XVIII ENCONTRO NACIONAL DE CONFORTO NO AMBIENTE CONSTRUÍDO
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AMBIENTE CONSTRUÍDO E USUÁRIO: PERSPECTIVAS LATINO-AMERICANAS

Reflectance and color appearance of non-white cool concrete tiles for single- and double-layer coating methods

Refletância e coloração de telhas de concreto frias coloridas com aplicação de pigmentos em uma ou duas camadas

Reflectancia y coloración de teja de concreto frías coloridas com aplicación de pigmentos en una o dos capas

Thermal performance of the built environment

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Abstract

This paper investigates the influence of coating methods on the production of non-white cool concrete tiles. Measurements of spectral reflectance and color coordinates were performed on 60x60x11 mm mortar samples with coating in single- (SL, only colored topcoat) or double-layer (DL, white basecoat and colored topcoat). Solar reflectance (SR) was higher for DL and the white basecoat increased the samples' SR in the 0.034 – 0.104 range, with a greater impact on near-infrared reflectance. Total color-differences between SL and DL are perceptible by human eyes. Although DL samples are lighter than SL ones, the color coordinates L*, a*, and b* are not different (p-value > 0.05, Student t-test). It can be concluded that coating methods influenced the samples' SR and color appearance, and the DL method is recommended for cool concrete tiles if small color changes are acceptable.

Keywords: Cool roof. Solar absorptance. Titanium dioxide. Iron oxide. Reflective coating.

Resumo

Este artigo analisou a influência do método de aplicação de revestimentos na produção de telhas de concreto frias coloridas. Medições de refletância espectral e coordenadas de cor foram realizadas em amostras de argamassa (60x60x11 mm) pintadas com uma (SL, apenas uma camada colorida) ou duas camadas (DL, base branca e uma camada colorida). A refletância solar (RS) é maior para o sistema DL, na qual a base branca aumentou entre 0,034 e 0,104 a RS da amostra, com maior impacto no infravermelho próximo. Diferenças de cor totais entre os métodos SL e DL são perceptíveis ao olho nu. Amostras com DL são mais claras que aquelas com SL, contudo as coordenadas de cor L, a*, e b* não são diferentes estatisticamente entre amostras SL e DL (p valor > 0.05, teste t de Student). Conclui-se que o método de aplicação dos revestimentos tem influência na RS e aparência das amostras. Além disso, o sistema DL é indicado para produzir telhas de concreto frias se pequenas variações de coloração sejam aceitáveis.*

Palavras-chave: Cobertura fria. Absortância solar. Dióxido de titânio. Óxido de ferro. Revestimento refletivo.

Resumen

Este trabajo investiga la influencia de los métodos de recubrimiento para la producción de tejas de hormigón no blancas frías. Se realizaron mediciones de reflectancia espectral y coordenadas de color en muestras de mortero de 60x60x11 mm con revestimiento en monocapa (SL, solo una capa de color) o doble capa (DL, base blanca y una capa de color). La reflectancia solar (RS) es mayor para DL. La base blanca aumenta la RS en el rango de 0,034 a 0,104, con un mayor impacto en la reflectancia en el infrarrojo cercano. Las diferencias total de color entre SL y DL son perceptibles para el ojo humano. Las muestras con DL son más claras que las de SL, sin embargo, las coordenadas de color L, a*, y b* no son diferentes (valor p > 0,05, t-test de Student). En conclusión, los métodos de recubrimiento influyen en la RS y la apariencia de las muestras. Se recomienda la DL para tejas de hormigón frías si se aceptan pequeños cambios de color.*

Palabras clave: Techo frío. Absorbancia solar. Dióxido de titânio. Óxido de hierro. Capa reflectante.

1. Introduction

Cool roofs and walls, i.e., materials with high solar reflectance and high thermal emittance, are a cost-efficient and easy solution for cooling buildings and pavements (Alhazmi; Sailor; Levinson, 2023), for they lower surface temperatures compared to conventional materials. However, the development of cool cement-based materials can be challenging, since the low solar reflectance of Portland gray cement (0.32-0.47) and sand (0.20-0.45) causes low solar reflectance on the final products (Levinson; Akbari, 2002; Marceau; Vangeem, 2008).

