A Method to Identify the Solar Absorptance of Opaque Surfaces with a Low-cost Spectrometer

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ABSTRACT: The factor with major influence over solar heat gains of a building is the solar absorptance of its external surfaces defined as the ratio of the solar energy absorbed by the surface to the total of the incident solar energy. For several cases, particularly in low latitudes, these gains can represent more than 50% of the building total thermal load, with great influence over its indoor temperatures. For opaque surfaces, the absorptance corresponds to the difference between its reflectance and the unity. Currently, the most accurate process used to identify the solar absorptance of a sample is to measure its reflectance using a spectrophotometer, a very expensive equipment rarely available for specialists or designers. For these reasons, they use simplified tables based only on the object colours. This paper presents a method to identify, with very satisfactory accuracy, solar absorptances of opaque surfaces using the ALTA II, a low-cost spectrometer that measures reflectances correspondent to radiations at eleven different wavelengths, from 470 to 940 nm. Firstly, reflectances of painted samples with different colours were measured using the ALTA, and they were compared with correspondent determined values using a spectrophotometer. After this, based on ALTA II data, equations were developed to calculate reflectances for the visible range (380 to 780 nm) of the solar spectrum, the near-Infrared range (780 to 2500 nm), and for the total solar spectrum (380 to 2500 nm). The main contribution of this work is to indicate a reliable and accessible procedure to specialists, which will be useful as an alternative to usual techniques to obtain reflectances and absorptances.

Keywords: solar absorptance, solar reflectance, spectrometer, opaque surfaces, solar radiation.

1. INTRODUCTION

In tropical countries, solar radiation is the main responsible factor for the thermal load of buildings. The heat gain of opaque surfaces of buildings due to solar radiation affects the indoor thermal comfort conditions. The heat flow between outdoor and indoor will depend on the building envelope and the thermal and physical properties of the building elements [1].

The factor with major influence over the solar heat gains of the envelope is the solar absorptance defined as the ratio of the solar energy absorbed by the surface to the total of the incident solar energy. This characteristic of an opaque surface can be considered as a criterion in designing the building envelope, which affects the selection of the exterior surface material. Therefore, the knowledge of absorptances is extremely important to evaluate the thermal and energetic performance of buildings [2].

Despite of being aware of the importance of this property, the specialized literature has not been concerned in this regard with the desirable rigour. Many authors published only a few tables of absorptances, according to the surface colours, with outdated and imprecise data [3, 4, and 5]. Even paints manufacturers rarely inform about the thermal properties of their products. The authors frequently mention a supposed direct relationship between colours and absorptances. Actually, colours are visual sensations, and they can cause mistakes because 55% of the solar radiation occurs out of the visible range of the solar spectrum. For this reason, a colour with clear appearance can absorb more heat than another considered darker.

The intensity of solar radiation is not constant along the solar spectrum, and its distribution depends on the atmospheric conditions, cloudiness, etc. Most of this radiation is distributed in different proportions from 300 to 2500 nm. The American Society for Testing and Materials (ASTM) defined a standard solar spectrum based on measured data, which indicates the intensity correspondent to each wavelength [6]. In Figure 1 this standard is compared to the human eye sensitivity curve, which also varies from different wavelengths.

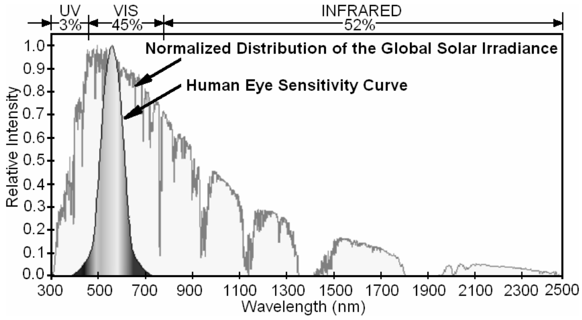

Figure 1: Standard solar spectrum.

Because the reflectance varies according to the wavelength of the incident energy, the optical behaviour of each surface can be represented by a distribution curve of its reflectances along the solar spectrum. An average reflectance can be calculated for a specific interval or for the whole spectrum by the curve integration. The eye detects the radiation reflected on the visible range, and it provokes chromatic sensations. However, the human eye detects only a narrow range of radiations (Fig. 1); for this reason, it does not provide reliable information about solar reflectances or absorptances. In consequence, it is essential to publish more accurate and updated solar absorptance data.

