The effect of incorporating high reflectance pigments in thermal enhanced exterior finishing systems

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Abstract

In the recent years, the concerns on building thermal performance tend to follow the challenges imposed by more demanding building design. The increase of new building materials and technologies with improved thermal characteristics, such as ETICS, thermal mortars and high reflectance coatings, contribute to meet the thermal requirements, by lowering the façade U-value and/or the surface temperature variation.

This paper has the objective of evaluating the effect of incorporating high reflectance pigments in organic coatings applied in thermal systems, such as ETICS and thermal rendering. The effect on the thermal behaviour is also discussed by comparing them with a non-insulated system.

The solar absorptance and the surface temperature of different façade systems with distinct coatings were measured “in situ”. The solar absorptance was measured with a pyranometer with an adapted methodology based on the ASTM E1918 standard. The surface temperature of the specimens was continuously monitored for an extended period enabling a comparison under different climatic conditions.

The results showed that the incorporation of high reflectance pigments allowed a significant decrease of the solar absorptance even in darker colours and that the absence of thermal insulation proved to have a significant effect on the surface temperature.

Keywords: High reflectance pigments, Façade, ETICS, Thermal render, Surface temperature, Solar absorptance.

1. Introduction

In Europe, buildings account for more than 40% of energy consumption and greenhouse gas emissions [1,2]. Increasing the energy efficiency of buildings is crucial for the transformation of the EU energy framework [3].

The use of thermal insulation materials is an effective way to reduce heat losses in buildings by increasing thermal resistance through the building envelope. In addition, new eco-efficient materials and technologies have been developed to mitigate the climatic requirements of buildings [2,4]. One of these technologies corresponds to the application of reflective materials, which are defined as having high solar reflectance and high emission of infrared radiation. The use of reflective materials is intended to contribute to the reduction of cooling loads, a goal that is a prerequisite for achieving the Near Zero Energy Buildings as defined by the Building Energy Performance Directive 2010/31/EC [5]. Another benefit of these materials is to increase the range of colours applicable in urban coatings.

Reflective coatings have been shown to have a considerable effect in improving internal and external thermal comfort, while reducing the energy consumption of buildings [6]. The colour change can contribute to the energy efficiency by reducing the cooling load by almost 20% [7].

Evaluating the actual performance of these innovative solutions is fundamental to the generalization of their application. In this work, a methodology was developed to evaluate the thermal performance of coatings, including ETICS specimens with different colours and / or with the addition of refining pigments.

2. Solar reflectance

2.1 Basic principles

The materials that constitute the envelope of a building are, obviously, determinants for its thermal and energetic performance, since the heat exchanges (conduction, radiation and convection) between the interior and the exterior are conditioned by their properties.

In relation to heat exchanges by radiation, the sun is the main source of radiation (which affects the building in the form of shortwave) and its effect on the building essentially depends on the solar reflectance (ρ) and solar absorption (α) of the materials of coating. These properties are defined as follows:

$$\rho = \frac{q_r}{q_i} \quad [1]$$

$$\alpha = \frac{q_a}{q_i} \quad [2]$$

where q_r is the incident energy reflected, qi is the incident energy and q_a is the incident energy absorbed. The solar reflectance is thus the ratio between the rate of solar radiation reflected by a surface and the rate of solar radiation incident on it and the solar absorptance is the ratio between the solar radiation rate absorbed by a surface and the incident solar radiation rate in the same. There are several standardized methodologies for measuring these properties [8-10].

Reflectance and absorptance assume values between 0 and 1, being sufficient to know one of these properties of the surface, since their sum on opaque surfaces is always unitary (α + ρ = 1). As an example, a sample with solar reflectance of 1.0 means that its surface temperature will not suffer any effect from the incident radiation, since no radiation will be absorbed. With regard to absorbed energy, part will be emitted in the form of long wave radiation to the outside and the other part emitted into the interior by conduction along the construction element (Figure 1).

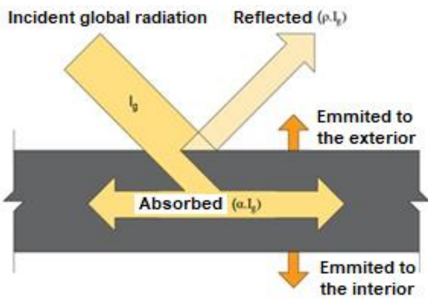


Figure 1: Radiation heat exchanges in an opaque material

2.2 Measurement procedures in opaque surfaces

In the evaluation of the thermal and energetic performance of buildings, the absorptance is the parameter typically adopted in the normalization to characterize the coating materials. However, since it is generally simpler to measure the portion of incident solar radiation that is reflected rather than the absorbed one, it is common to use reflectance measurement methods and then to determine the absorbance.