Brady Jr. and Wake (1992) recommended using a highly reflective white basecoat and a colored topcoat transparent to solar radiation or with low near-infrared (NIR) reflectance to create a non-white high NIR reflectance coating for low reflectance materials, such as cement-based ones. That double-layer method was tested by Levinson *et al*. (2010) and Ravel *et al*. (2014), who successfully developed cool non-white concrete, ceramic, and asphalt shingle tiles. Additionally, Levinson *et al*. (2007) recommended using high NIR backscattering pigments in both basecoat and topcoat for low NIR reflectance substrate, i.e., using cool coatings on both layers. They also suggested a single-layer coating method using pigments with weak NIR absorption strong NIR backscattering for increasing reflectance in the NIR spectrum, i.e., coatings with pigments such as red, brown iron oxides, and chrome titanate yellow, which can increase reflectance in the 0.06-0.28 range (Levinson *et al*., 2007).

Although double-layer coating is commonly adopted to increase solar reflectance for non-white surfaces, no study has provided results for cool non-white cement-based materials from the Brazilian built environment. Therefore, this paper analyzes the influence of single- and double-layer coating methods on both reflectance and color appearance of cement-based materials for the production of cool non-white Brazilian concrete tiles.

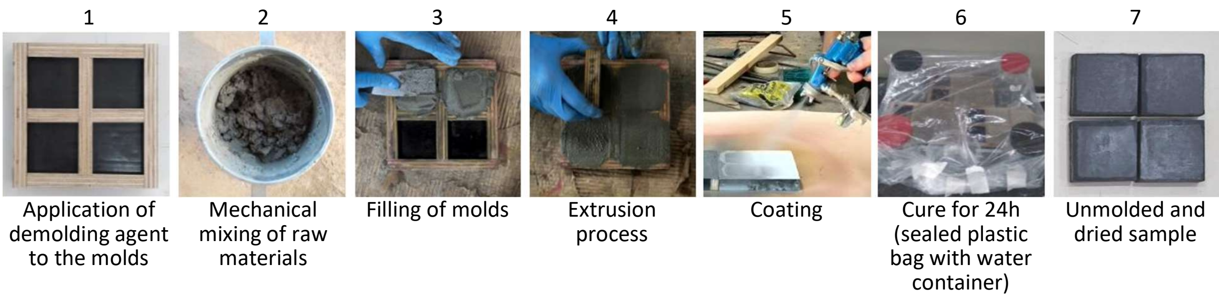
Much of the national research on cool materials analyzes the thermal and optical properties of conventional materials and coatings from the market, leading to a lack of studies on the development of reflective materials, especially tiles. This study aims to provide insights about the development of cool tiles using coating methods.

2. Materials and methods

2.1 Samples

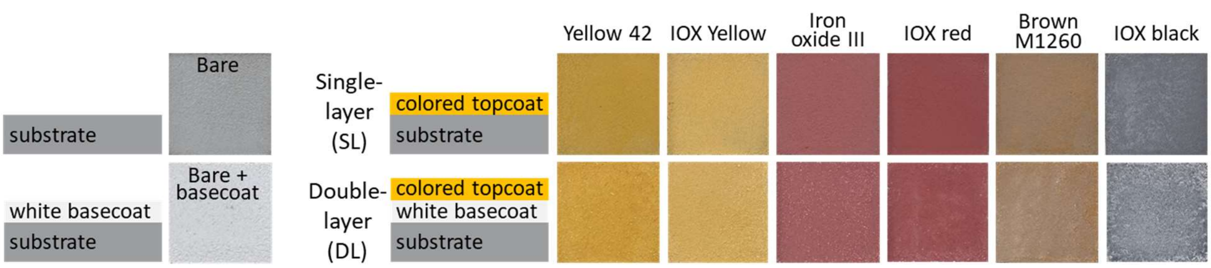
Figure 1 illustrates the process of production of mortar samples of 60 mm x 60 mm x 11 mm dimensions and 1:4:0.7 cement mix (i.e., 1 part of gray Portland Cement CP-V ARI from Liz Cimentos®, 4 parts of fine sand of < 1.2 mm grain size, and 0.7 water-cement ratio). It is similar to the real process of production of concrete tiles, i.e., application of a demolding agent to molds, mixing of raw materials, filling of molds with the use of vibration for the removal of air bubbles, molding by extrusion, curing for unmolding, and natural drying. The additional coating stage occurs right after the molding process and consists of spraying the coating over the fresh mortar by an air gun of Ø2.16 mm at 40 psi. Levinson *et al.* (2010) indicated the spraying method to maximize both solar reflectance and factory-line throughput of concrete tiles and asphalt shingle roofing materials. Figure 2 shows the samples produced.

