NIR reflective Paints as an Alternative for Sustainable Façade Renovation

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Abstract. Several studies of infrared reflective materials used on opaque envelopes have shown that their application can reduce the surface temperature and the cooling energy needs of buildings and help mitigate the urban heat island effect. Some of these studies were carried out by incorporating near-infrared (NIR) reflective materials on new buildings or as part of new construction systems, considering that one of the simpler and most used façade renovation methods is repainting. In a repainting process, the reflectance could change since the reflectance depends on the interaction between the reflective layer and the substrate. A study was carried out on the reflectance of paints with NIR reflective properties applied on the finishing coat of external thermal insulation composite systems (ETICS), simulating a façade renovation. A black NIR reflective paint was applied in one layer over the existing finishing coat of two ETICS samples: one with a grey mortar colour and another with a conventional black colour. A second configuration was considered by adding an intermediate layer of regularisation with white colour. Traditional black colour and the mortars were applied on a transparent acrylic base as a reference. The samples were assessed with a modular spectrophotometer to assess the total and NIR reflectance and the colour coordinates on the CIELab space. The results showed that the reflectance and colour of the new layer are independent of the colour or type of the first layer in the case of conventional paint. Conversely, the substrate affects the NIR paint performance, where a lighter substrate can help improve the reflectance but can also lead to a more significant colour change. Likewise, the results of the paint over a new white layer resulted in a lower reflectance compared to the reflectance of a single paint layer.

1. Introduction

The search for sustainable buildings meets the need to evaluate energy improvement strategies aimed at reducing the annual demand for energy in the use of the building [1]. Recent studies estimate that the energy efficiency concerning building heating and cooling could be optimised with thermal retrofits of building envelopes [2, 3].

External Thermal Insulation Systems (ETICS) have been considerably applied as an insulation system to improve the thermal performance of buildings. However, exposure to weathering leads to physical-aesthetical anomalies [4]. The colour of the finishing coat of ETICS can impact the durability of the system [5] since it contributes to the protection against weathering but can cause thermal shock leading to cracking and the loss of hygrothermal performance. To prevent thermal stress, the European Association for the External Thermal Insulation Composite Systems (EAE) [6] recommends that the finishing coat should have a solar absorption under 70% and the surface temperature should not go above 80º C. But coatings with dark colours like brown, grey, and black could present around 80% and 95% solar absorption, as demonstrated by Ramos *et al.* [7].

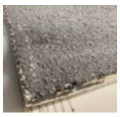
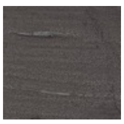
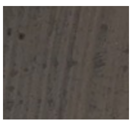
To minimise the effect of the high solar absorption of dark paints, a new family of near-infrared pigments, i.e., cool paints, are being used on new coatings or as paint [8, 9]. These pigments can improve the solar reflection on the infrared region, leading to lower surface temperature, and keeping the visual aspect. Therefore, this paper aims to evaluate the use of paints with high near-infrared (NIR) reflectance as a possibility to improve the façade with ETICS assessing the thermal and optical properties of the painted system.

2. Materials and methods

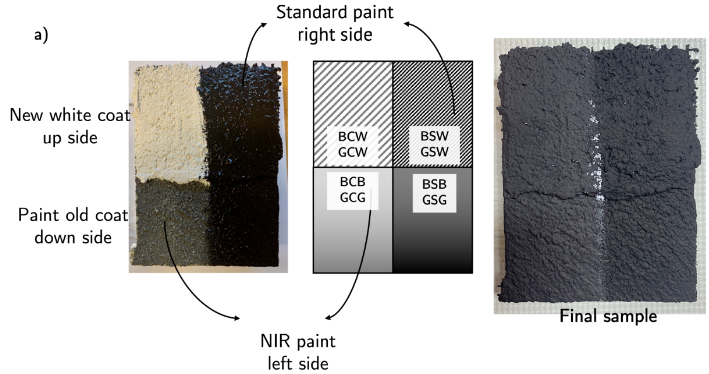
2.1. Materials and sample preparation

Extracted samples of ETICS were prepared to simulate the façade renovation. The properties of the ETICS original system, the used paint pigment and regulating mortar are detailed in Table 1.