The American Association for Testing and Materials (ASTM) suggests three methods of measuring surface reflectance, whose procedures and equipment are defined in specific standards.

The standard ASTM E903-12 (2012) – "Standard Test Method for Solar Absorption, Reflectance and Transmittance of Materials Using Integrating Spheres" [8] – proposes a methodology based on the use of a UV-VIS-NIR spectrophotometer equipped with integration sphere to measure, in laboratory, the reflectance to the solar spectrum of a flat and homogeneous surface of reduced dimensions. A light source emits a beam with a wavelength range between 250 and 2500 nm, which corresponds to approximately the same wavelengths as those of the solar spectrum. This equipment will subsequently measure through two detectors (one detector measures the ultraviolet and visible bands, and the other the near infrared band) the energy that is reflected at each wavelength, considering a constant energy across the spectrum. Being the spectral reflectance given by the ratio of the reflected energy to the incident. However, it should be noted that the intensity of the solar radiation is not constant throughout the spectrum. Thus, to obtain the solar reflectance, it is necessary to correct the values of this spectral reflectance based on the intensity of the solar radiation of each wavelength and to integrate in the measured range [11].

The ASTM standard C1549-09 (2014) – "Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer" [9] – proposes a methodology for the measurement of the solar reflectance of flat and opaque materials through a portable solar reflectometer, also called SSR (Solar Spectrum Reflectometer). The portable solar reflectometer consists of a measuring head, which has a diffused tungsten-halogen lamp. This source causes an electromagnetic radiation on the surface of the sample during three measurement cycles of 10 seconds each. The radiation reflected by the surface at different wavelengths will be measured by a set of four detectors (inclined at an angle of 20 ° to the direction of the incident radiation) designated L1 (near infrared), L2 (red), L3 (blue) and L4 (ultraviolet). This equipment, however, only performs the measurements for a relatively small wavelength range when compared to the spectrophotometer. In fact, the portable solar reflectometer only measures four wavelengths: 380, 500, 650 and 1220 nm, thus explaining the need for the four detectors. In addition, the procedure implies a previous calibration of the equipment, which will serve as a basis for the extrapolation of the measurements. This calibration corresponds to the measurement of a black body (zero reflection) and standard specimens with high reflectance. In addition, this equipment allows measurements in laboratory and in-situ in larger specimens (greater than 2.5 cm in diameter of the measurement head opening) [12,11].

The proposed ASTM E1918-06 (2015) – "Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-sloped Surfaces in the Field" [10] – proposes a method for measuring in-situ solar reflectance of horizontal or low slope surfaces (lower than 9.5° or 16.7% relative to the horizontal plane) using a pyranometer. In addition to being able to be applied in situ, this method allows the measurement of large surfaces, unlike the method of ASTM E903-12 [8]. On the other hand, its application is conditioned when it comes to curved or very rough surfaces. The pyranometer is an equipment that measures the total amount of solar energy radiated on a surface per unit of time and unit area. It can also be used to measure the total radiant solar energy that is reflected on a surface per unit time and unit area. From these measurements, it is possible to determine the solar reflectance of the surface. During the test, the equipment is placed at the end of an "arm" about 1 to 1.5 meters parallel to the surface of the sample, which is secured to a support structure that is aligned toward the sun. This "arm" must be thin and long, in order to make the least possible shade on the surface to be analyzed, and it must also enable rotational movements around its axis, so that in a first phase the pyranometer is facing up (measuring incident solar radiation) and a second downward-facing phase (measuring reflected solar radiation). These measurements, carried out in phases, must be constant for at least 10 seconds and be carried out within a time interval of less than 2 minutes. The procedure must be repeated at least three times, and the solar reflectance values cannot vary more than 0.01 from each other on a scale of 0.00 to 1.00. The solar reflectance of this surface corresponds to the average of these three values. The equipment must be at least 50 cm away from the surface under analysis, and this distance will have an influence on the dimensions of the sample, since its dimensions (diameter or side) must be at least 8 times this distance. Thus, if the sample is circular, it must be at least 4 m in diameter, and if it is quadrangular, its sides must be at least 4 m. It should also be noted that this methodology can only be applied on clear, sunny, cloudless or hazy days, and the surfaces of the specimens should be homogeneous and dry. If these conditions are met, the test shall only be performed when the angle of the sun to the normal surface is less than 45°.