The most accurate process used to identify the solar absortance of a surface is to measure its reflectance with a spectrophotometer, a very expensive equipment rarely available for specialists. For this reason, this paper presents and discusses a method to identify, with very satisfactory accuracy, solar absorptances of opaque surfaces using the ALTA II, a low-cost spectrometer that measures reflectances correspondent to radiations at eleven different wavelengths, from 470 to 940 nm. This equipment was chosen as an alternative to the spectrophotometer because it is cheaper, and it presents more reliable and real data than those presented in absorptance tables published until now.

2. METHODOLOGY

2.1 Analysed Samples

The analysed samples were painted with several paint colours from the same industry, which are commonly used in Brazilian façades. The colours were selected from a catalogue of basic paint colours of latex PVA and acrylic paint produced by Sherwin Williams Company, in Brazil. Despite that latex PVA paints are recommended only for interior surfaces because they have lower resistance to sunlight and weather conditions, these paints were also chosen because they are cheaper than acrylic paints, and for this reason they are frequently used to paint exterior building surfaces.

In order to obtain results closer to actual surfaces, the samples were prepared with ceramic tablets (35 x 35 mm), with a smooth surface to avoid the roughness effect on the reflectance results. The tablets were painted with a coat of light grey colour paint as a back colour to avoid the effect of the ceramic dark colour, followed by two coats of paint with the colour to be analysed, with a minimal interval of two hours between coats. The samples were carefully painted to obtain homogeneous and uniform surfaces, with the predominance of the considered paint colour. The tablets square shape presents better adjustment to the spectrophotometer support, which ensures greater stability during the measurements.

2.2 Spectrophotometer Measurements

Several laboratory measurements were performed through optical analyses using a double-beam spectrophotometer (Varian CARY 5G), according to the ASHRAE 74-1988 standard [7]. This equipment was chosen because it measures the spectral characteristics of the samples over the solar spectrum from 185 to 3000 nm. Reflectance was determined at wavelength intervals of 1 nm, from 300 to 2500 nm, which is the solar spectrum range with the major concentration of solar energy according to the ASTM G173-03 [5]. This region was divided into three parts: ultraviolet (300 to 380 nm), visible (380 to 780 nm), and near-infrared (780 to 2500 nm). Actually, analyses by spectrum ranges are not commonly studied by the specialized literature, which only presents data referring to the visible reflectance. Many authors consider that visible reflectance repeats for the entire solar spectrum. However, some studies demonstrated that opaque surfaces reflect differently for the three solar spectrum ranges [8, 9, 10, and 11]. Therefore, absorptance data only for the visible range can cause mistakes because they do not effectively represent how much solar heat a surface reflects or absorbs.

2.3 ALTA II Spectrometer

The ALTA II spectrometer was firstly developed by the Lunar and Planetary Institute (Houston, Texas-USA) as a tool for teaching about light and remote sense at schools. Nevertheless, the first results of this paper indicate that the ALTA II can be a reliable tool for researchers and specialists that require reflectance data of opaque surfaces. This tool avoids the use of simplified tables based only on the visible reflectances of some colours.

Figure 2: ALTA II spectrometer.

The spectrometer ALTA II measures reflectances correspondent to radiations at eleven different wavelengths, from 470 to 940 nm, which are seven in the visible range and two bands in the near-infrared range. There are 11 buttons on the front panel of the instrument that correspond to each band (Figure 2). Each button also corresponds to one of the bulbs on the back of the instrument. When a button is pressed, the equipment emits energy and measures how much of this energy is reflected back. The lamps that emit energy correspondent to each wavelength are in a circular hole in the back of the equipment, and the sensor that detects the energy reflected back is in the middle of this circle. On the front panel of the instrument there is a screen that indicates how much of the energy was reflected back.