Figure 1: Production process of samples.



Source: Elaborated by the authors, 2025.

Figure 2: Coated mortar samples.



Source: Elaborated by the authors, 2025.

The single-layer method (SL) consists of spraying one layer (only) of colored topcoat over the substrate, whereas the double-layer method (DL) involves the spraying of two layers of coating, of which the first is a white basecoat and the second is a non-white topcoat. The use of a white basecoat in DL is the only difference between SL and DL. Each layer is a pigment dispersion on acrylic white matte paint by Haus (Tinta Látex Acrílico Fosco Standard) diluted in water, 20%, as indicated by the supplier. Levinson *et al*. (2010) also used a pigmented latex paint based on acrylic to create cool non-white concrete tiles through DL coating application.

The non-white topcoat is a suspension of non-white pigments at 3% concentration in diluted acrylic paint. Higher pigment concentrations can decrease solar reflectance for DL coating applications (Levinson *et al*., 2010). Cool and commercial pigments in yellow, red, brown, and black colors, namely, yellow 42, IOX yellow, iron oxide III, IOX red, brown M1260, and IOX black (Table 1) were selected through a literature review conducted for this study for the production of cool colored concrete tiles that match colors of market Brazilian concrete tiles.

Table 1: Yellow, red, brown, and black pigments used for non-white topcoats.

Name	Description	Comment
PY42 Yellow 42	Water-based pigment dispersion. Commercial name: Aquatint Amarelo Óxido 42	Cool and commercial pigment. NIR reflectance of 0.70 over a white background and 0.21 over a black background (LBNL, 2024).
IOXY IOX yellow	Yellow powder inorganic pigment composed of yellow oxide and iron hydroxide - FeO(OH). CAS 51274-00-1	Commercial pigment for concrete. Reflectance not reported in the literature.
Fe_2O_3 Iron oxide III	Red powder, pure reagent, 97% concentration. CAS 1309-37-1	Cool pigment. Component of Pigment Red 101 of NIR reflectance of 0.37-0.67 over a white background and 0.19-0.38 over a black background (LBNL, 2024)
IOXR IOX red	Red powder inorganic pigment composed of iron oxide III - Fe_2O_3. CAS 1309-37-1	Commercial pigment for concrete. Reflectance not reported in the literature.
M1260 Brown M1260	Water-based mix of pigments dispersion with 58% concentration. Commercial name: Marrom TP M1260.	Commercial pigment. Reflectance not reported in the literature.
IOXB IOX black	Black powder inorganic pigment composed of triiron tetroxide - Fe_3O_4. CAS 1317-61-9	Commercial pigment for concrete. Reflectance not reported in the literature.

Source: Elaborated by the authors, 2025.

The white basecoat is a suspension of titanium dioxide in diluted acrylic paint at 20% concentration. The air gun apparatus used could not spray a higher pigment concentration.

Titanium dioxide rutile (CAS 13463-67-7) by Êxodo Científica is a cool white pigment that shows a NIR reflectance between 0.87 and 0.88 (LBNL, 2024; Levinson; Berdahl; Akbari, 2005).

2.2 Reflectance

A Varian Cary 7000 UV-Vis-NIR spectrophotometer from [name of the laboratory and university] measured spectral reflectance with 5 nm step from 300 nm to 1900 nm wavelength on the geometric center spot of the samples of ages between 42 and 60 days. Six weeks are necessary for stabilizing the reflectance of cement; therefore, 42 days is the minimal age for reflectance measurements of cement-based materials (Levinson; Akbari, 2002; Marceau; Vangeem, 2008). Reflectance data for longer wavelengths was unusable due to significant errors in the spectral reflectance readings. Although the 1900 nm – 2500 nm wavelength range is 27,27% of the whole solar spectrum, it represents only 3.19% of the total hemispherical tilted irradiance of the reference solar spectrum according to ASTM Standard G173 (ASTM, 2023b). Therefore, the lack of spectral reflectance from 1900 nm to 2500 nm does not invalidate the data analysis.