Table 1. ETICS and materials characterisation.

Sample	Composition	Physical and optical properties			
		Thickness (mm)	Reflectance ASTM E903		CIE Lab
			Total	NIR	
	• Insulation slab: EPS. • Base coat: commercial cementitious mortar on grey colour. • Finishing coat: not present	• EPS: 40 • Coat: ± 6.40	0.270	0.298	L=56.384 a*=0.215 b*=5.608
	• Insulation slab: EPS. • Base coat: commercial mortar cement based. • Finishing coat: commercial mortar with organic mineral fillers, resins in aqueous dispersion, pigments, and specific additives on black colour.	• EPS: 40 • Coat: ± 2.50	0.076	0.085	L=30.959 a*=-0.255 b*=-0.087
	• Inorganic generic pigment name PBr29. • Aqueous dispersion 74%. • NIR Black chrome iron chromium oxide base. • Very dark brown almost black, blueish black tones.	• Not applicable	0.202	0.299	L=33.413 a*=0.433 b*=-1.953
	• Inorganic generic pigment name PBk11. • Aqueous dispersion 48%. • Ferroso-ferric oxide-based. • Dark grey or black w/ bluish to yellowish undertones.	• Not applicable	0.076	0.094	L=27.287 a*=0.739 b*=-3.402
	• Organic coating with high performance on white colour. • Commercial mortar based in selected mineral fillers, resins in aqueous dispersion pigments and specific additives.	• Not applicable	0.615	0.591	L=87.047 a*=-1.026 b*=0.942

The ETICS samples, a sample of 10 x 10 cm for each system, were cut-off systems previously submitted to natural ageing. Besides, they were washed with water, air-dried (24 ºC) for 48h and submitted to a renovation process. The paint samples were separated in quarters, with the left side painted with NIR reflectance, the right side with the conventional colour and a regulation layer with a white coating in the upper part of the samples. Figure 1 shows the process and the final sample.



b)

Final sample	Original base 1 layer	Paint 2 layer	Layer under paint
BCB BCW BSB BSW	B – Black system	C – NIR	B – Black original W – White new regulation layer
GCG GCW GSG GSW	G – Grey system	S – Standard	G – Grey original

Figure 1. Final sample: a) Paint procedure, b) Sample code explanation.

2.2. Methods of evaluation

The samples were assessed considering optical and thermal parameters, reflectance, colour, emissivity, and surface temperature.

The reflectance (R) was measured using a modular spectrophotometer (FLAME-T and FLAME-NIR Ocean Optics) equipped with an integrating sphere of 30 mm diameter. The spectral reflectance was calculated based on the 100 selected ordinates, as defined by equation (1) according to ASTM E903ASTM E903 [10] and tables of ASTM G197 [11]:

$$SR_{spectral} = \sum_{i=1}^{100} R\lambda/100 \tag{1}$$

where *R* is the measured total reflectance by the spectrophotometer, and λ is the wavelength weight of ASTM E903 [10]. The average reflectance value was obtained after three records for each sample.

The colour parameters were given in the CIE Lab colour space [12] using the FLAME-T spectrophotometer on the illuminant D65 10º complimentary observer's condition. The measurements were conducted in triplicate for each colourimetry parameter, and the colour difference between the ETICS samples and the Acrylic control was calculated by equation (2) [12].

$$\Delta E^*_{ab} = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{2}$$

Where ΔL, Δa, Δb is the colour coordinates variation between two surfaces.

The infrared emittance (ε) was measured using Devices and Services emissometer model AE, as preconises ASTM C1371 [13]. This emittance device determines the total thermal emittance compared to standard high (0.88) and low emittance (0.05) materials.