3. Materials and methods

3.1 Materials

The proposed methodology was applied to a set of specimens constituted by three distinct layers:

- Finishing coating: organic coating composed by mineral fillers, resins in aqueous dispersion, pigments and specific additives (antifungals and others);
- Base coat: cement, mineral fillers, resins, synthetic fibres and special additives;

- Insulation or concrete slab:
    a. EPS slab: expanded polystyrene 20 kg/m^3;
    b. Thermal render (TR): lime, mineral fillers, EPS granules, special additives;
    c. Concrete slab: lightweight concrete (LC).

To evaluate the effect of high reflectance pigments (HRP), some specimens include these pigments in the finishing coating. The referred pigments are “Navapint D Solar Reflective", from "Chromaflo Technologies". They result of a combination of the conventional pigments used in façades, which have good solar reflection, with a black pigment reflective in the near infrared zone, designated D803 [13].

The finishing coating consists of a thin layer of mortar of approximately 2 mm. The base coat is applied in two layer of 1.5 mm with a glass fibre mesh between them. The insulation slab has a thickness of 4 cm, while the lightweight concrete has 12.5 mm. Taking into account the different variables, a total of 8 specimens, with 1x1 m^2, were placed horizontally on a roof of the Civil Engineering Department of the University of Porto, as shown in Figure 2.

The specimens shown in Figure 2-a) and the white one in Figure 2-b were under natural ageing since 2016. The 3 remaining specimens were placed one year later (in 2017). The newest specimens also have a primer, between the base and the finishing coating, and the finishing also includes high reflectance pigments and TiO_2. Table 1 presents the constitution of the different specimens. Excluding the white specimen, all the remaining present the same black colour.

a) b)

Figure 2: Analysed specimens: a) 3-years ageing; b) 2-years ageing (excepting the white specimen).

Specimen	**Substrate**			**Base coat**	**Finishing coating**		
	EPS	TR	LC		Regular	With HRP	Primer+HRP+TiO_2
TR		X		X	X		
TR_{HRP}		X		X		X	
ETICS	X			X	X		
$ETICS_{HRP}$	X			X		X	
White (W)	X			X	X		
$ETICS_{TiO2}$	X			X			X
TR_{TiO2}		X		X			X
LC_{TiO2}			X	X			X

Table 1: Constitution of the specimens.

3.2 Experimental methodology

In this research, the performance of coating materials was evaluated by determining their solar absorptance and the maximum surface temperatures reached by the surfaces.

The evaluation of solar absorptance was carried out using a method called E 1918A, proposed by Akbari and Levinson [14]. This method consists of an adaptation of the ASTM E1918 Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-sloped Surfaces in the Field [10] described in section 2.2. The E 1918A method also uses a pyranometer in measuring the radiant solar energy that is incident and the energy that is reflected at the surface per unit time and unit area. However, unlike the original procedure that is indicated for large surfaces, this method allows the measurement of square surfaces with an area of 1 m^2. In the tests carried out in this work, a SR05 Hukseflux Thermal Sensors pyranometer was used, which presents an estimated precision of 4.4%. This pyranometer meets the requirements of the second class of ISO 9060 [15].

The application of the method assumes a 3-step measurement, where the sample itself is evaluated, and the effect of a black mask and a white mask that allow eliminating the contribution of the contour to the reflection detected by the pyranometer. The measurement procedure is repeated three times and the resulting mean is calculated. At the time of measurement, clear sky conditions and an angle of the sun with normal specimen surface area of less than 45° are required.

Surface temperature measurement was performed using T-type thermocouples using a standard metal combination (Copper Alloys and Constantan Alloys), and are attached to a Technetics datalogger designated by Mikromec Logger Multisens. The measuring accuracy is 0.2°C and at least two thermocouples were always applied in each sample. The ambient temperature was recorded by the LFC-FEUP weather station.