Solar reflectance was obtained by integrating spectral reflectance over the standard spectral irradiance distribution of ASTM Standard G173 (ASTM, 2023b), following ASTM Standard E903 (ASTM, 2020), and NBR Standard 17162 (ABNT, 2024). Reflectance for ultraviolet (UV, 300 nm – 380 nm), visible (VIS, 380 nm - 780 nm), and near-infrared (NIR, 780 nm – 1900 nm) regions was calculated for quantifying differences between SL and DL coating methods for each spectral range.

2.3 Color parameters

A Colorium portable colorimeter by Delta Color® measured the samples' color coordinates through CIELAB chromatic system of the International Commission on Illumination (CIE), i.e., lightness-darkness (L*), redness-greenness (a*), and yellowness-blueness (b*). Three diagonally aligned measurements were taken on each sample at ages between 42 and 60 days. Total color-difference (ΔE*ab) was calculated using the following equation: $\Delta E^*ab = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$, where ΔE*ab is the total color-difference between SL and DL samples, and ΔL*, Δa*, and Δb* are the direction color-difference of the mean values of L*, a*, and b* color coordinates, respectively (ASTM, 2023a). Although the perception of color differences by human eyes can be affected by both subjective and objective phenomena, such as ambient lighting, $\Delta E^*ab < 1$ is imperceptible, and $\Delta E^*ab = 100$ denotes opposite colors (Betrisey *et al.*, 2016; Johnston; Kao, 1989; Xie *et al.*, 2020).

A desktop version of Jamovi 2.3 software (Jamovi, 2024) applied Student t-test for independent samples for L*, a*, and b* color coordinates mean values towards finding statistical differences between SL and DL samples. Color coordinates L*, a*, and b* showed > 0.05 p-value in Shapiro-Wilk normality test; therefore, they show a normal distribution and parametric tests such as Student t-test can be applied for data analyses.