The spectrometer does not provide the reflectance absolute value, but with some simple calculations the percentage of the reflectance can be determined, based on the reflectance of a reference sample. In this case, it is recommended to adopt, as a reference, data measured in a spectrophotometer for a surface with high reflectance. In this paper a regular white paper (75g/m²) commonly used at school or offices was chosen as a reference, with spectral curve as presented in figure 3. The white paper was chosen because it is commonly used for designers and students, without the need to obtain another material as a reference.

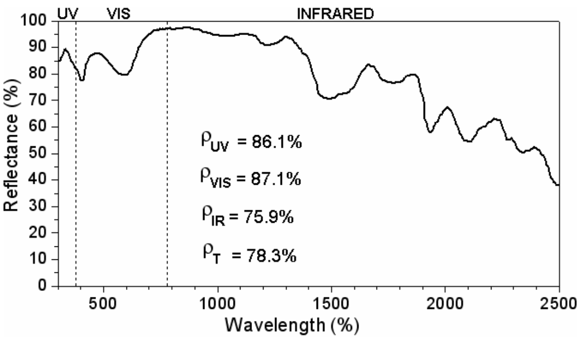

Figure 3: Spectral reflectance curve - white paper.

In order to establish the samples reflectance for each one of the 11 wavelengths, the following procedure was adopted:

a) Turn on the spectrometer and place it over any surface to measure the "dark voltage" that is the voltage measured with no light impinging the sensor in the back of the equipment. Take note of this value. This measurement is for the equipment calibration.

b) Measure the spectral response of the reference sample (white paper) by pressing down the buttons for each wavelength. It is recommended to repeat this procedure for three times to avoid differences among the results. Take notes of these values.

c) Repeat step *"b"*, for each sample

d) With data obtained on steps *a*, *b*, and *c*, the reflectance of each sample is calculated as follows:

$$\rho_{sample} = \left(\frac{V_{sample} - V_{dark}}{V_{reference} - V_{dark}} \right) \times \rho_{reference} \qquad \text{[Eq.1]}$$

ρ_{sample}: sample reflectance, for each wavelength (%);
V_{sample}: sample voltage (mV), for each wavelength;
V_{dark}: dark voltage (mV);
$V_{reference}$: reference voltage (mV) for each wavelength;
$\rho_{reference}$: reference reflectance, for each wavelength (%).

3. RESULTS AND DISCUSSIONS

3.1 Spectrophotometer Measurements

The reflectances of 35 samples were measured using the double-beam spectrophotometer. The samples were divided into four groups to facilitate the analyses (matt acrylic paint, semi-gloss acrylic paint, matt latex PVA paint, and white paper). The samples spectral reflectance curves are presented in figures 4 to 6, also called "samples spectral signatures". Average reflectances for each solar spectrum range were obtained to understand the surfaces spectral behaviour in different wavelengths (Table 1).

When comparatively analysed for the same colour and finish, acrylic paints presented lower reflectance along the solar spectrum than latex PVA paints, as presented on Table 1, for instance, for the samples n° 1 and 32 (White colour), n° 7 and 29 (Sand colour), and n° 10 and 34 (Straw colour).