4. Results and discussion

The results will be presented in terms of solar reflectance and surface temperature, in order to evaluate the influence of high reflectance pigments and the existence of a thermal insulation layer. The influence of the high reflectance pigments will be analysed regarding the 3-year ageing specimens (TR, TR_{HRP}, ETICS, $ETICS_{HRP}$ and W), while the influence of the existence of thermal insulation will be analysed using the 2-year ageing specimens ($ETICS_{TiO2}$, TR_{TiO2} and LC_{TiO2}).

4.1 Solar reflectance

4.1.1 Influence of the high reflectance pigments

The solar reflectance of the specimens was measured once per year since year 0 until year 3, as shown in

Figure 3.

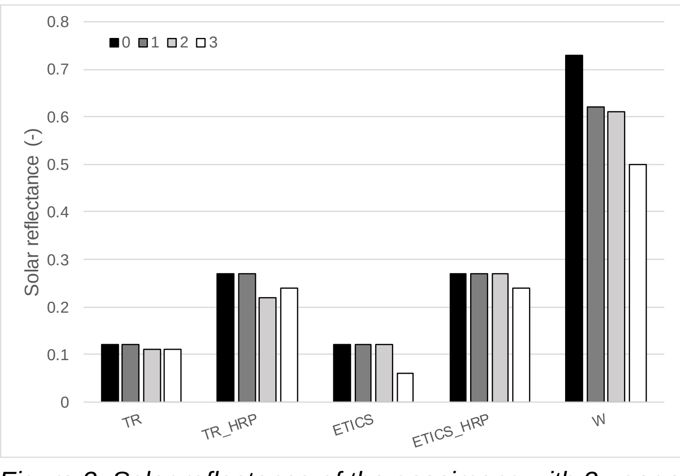


Figure 3: Solar reflectance of the specimens with 3-year ageing.

As it can be observed, the solar reflectance more than doubles when comparing the same system (ETICS or TR) with high reflectance pigments, with the same colour. This highlights a potential benefit of the incorporation of these specific pigments in façades by reducing the heat absorption of dark coatings.

In addition, the solar reflectance of the darker coatings is not significantly affected by the natural ageing since the values present a low variation in the 3-year monitoring. However, the white coating presents a significant decrease of the solar reflectance capacity, which could be attributed to the colour yellowing and waste deposition (favoured by the high roughness of the finishing coating).

4.1.2 Influence of the thermal insulation

The specimens influence of thermal insulation is depicted in Figure 4. The existence of thermal insulation prove not to have a direct influence on the solar reflectance, since the values are similar regarding ETICS, thermal render and lightweight concrete systems. Therefore, the constitution of the finishing coating proved to be dominant in obtaining specific solar reflectance values.

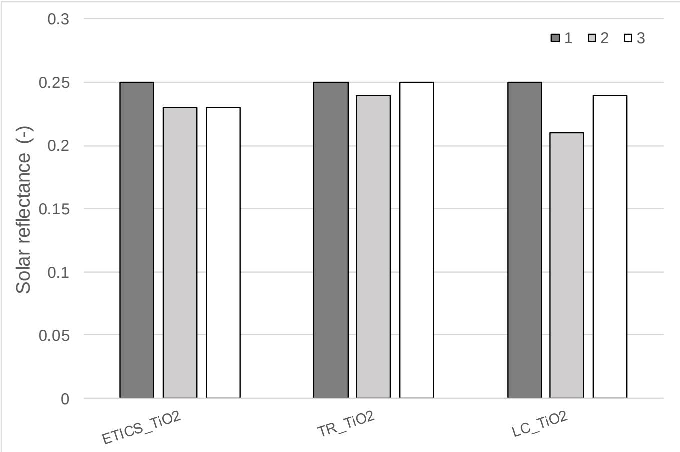


Figure 4: Solar reflectance of the specimens with 2-year ageing.

4.2 Surface temperature

4.2.1 Influence of the high reflectance pigments

Regarding the impact of the high reflectance pigments in terms of exterior surface temperature, the registered maximum temperature was analysed and compared to the exterior air temperature at the same period, as shown in Table 2. Due to a technical problem in the thermocouples, it was not possible to register the maximum surface temperature in some specimens in year 2.