3. Results and discussion

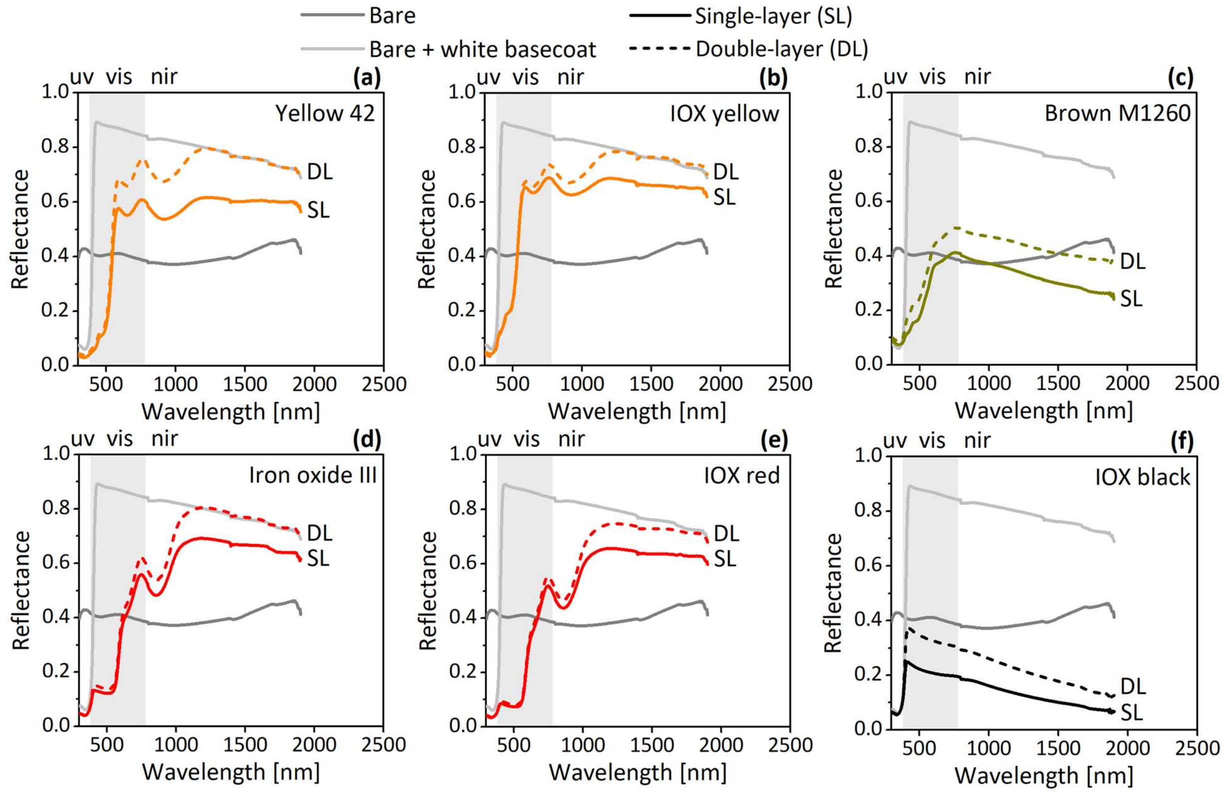
3.1 Reflectance results

Figures 3 and 4 show samples' spectral reflectance and the calculated reflectance, respectively. A white basecoat increased solar reflectance for all pigments tested, mainly in the NIR spectrum, and solar reflectance of a gray mortar from 0.398 (bare sample) to 0.801 (white basecoat over bare sample). SL and DL samples showed solar reflectance above 0.18 and above 0.28, respectively.

Levinson *et al*. (2010) reported solar reflectance above 0.25 for 24 colored concrete tiles using a similar DL coating method. Solar reflectance increased at least 0.034 (IOX red) with the use of a white basecoat. The highest increases were 0.103 and 0.104 for IOX black and yellow 42 pigments, which represent 23% and 56% of increase from the SL coating method, respectively. Although solar reflectance increases with the use of a white basecoat for all pigments, the spectral reflectance charts in Figure 3 show non-uniform changes through the solar spectrum.

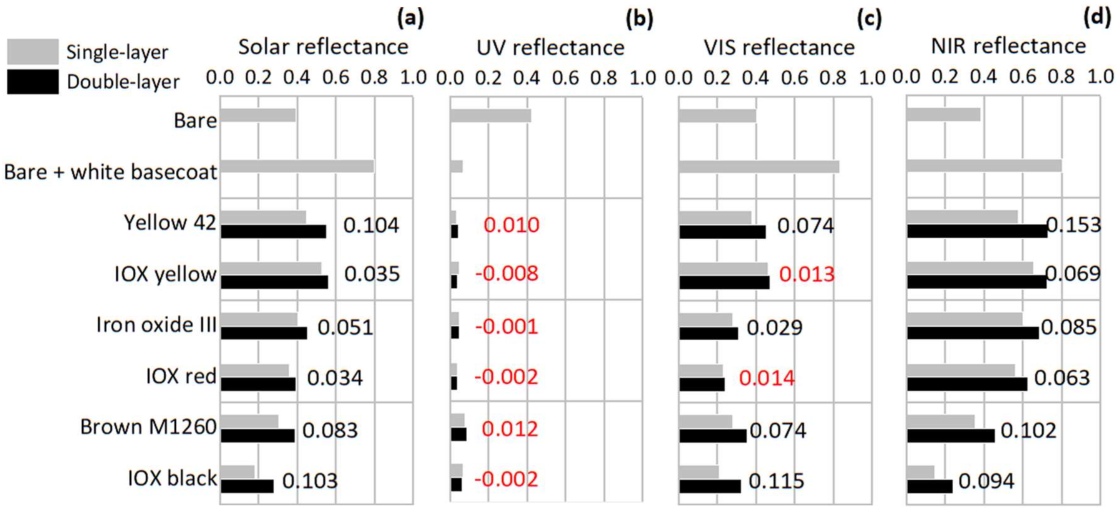
Concerning UV spectrum, no difference in UV reflectance was observed between SL and DL samples. Their values differed by a maximum value of ±0.01, and up to ±0.02 is an acceptable variation in solar reflectance according to ASTM Standard E903 (ASTM, 2020). The UV reflectance for all colored samples ranged between 0.034 and 0.090; however, it was 0.425 in the bare sample. It represents a reduction between 79% and 92% in UV reflectance caused by the absorption of ultraviolet radiation by titanium dioxide, a component of the white basecoat and the acrylic white paint in which the pigments were dispersed (Barbosa, 2017). Although a strong UV absorption is usually desirable for topcoat-layer pigments or aggregates for preventing UV damage of the basecoat or substrate, high UV reflectance would be better for the material's performance (Levinson *et al*., 2007). Changes in VIS reflectance were insignificant (i.e., lower than ±0.02) between SL and DL samples for IOX yellow and IOX red, but significant for other pigments. Changes in VIS reflectance also influenced color appearance, as discussed in the next subsection through an analysis of the color parameters of each sample. On the other hand, the use of a white basecoat in DL method increased NIR reflectance by at least 0.063 (IOX red) but not above 0.153 (yellow 42). Increases in VIS and NIR reflectance maximize solar reflectance, for they together contain 95% of the incident solar radiation (Levinson *et al*., 2007).