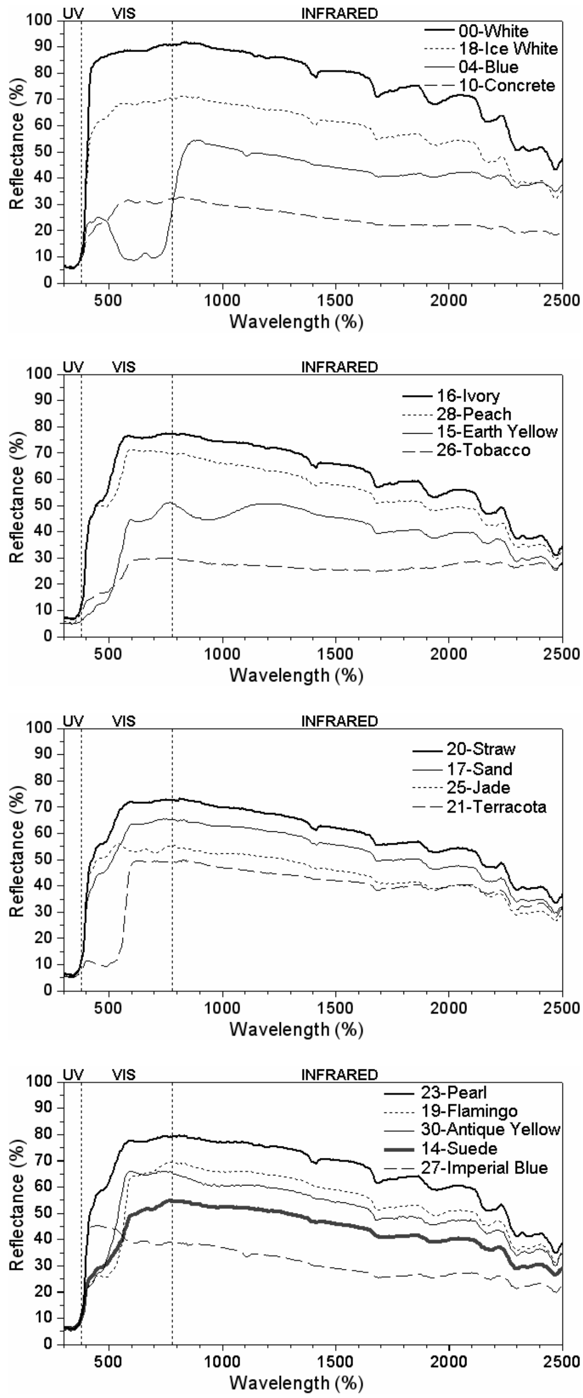

Figure 4: Spectral reflectance curves: Matt Acrylic.

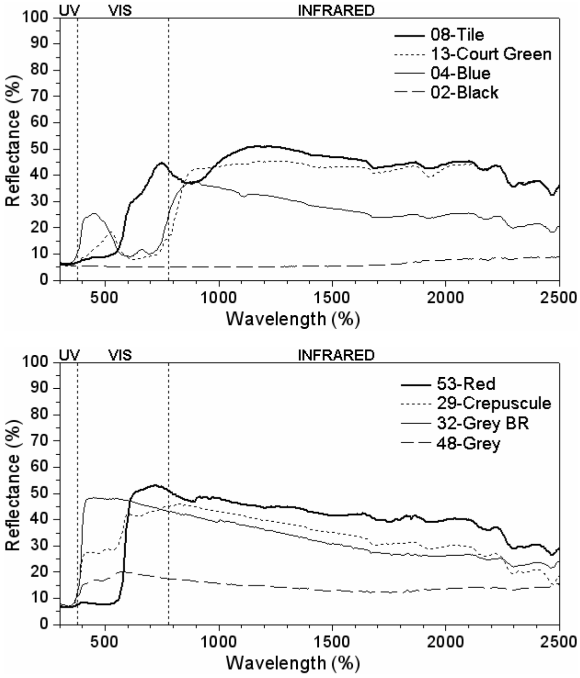

Figure 5: Reflectance curves: Semi-gloss Acrylic.

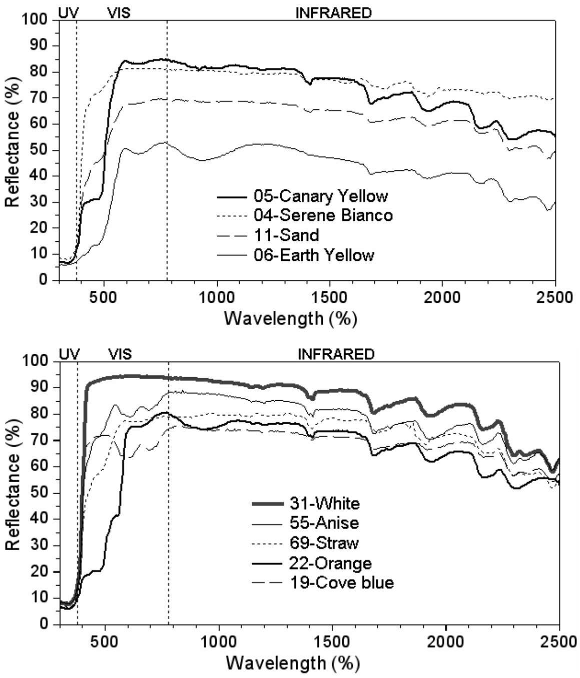

Figure 6: Reflectance curves: Matt Latex PVA.