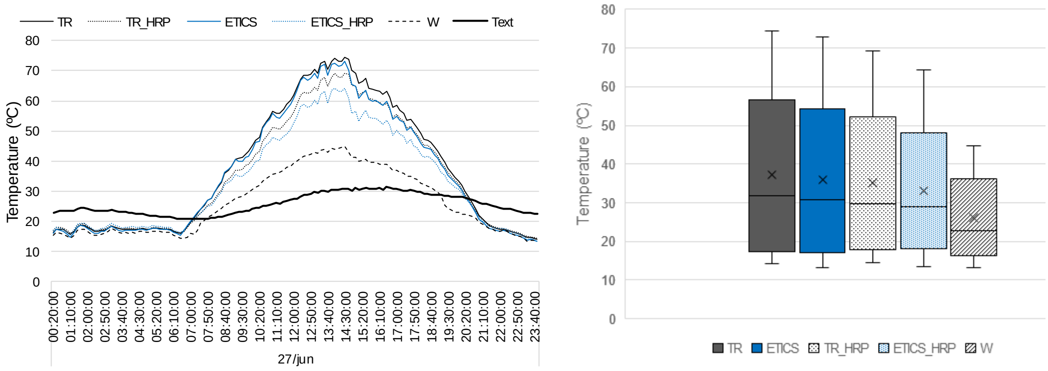
Year	**0**		**1**		**2**		**3**	
T (ºC)	$T_{surf,max}$	T_{ext}	$T_{surf,max}$	T_{ext}	$T_{surf,max}$	T_{ext}	$T_{surf,max}$	T_{ext}
TR	76.5	34.9	68.7	25.0	-	-	67.3	25.0
TR_{HRP}	71.1	34.9	64.3	25.0	-	-	64.4	25.0
ETICS	75.6	34.9	67.4	25.0	-	-	73.5	32.3
$ETICS_{HRP}$	68.2	34.9	60.8	25.0	-	-	72.4	32.3
White (W)	49.0	34.9	57.5	37.0	50.6	24.4	58.8	32.3

Table 2: Maximum surface temperatures and respective exterior air temperature in 3-year ageing specimens.

In general, and as expected, the higher the exterior air temperature the higher the maximum surface temperature. The inclusion of high reflectance pigments also reduces the maximum surface temperature in approximately 7% and 10% in TR and ETICS, respectively, in the first 2 years. However, the natural ageing promoted a decrease of the effect of high reflectance pigments. Considering the white sample, a quite significant difference, comparing to $ETICS_{HRP}$ (lower temperature registered regarding the black colour), is observed (around 30%). However, the decrease of solar reflectance contributes to lowering the difference in

10%, after 3 years of ageing.

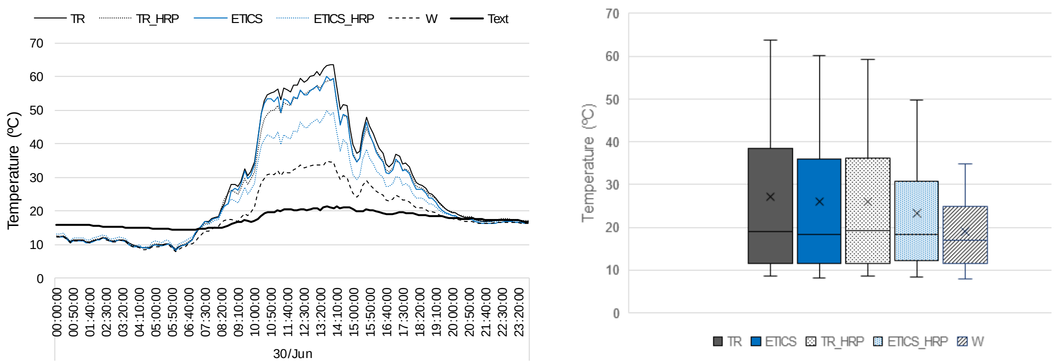
Observing a clean sky situation (in year 0), presented in Figure 5, it can be observed that the specimens without HRP presented higher surface temperatures with the incidence of solar radiation. In addition, the presence of HRP contribute to reduce the temperature amplitude. The TR also reached higher values than ETICS, which could be related to the higher thermal effusivity of the TR (higher ability to absorb heat).



a) b)

Figure 5: Surface temperature variation in clean sky situation in year 0: a) Temperature vs Time; b) Box-plots.