Equation (3), described in Akbari *et al.* [14], was used to verify the performance of painting ETICS with black colour with the surface temperature (T_s) calculated for two cities in Portugal. The temperature was calculated using the measured reflectance and emittance values and the maximum air temperature and the solar irradiance on tilted surface (Total surface radiation) of EnergyPlus weather files.

$$(1-R)I = \varepsilon\sigma\left(T_s^4 - T_{sky}^4\right) + h_c(T_s - T_a) \tag{3}$$

Where I is the surface incident solar flux (W/m^2), T_s is the surface temperature (K), ε corresponds to the emittance, T_{sky} is the sky temperature (K), σ is the Stefan Boltzmann constant (5.67x10^{-8} W/m^{2}K^4), h_c is the convective coefficient (18.5 W/m^{2}K), and T_a is the air temperature (K).

3. Results and discussion

3.1. Emissivity and reflectance

The optical properties of the ETICS and control sample are given in Table 2, while the spectral reflectance is exhibited in Figure 2.

Table 2. Optical properties.

Sample	Emissivity	Reflectance	Sample	Emissivity	Reflectance
ASW	0.92	0.129 ± 0.006	BCB	0.91	0.118 ± 0.009
ACW	0.92	0.065 ± 0.016	GSW	0.90	0.070 ± 0.066
BSW	0.91	0.064 ± 0.007	GCW	0.89	0.148 ± 0.035
BCW	0.90	0.107 ± 0.007	GSG	0.90	0.079 ± 0.003
BSB	0.91	0.077 ± 0.001	GCG	0.88	0.176 ± 0.018

From the results of Table 2, it can be observed the influence of the roughness in the emissivity values. Smooth surfaces have lower values than rough surfaces.The grey ETICS surface coat is smoother than the black and has lower emissivity results. Besides, in the rough surface, using near-infrared paint reduces the emissivity, e.g., BSW vs. BSB, an effect not verified on the standard paint. This roughness effect also was confirmed by Sharma *et al.* [15].

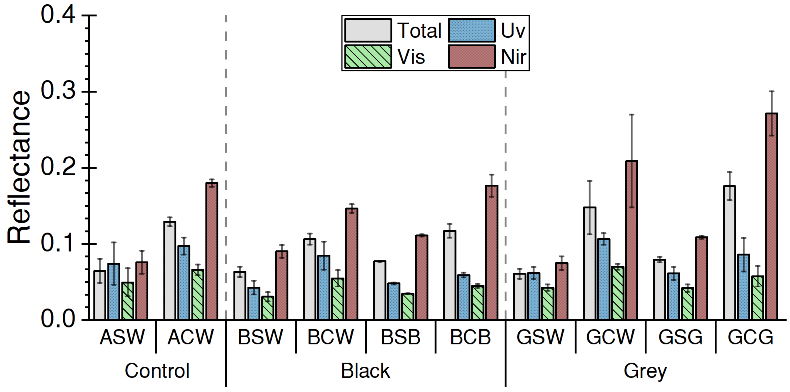


Figure 2. Reflectance values ASTM E903.

The total reflectance evaluates the efficiency of the solar spectrum (direct and diffuse). In this case, the grey system showed a higher efficiency than the black system, considering the samples with NIR reflectance colour (GCW and GCG). A significant difference between the colours was not found in the samples that used standard paint, as seen in Figure 2.

As expected, using the near-infrared reflectivity paint (samples with C) increased the total reflectance (see Figure 3). The gain was 67% in samples with the original black system using the regulation layer (BCW vs. BSW), while in the grey system, the improvement was 123% without the regulation layer (GCG vs. GSG). The reflectance modification due to NIR reflectance was also verified in [7, 16].