Figure 3: Spectral reflectance of (a) yellow 42, (b) IOX yellow, (c) brown M1260, (d) iron oxide III, (e) IOX red, and (f) black pigments sprayed over mortar for single- (SL) and double-layer (DL) coating methods.



Source: Elaborated by the authors, 2025.

Figure 4: Charts of (a) solar reflectance (300 nm – 1900 nm) and (b-d) reflectance for ultraviolet (UV, 300 nm-380 nm), visible (VIS, 380 nm – 780 nm), and near-infrared (NIR, 780 nm – 1900 nm) spectral regions for single- (gray bars) and double-layer (black bars) coating methods.



Note. Numbers such as -0.123 denote the difference in reflectance between double- and single-layer samples; differences lower than ±0.02 are highlighted in red color.

Source: Elaborated by the authors, 2025.

3.2 Color parameters results

Table 2 shows color coordinates, color-differences (ΔL*, Δa*, Δb*, and ΔE*ab), and the statistical analysis. Pigment yellow 42 showed the highest ΔE*ab value (11.51), followed by pigment IOX black (9.42), meaning they changed their color mostly with the addition of white basecoat, among all pigments tested. Both showed the highest increase in solar reflectance.

According to the levels of ΔE*ab perception described by Betrisey *et al.* (2016) and Xie *et al*. (2020), the total color-difference between SL and DL samples is perceptible by a close observation for IOX red (1 < ΔE*ab < 2) and perceptible with a glance for IOX yellow, iron oxide III, brown M1260, and IOX black (2 < ΔE*ab < 10). The total color-difference of 11.51 for yellow 42 means SL and DL samples showed a perceptible total color-difference (10 < ΔE*ab < 49); however, they are not opposite colors (ΔE*ab = 100).

Table 2: Mean value of color coordinates (L*, a*, and b*), color-difference (ΔL*, Δa*, Δb*, and ΔE*ab), levels of total color-difference perception and statistical analysis of samples for single- (SL) and double-layer (DL).

Color coordinate	L*			a*			b*			Color-difference	
	SL	DL	ΔL*	SL	DL	Δa*	SL	DL	Δb*	ΔE*ab	Level of perception
Yellow 42	63.39	68.20	4.81	6.59	10.26	3.67	43.59	53.37	9.79	11.51	Perceptible. Similar color
IOX yellow	69.20	70.48	1.27	5.60	6.68	1.08	43.00	44.95	1.94	2.56	Perceptible with a glance
Iron oxide III	47.84	49.60	1.76	19.39	20.83	1.44	11.95	12.63	0.67	2.37	Perceptible with a glance
IOX red	43.42	44.64	1.22	20.79	21.64	0.86	11.34	11.65	0.31	1.52	Percep. by a close observ.
Brown M1260	55.45	60.19	4.74	6.20	5.73	-0.46	18.98	18.50	-0.48	4.79	Perceptible with a glance
IOX black	51.06	60.32	9.26	-3.32	-4.35	-1.03	-1.40	-1.18	0.22	9.32	Perceptible with a glance
SD	9.73	10.10		9.21	9.88		18.3	21.20			
Student t-test	-0.670			-0.168			-0.182				
p-value	0.518			0.870			0.859				
Comment	No difference between SL and DL			No difference between SL and DL			No difference between SL and DL				