The finish differentiation of the same paint (matt or semi-gloss) also interferes in its spectrophotometric behaviour. The Blue colour (samples n° 2 and 19) presented a big difference between its reflectances in the near-infrared range (matt: ρ_{IV} = 43.9% and semi-gloss: ρ_{IV} = 27.4%). Although these samples presented very similar reflectances for the visible range (in other words, similar appearance), their total reflectances differ about 13%. Hence care has to be taken when choosing a paint colour only for its appearance, because the chosen paint finish can modify considerably the solar heat gains of a surface.

Table 1: Average reflectances measured with the spectrophotometer (%)

	N°	Commercial Name	UV	VIS	IR	Total
Matt Acrylic Paint	1	00-White	6.7	83.4	75.0	74.1
	2	04-Blue	6.8	15.5	43.9	37.4
	3	10-Concrete	6.4	27.4	24.5	24.4
	4	14-Suede	6.8	41.1	43.4	41.7
	5	15-Earth Yellow	5.2	31.9	41.8	38.7
	6	16-Ivory	7.7	65.3	60.4	59.4
	7	17-Sand	6.4	54.4	51.8	50.6
	8	18-Ice White	7.3	63.6	57.3	56.7
	9	19-Flamingo	6.0	47.0	55.0	51.8
	10	20-Straw	7.0	63.4	58.0	57.1
	11	21-Terracota	5.8	30.8	41.1	37.9
	12	23-Pearl	6.9	67.8	64.4	62.9
	13	25-Jade	7.5	50.8	43.4	43.4
	14	26-Tobacco	7.8	23.6	27.0	25.6
	15	27-Imperial Blue	7.8	40.0	29.3	30.5
	16	28-Peach	6.4	59.9	53.8	53.2
	17	30-Antique Yellow	6.9	50.0	51.0	49.2
Semi-gloss Acrylic Paint	18	02-Black	5.9	5.3	6.5	6.3
	19	04-Blue	7.2	15.8	27.4	24.6
	20	08-Tile	6.3	22.6	43.9	38.6
	21	13-Court Green	5.9	11.4	41.5	34.8
	22	29-Crepuscule	7.8	35.2	33.3	32.7
	23	32-Grey BR	7.8	45.1	30.7	32.5
	24	48-Grey	7.9	18.0	14.1	14.6
	25	53-Red	6.7	28.9	40.9	37.4
Matt Latex PVA Paint	26	04-Serene Bianco	9.3	74.6	75.8	73.2
	27	05-Canary Yellow	7.6	64.5	72.2	68.4
	28	06-Earth Yellow	6.3	35.5	43.4	40.6
	29	11-Sand	7.6	57.4	62.5	59.6
	30	19-Cove Blue	9.5	66.0	68.8	66.2
	31	22-Orange	6.8	52.2	68.2	63.1
	32	31-White	9.0	89.2	83.6	81.9
	33	55-Anise	9.0	75.2	77.8	74.8
	34	69-Straw	7.6	67.4	73.1	69.7
	35	White Paper	86.1	87.1	75.9	78.3

3.2 ALTA II Measurements

With the aid of the ALTA II spectrometer, the 35 samples reflectances were determined from equation 1 for 11 different wavelengths, from 470 to 940 nm. In figures 7 to 10 some comparative graphics are presented for reflectances obtained with the ALTA II and those obtained in the spectrophotometer.

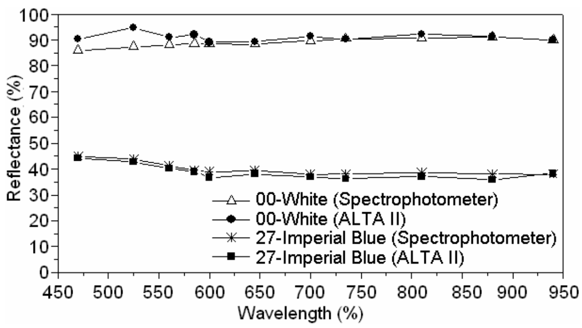

Figure 7: Reflectances: ALTA x Spectrophotometer, Matt Acrylic Paint.