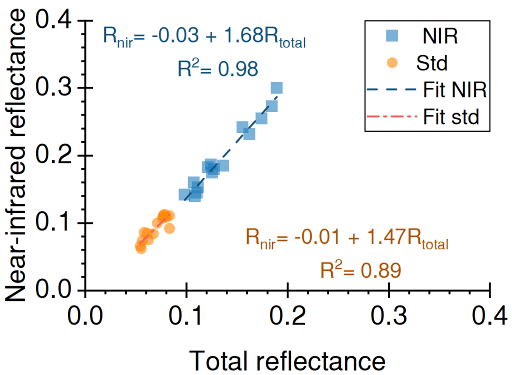


Figure 3. Correlation between NIR and total reflectance.

Figure 4a and Figure 4b present the reflectance spectral behaviour of the system after paint, respectively, for the UV-Vis and NIR regions. On the ultra-violet region, the BCW has higher initial values than the others, which can be explained by the UV protection of the white coat. In contrast, on the visible region, no significant variations between samples are verified, indicating an unimportant alteration in colour. Moreover, it was expected that the visible reflectance would keep under 10% to black colours, as found in [17, 18] (see Figure 4a).

The NIR reflectance paint affects the near-infrared spectra (Figure 4b), BCB and GCG have the higher reflectance distribution, while the standard pain leads to a lower value, BSW and GSW. On the other hand, the presence of the regulation layer reduces the NIR reflectance in all cases, regardless the original system and the type of paint. The NIR paint, GCG and GCW are more effective in improving the reflectance in grey than in black.

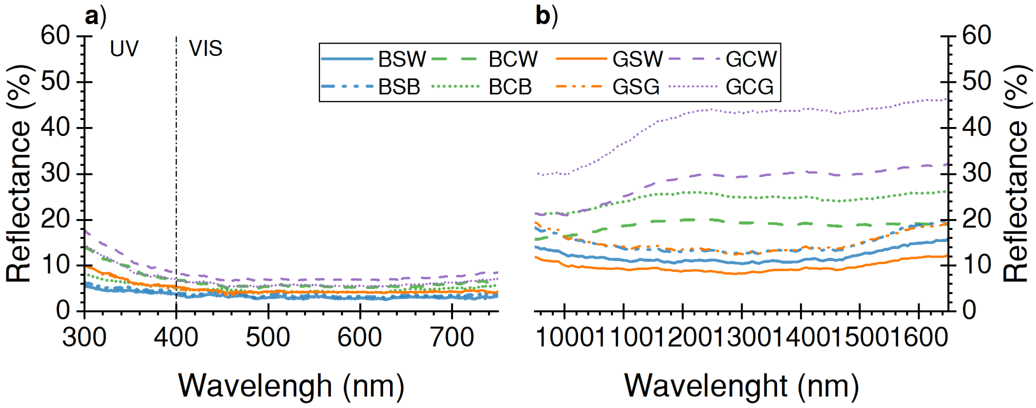


Figure 4. Spectral behaviour for refurbished ETICS. a) Ultra-violet and visible region, b) Near-infrared region.

Paint refurbishment changes the optical properties of existing systems, keeping the emissivity, and increasing the reflectance on the black system but reducing the grey, as expected due to the colour change.

3.2. Colour and surface temperature

The colour of the facades is an aesthetic parameter considered by the designers in the architectural development of the building. Figure 5 presents the measured CIE Lab colour coordinates.

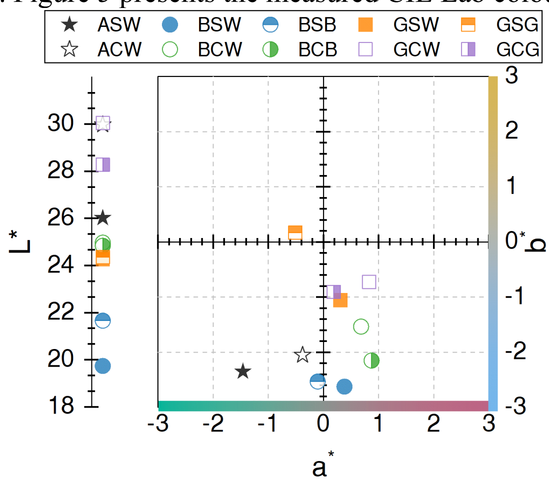


Figure 5. CIE L*a*b* coordinates for black and grey ETICS and white acrylic.