Observing a cloudy sky situation (in year 0), presented in Figure 6, the inclusion of HRP had the same effect on reducing the surface temperature. The presence of clouds resulted in less stability, which highlights the effect of the higher thermal diffusivity of EPS when compared to TR. The higher the thermal diffusivity, the lower the time to reach equilibrium, which could be observed by the quick decrease of temperature in ETICS comparing to TR, resulting in lower amplitudes.



a) b)

Figure 6: Surface temperature variation in cloudy sky situation in year 0: a) Temperature vs Time; b) Box-plots.

Observing a clean sky situation (2 days in year 3), presented in Figure 7, the inclusion of HRP had the same effect on reducing the surface temperature. However, it can be observed that the TR presented lower temperatures than ETICS, contrary to the previous years. The ageing and the higher water absorption of the thermal render contribute to the increase of the water content and consequently to the decrease of the temperature.

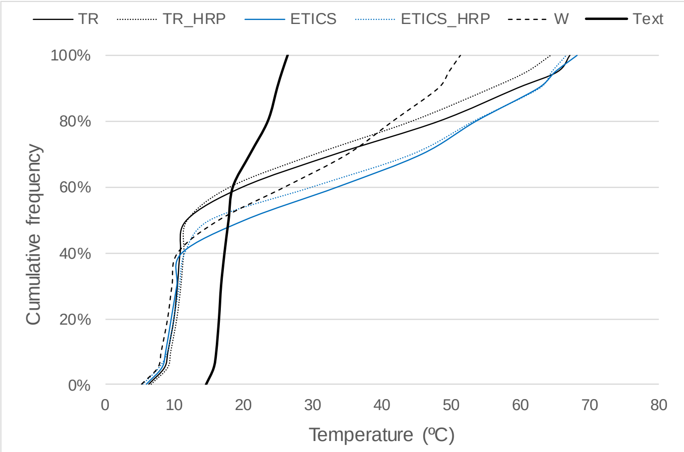


Figure 7: Cumulative frequencies of surface temperature in year 3.

4.2.2 Influence of the thermal insulation

The effect of the existence of a thermal insulation layer on the surface temperature was analysed and could be observed in Table 3. Due to the problems with the thermocouples, it was not possible to register the maximum surface temperature of 2 specimens in year 2.

Year	**1**		**2**		**3**	
T (ºC)	$T_{surf,max}$	T_{ext}	$T_{surf,max}$	T_{ext}	$T_{surf,max}$	T_{ext}
$ETICS_{TiO2}$	73.1	37.0	67.8	24.4	71.8	33.2
TR_{TiO2}	73.0	37.0	-	-	66.3	25.3
LC_{TiO2}	66.7	37.0	-	-	61.9	33.5

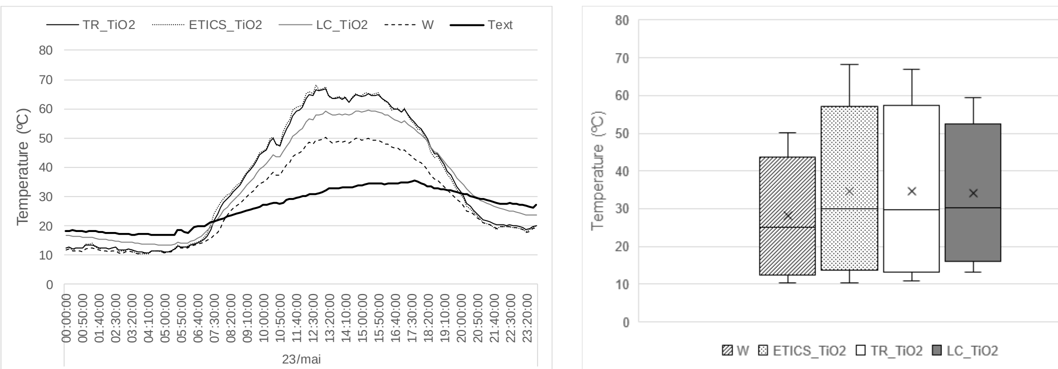
Table 3: Maximum surface temperatures and respective exterior air temperature 2-year ageing specimens.

It is obvious the effect of the existence of thermal insulation in the increase of the surface temperature. As explained by equation (3), considering the summer period ($T_e > T_i$), the higher the thermal transmission the lower the surface temperature (T_{se}).

$$T_{se} = T_e - U \cdot R_{se}(T_e - T_i) \qquad [3]$$

Where R_{se} is the exterior surface resistance. As such, the temperature dissipation rate is different for each configuration.