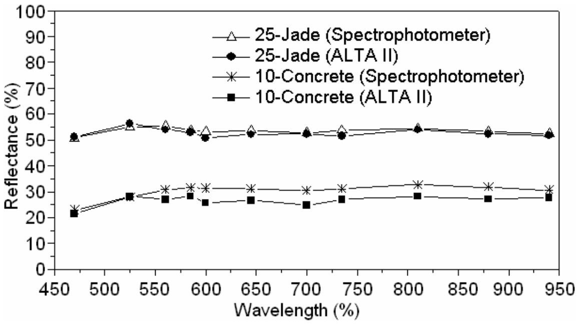

Figure 8: Reflectances: ALTA x Spectrophotometer, Matt Acrylic Paint.

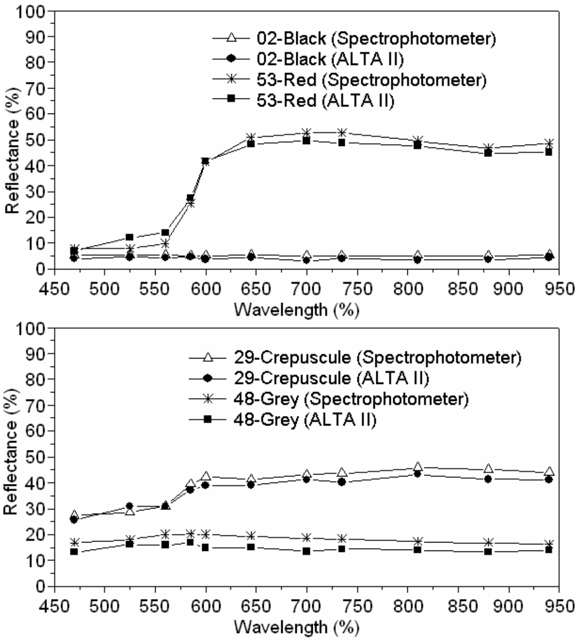

Figure 9: Reflectances: ALTA x Spectrophotometer, Semi-Gloss Acrylic Paint.

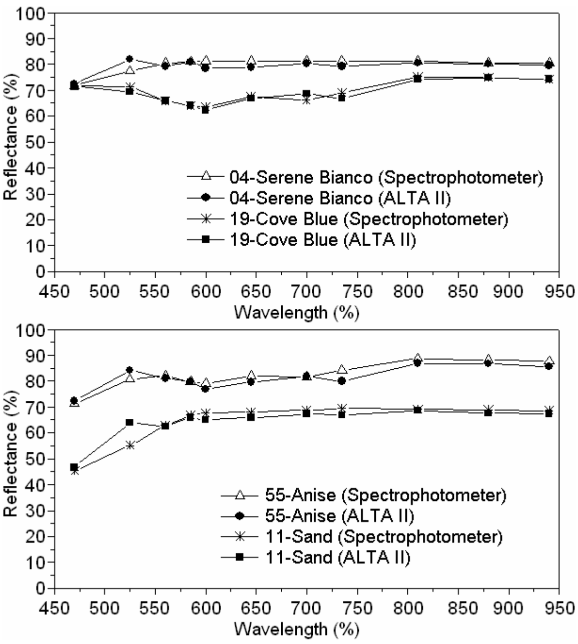

Figure 10: Reflectances: ALTA x Spectrophotometer, Matt Latex PVA Paint.

These graphics show small differences between data obtained in laboratory and those obtained with the ALTA II. This indicates that this equipment can be used as an alternative to the usual techniques to measure reflectances of opaque surfaces.

4. CORRELATIONS BETWEEN ALTA II DATA AND SPECTROPHOTOMETER DATA

From data obtained with the ALTA II spectrometer, it was intended to verify if the samples reflectances could be estimated without spectrophotometers. Through regression analyses, equations were identified to relate the reflectances measured in the spectrophotometer for different spectrum ranges to the reflectance values obtained with the ALTA II, for the 35 analysed samples.