The a^* and b^* coordinates indicate the hue, which is the variety of a colour considering the absorption on different wavelengths (red, green, blue, and yellow colour family), and the perception of the colour, the chroma.

Figure 5 shows that the samples are in the red-blue quadrant (except the GSG), confirming the effects of the colour on the reflectance system. This behaviour agrees with the manufacturer description of the pigments colour Table 1. The chroma of the samples is lower and can be considered achromatic, i.e., a mix of black, white, and grey tones. However, the base colour of the system significantly affects the chroma values.

Considering the lightness, the standard paint (S) is darker than the NIR paint (C) in all samples, which indicates a darker black colour once the L value is lower than 30 [19, 20]. The use of high near reflectance paint (C) can affect the lightness and lighter the samples in comparison to the standard one (S), as demonstrated by Rossi *et al.* [21]. Figure 6 shows the difference calculated between the samples and between the control coordinates, considering that the human eye perceives differences higher than three [17].

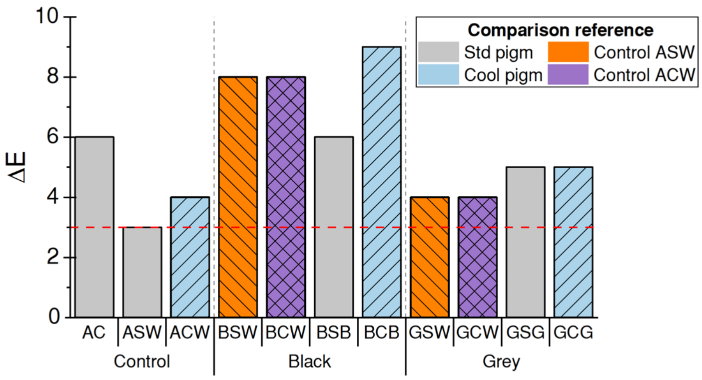


Figure 6. The colour difference between the samples and the standard paint between the samples and the painted white acrylic.

The grey-coloured ETICS contribute to the lower colour difference, while the black lead to the higher variation. Besides, the ETICS systems do not present representative changes comparing the paint type and using a white mortar as a new layer reduced the colour variation. The studied control samples have a colour difference superior to 3, and this difference is attributed to the lightness variation. The described results were similar to the found by Alonso *et al.* [24] and Ramos *et al.* [7], indicating that paint refurbishment changes the optical properties of existing systems, keeping the emissivity and increasing the reflectance on the black system but reducing the grey, as expected due to the colour change.

The NIR paint (AC) has a colour difference of 6 compared to the standard colour (AS), indicating that the colour variation is noticeable to the eyes, even if the reflectance has not been affected on the visible region, as can be evidenced in Figure 7.

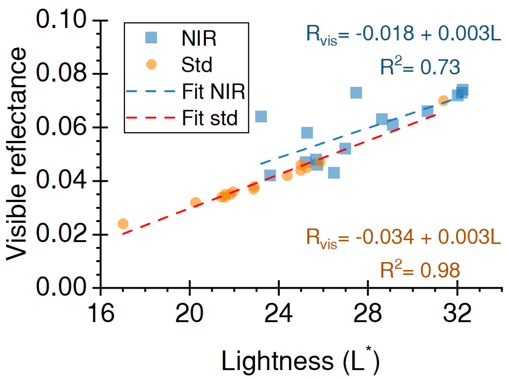


Figure 7. Correlation between the lightness coordinate and the visible reflectance.