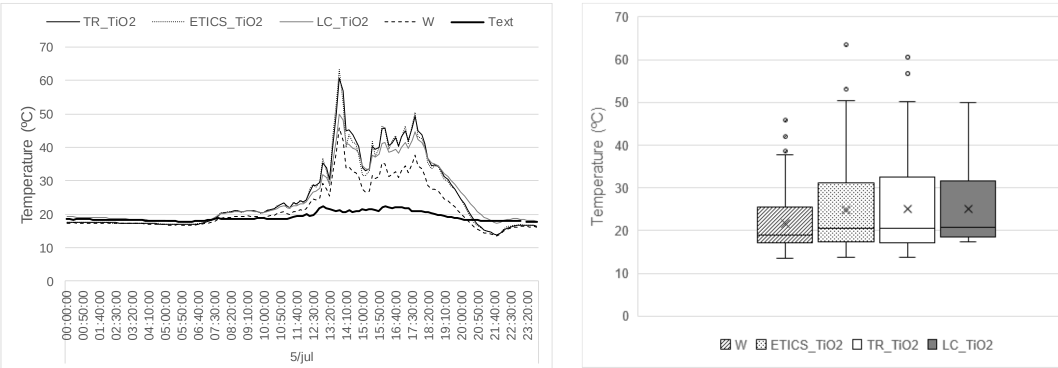
Observing the clean sky situation (in year 1), presented in Figure 8, this effect can be confirmed and also a non-significant difference between TR and ETICS can be observed.



a) b)

Figure 8: Surface temperature variation in clean sky situation in year 1: a) Temperature vs Time; b) Box-plots.

Observing a rainy day situation (in year 1), presented in Figure 9, the thermal shock effect can be detected, where an abrupt decrease of temperature is observed due to cold rain incidence in a hot surface, especially in systems with thermal insulation layer.



a) b)

Figure 9: Surface temperature variation in rainy situation in year 1: a) Temperature vs Time; b) Box-plots.

Observing a clean sky situation (2 days in year 3), presented in Figure 10, the TR showed the same kind of behaviour (lower temperatures than ETICS) as observed in 4.2.1, after 3 years of ageing. Once again, the lightweight concrete presented lower temperature amplitude.

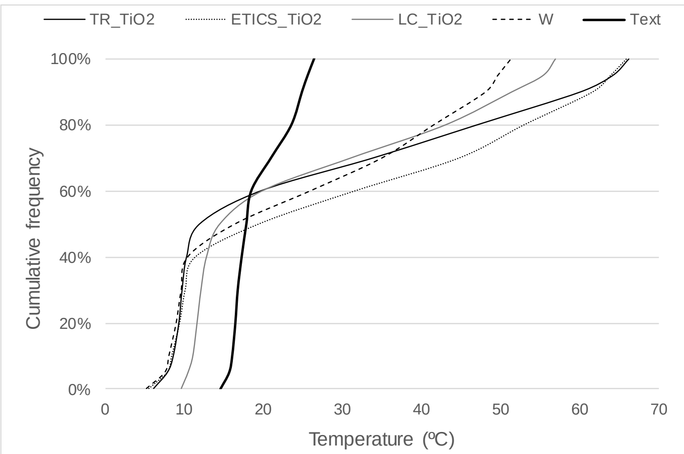


Figure 10: Cumulative frequencies of surface temperature in year 3.

5. Conclusions

In exterior façade thermal insulation systems, such as ETICS, the final layer properties are very important for the overall performance of the system. The solar absorptance is particularly determinant for the thermal performance of these systems and contributes decisively to their durability.

The inclusion of high reflectance pigments contribute directly to a significant increase of the solar reflectance and consequently to the decrease of surface temperature, even in darker colours: the higher the solar reflectance the lower the surface temperature.

In the summer period, the existence of thermal insulation contributes to the increase of the maximum surface temperature and to the temperature amplitude when compared to a traditional system without insulation (substrate and cementitious render).

The natural ageing did not promoted a degradation of the solar reflectance properties of the studied dark coatings, while contributed to an increase of the solar absorptance of the white sample due to the yellowing and waste accumulation. In addition, a faster degradation of the thermal rendering system, comparing to ETICS was observed.

In summary, thermal wall systems with the inclusion of high reflectance pigments can contribute to a significant increase of the durability of façades, by lowering the thermal induced stresses. However, the thermal system should be well analysed regarding the climatic conditions where it will be applied.

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