To estimate the reflectance in the visible, near-infrared and total ranges, following equations were obtained:

$$\rho_{VIS} = 5.1269 + 0.2542*\rho_{470} + 0.6542*\rho_{585} \quad [Eq.2]$$

Correlation Coefficient: R = 0.99
Standard Deviation: SD = 2.98

$$\rho_{IR} = -4.6768 - 4.0798*\rho_{880} + 5.0742*\rho_{940} \quad [Eq.3]$$

Correlation Coefficient: R = 0.98
Standard Deviation: SD = 4.03

$$\rho_{T} = -2.7797 + 0.1213*\rho_{735} - 2.7632*\rho_{880} + 3.5739*\rho_{940} \quad [Eq. 4]$$

Correlation Coefficient: R = 0.99
Standard Deviation: SD = 3.26

ρ_{VIS}: estimated reflectance in the visible range (%);
ρ_{IR}: estimated reflectance in the near-infrared (%);
ρ_{T}: estimated reflectance for total solar spectrum (%);
ρ_{470}: ALTA II reflectance at 470 nm (%);
ρ_{585}: ALTA II reflectance at 585 nm (%);
ρ_{735}: ALTA II reflectance at 735 nm (%);
ρ_{880}: ALTA II reflectance at 880 nm (%);
ρ_{940}: ALTA II reflectance at 940 nm (%).

Figures 11 to 13 indicate the first correlations found between reflectances measured with the ALTA II spectrometer and estimated values by regression equations based on the spectrophotometer measurements for the 35 analysed samples.

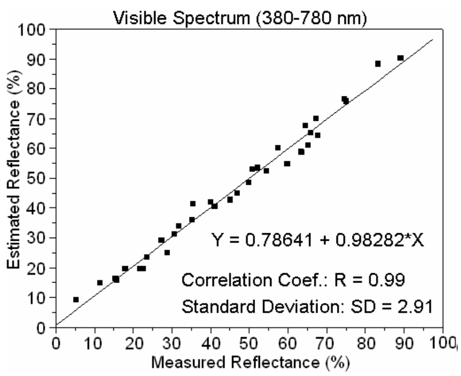

Figure 11: Correlation for the visible range.

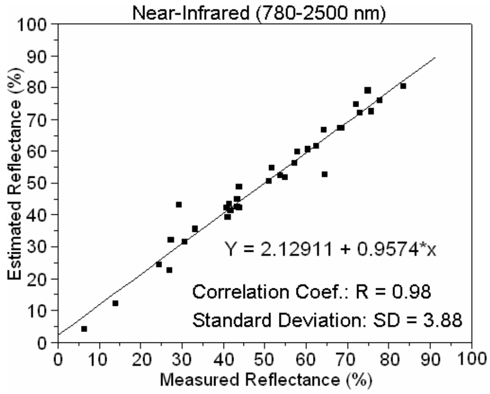

Figure 12: Correlation for the near-infrared range.

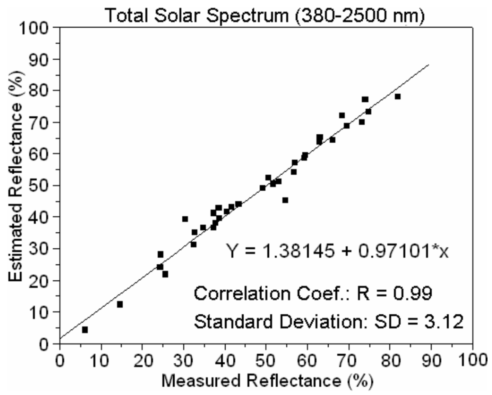

Figure 13: Correlation for the total solar spectrum.

5. CONCLUSION

In this paper, it was presented and discussed a procedure to identify, with very satisfactory accuracy, solar absorptances of opaque surfaces using the ALTA II spectrometer. Reflectance values were obtained in laboratory with spectrophotometer, whose results showed that visual perception is not an appropriate tool to identify this surface property.

Therefore, it is necessary to obtain alternative procedures to measure reflectances and absorptances of opaque surfaces. The correlations found in this work suggest that this procedure is reliable and accessible to specialists, which can be useful as an alternative to the usual techniques to obtain reflectances and absorptances. Furthermore, the low-cost of the ALTA II allows designers and researchers to acquire this equipment without the need to purchase expensive spectrophotometers, which are usually found only in important research laboratories.

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