Note. L* - lightness-darkness; a* - redness-greenness; b* - yellowness-blueness; ΔL*, Δa*, and Δb* - direction of color-difference for L*, a*, and b*, respectively; ΔE*ab – total color-difference; SD – Standard deviation; Student t-test – null hypothesis (p-value > 0.05): no statistical difference between group mean value, alternative hypothesis (p-value < 0.05): statistical difference between group mean value.

Source: Elaborated by the authors, 2025.

The direction of color difference, ΔL*, is positive, indicating the samples with DL coating method became lighter, according to ASTM Standard D2244 (ASTM, 2023a). This is more expressive for pigment IOX black, which showed a 9.26 increase in L* color coordinate, possibly caused by the white dots spread over the surface (see Figure 2). Regarding yellow 42, IOX yellow, and iron oxide III samples, the white dots are small and well distributed along the surface, differently from IOX red, brown M1260, and IOX black, which those white dots are concentrated and form small white spots. The non-white topcoat was applied over a wet white basecoat and both might mix, creating those small white spots. Levinson *et al*. (2010) used a similar DL coating method and reported no white spots. However, small white dots could be seen on the samples.

Coordinate a* also increased for yellow and red pigments, and the samples became redder (less green) with the white basecoat. Conversely, brown and black samples became greener (less red) because Δa* is negative. Coordinate b* increased for samples with a white basecoat, becoming yellow (less blue) - except for pigment brown M1260, which became bluer (less yellow) with the addition of a white basecoat, because Δb* is negative.

No statistical difference was observed between SL and DL coating methods according to the statistical analysis. The p-value for Student t-test for independent samples grouped by coating method was above 0.05; therefore, the null hypothesis (Ho) was accepted, meaning there is no statistical difference between SL and DL samples for L*, a*, and b* color coordinates.

4. Concluding remarks

The coating method significantly affected solar reflectance and NIR reflectance, with a lower influence on VIS reflectance and color appearance. The white basecoat of the DL method increased the samples' solar reflectance by at least 0.034 (IOX red), but not above 0.104 (IOX black) for the pigments tested. UV reflectance did not change between SL and DL samples; VIS reflectance can be greater for DL samples according to the pigment; and NIR reflectance for samples with white basecoat (DL) was at least 0.063 (IOX red) higher than samples without it (SL), but not greater than 0.153 (yellow 42). A positive color difference in L* (+ΔL*) indicates DL samples are lighter than SL ones. All pigments showed total color-differences (ΔE*ab) perceptible by human eyes (Betrisey *et al*., 2016; Xie *et al*., 2020). Yellow 42 and IOX black pigments showed the highest ΔE*ab, namely, 11.51 and 9.42, respectively, and the highest increases in solar reflectance with the use of a white basecoat. However, a p-value above 0.05 for Student t-test indicates no statistical difference between SL and DL samples for L*, a*, and b* color coordinates.

Significant differences in solar and NIR reflectance between SL and DL samples, and small changes in both VIS reflectance and color appearance were observed for all pigments. Therefore, a DL coating method is recommended for increasing solar reflectance and producing cool non-white cement-based materials such as concrete tiles if small color changes from SL method are acceptable for the material. These results can encourage the Brazilian building sector to adopt small changes in the production process to produce cool materials similar to market ones. However, a high number of pigments and distinct pigment concentrations should be investigated to confirm the trends observed. Moreover, a natural aging campaign might identify the reflectance loss for SL and DL samples and explore their cost-effectiveness for the Brazilian built environment toward verifying the long-term effectiveness of white basecoat in DL coating method for improving material performance compared to SL.

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