf. shade	color	ρ_λ 0.3 - 2.5 µm	ε_λ 2.5 -18.0 µm
1	Blacksmith refractory coating	semi-gloss	black	0.15	0.82
2	Standard synthetic coating	mat	black	0.04	0.94
3	Standard synthetic coating	gloss	black	0.05	0.93
4	Spectrally selective coating TiNOx - Nano	mat	black	0.10	0.06
5	Spectrally selective coating TiNOx - Cu	gloss	blue	0.05	0.07
6	Spectrally selective coating TiNOx - Al	gloss	blue	0.06	0.04
7	Titanium nitride coating	mat	black	-	0.45

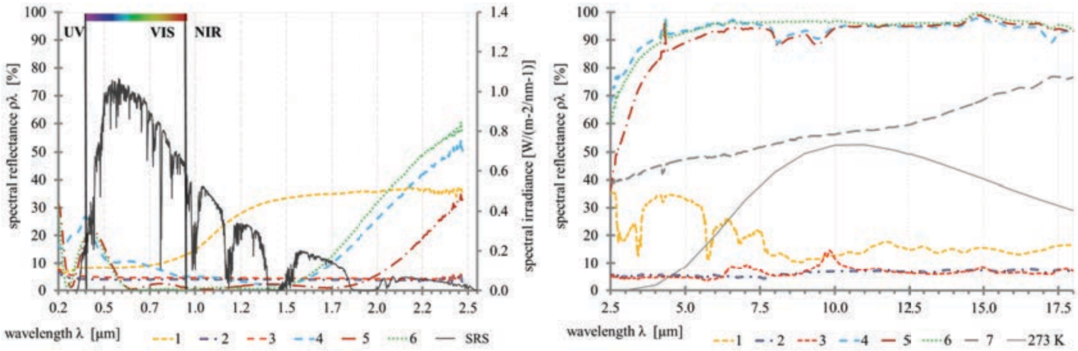


Figure 6 (a) Solar reflectance measurements (b) thermal emissivity measurements

Conclusion

The paper presents an overview of the optical efficiency in the field of selected solar technologies that was under observation to find the property of which the secondary functions may be applied to improve the thermal and energy efficient properties of building envelopes. The results are a comparison of spectral curves and reflectance radiative parameters which are of crucial importance for a detailed examination of heat transfer phenomena at the boundary with the surrounding built and urban environment. It can be observed from the results that the recent technologies and advances which are currently used to produce solar based materials may be used in applications where it is useful to activate the selective functions of surface layers to contributing of various thermal aspects of building envelopes in the heat transfer phenomena. The analysis demonstrates that from the colored solar cell area the blue mono-crystalline one indicates the most suitable properties in the analyzed indicators related to the attributes of building thermal performance.

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