From Figure 7, it is possible to verify that the colour of the materials affects the reflectance on the visible region. Lighter colours have a higher value of lightness (L^*) and higher reflectance, while dark colours have lower L^* and reflectance values [22, 23].

Figure 8 shows the surface temperature for the numerical surface temperature, calculated for two Portuguese cities according to equation (3). On the application of the equation were used the EnergyPlus weather data of maximum Air temperature and Surface radiation for the south façade. The used data is shown in Table 3.

Table 3. Weather data.

City	Tair (ºC)	Total surface radiation (Wh/m^2)	Day of year
Porto	36.0	443.92	03 July
Bragança	36.7	279.30	16 July

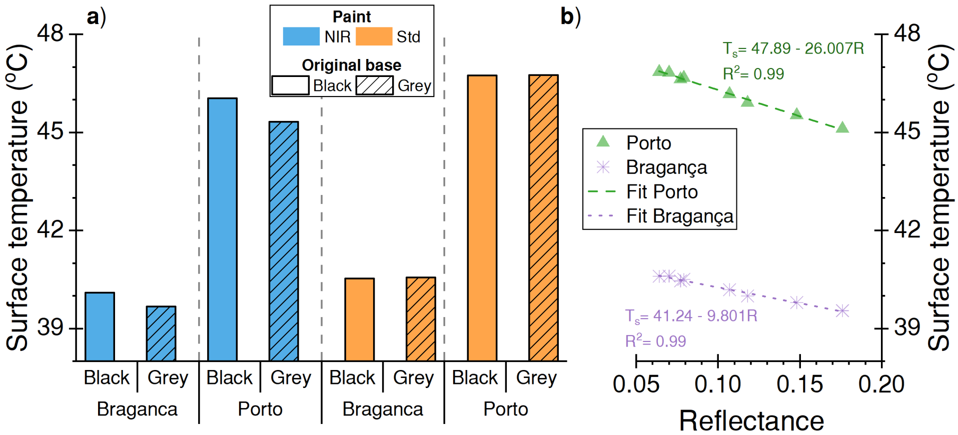


Figure 8. Surface temperature analysis. a) Calculated surface temperature, b) Correlation between surface temperature and reflectance.

The original surface characteristics significantly affected the reflectance values but not the surface temperature. The differences between the grey and black systems have been less significant than the effect of the paint, as seen in the values of Figure 8a. Besides, in Figure 8a, the reduction of the temperature due to the NIR paint is higher when the surface radiation increase, case of Porto of 3% against 1% of Bragança.

The NIR paint reduces the temperature compared to the standard black, which can be explained by the higher reflectance values (see Figure 8b). The reduction in the surface temperature for dark colours also was found by Alonso *et al.* [24] and the cooling effect of the surface due to the NIR paints was well verified by Dias *et al.* [25]. Further simulations are needed to assess the energy consumption and thermal impact on building service life once the surface temperature and the cooling effect depending on the environmental conditions.

4. Conclusion

One of the most frequent alterations in the ETICS envelopes is the aesthetical change due to the microbiological and pollution agents, the UV degradation, and the thermal cracking. This study evaluated the optical aesthetics and thermal behaviour of paint renovation in the finishing coat of external thermal insulation systems (ETICS).

The findings highlight the expected behaviour of the NIR reflectance materials, even during the experimental campaign where this type of material was applied over a weathered envelope, listing:

- The applied coatings did not change the emissivity of the system,
- Paints with near-infrared reflectivity increase the total reflectance and do not affect the visible region,
- The effect of the lightness of the colour is significant in the visible reflectance,
- Increasing the reflectance will reduce the surface temperature.

The paint renovation process can be applied to improve the weathering protection and renovate the aesthetical aspect contributing to the lower heat absorption of the system, improving the durability, and reducing the thermal stress. However, a better assessment of the overall effect of the building through simulations is still needed. It is also emphasised that few works still focus on the thermal and energy impact of renovations on facades, as well as the analysis of the life cycle of these elements.

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