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AMBIENTE CONSTRUÍDO E USUÁRIO: PERSPECTIVAS LATINO-AMERICANAS

Effect of amount of pigment on the solar reflectance of mortars for the production of cool colored concrete tiles

Influência da quantidade de pigmento na refletância solar de argamassas para telhas de concreto frias coloridas

Influencia de la cantidad de pigmento en la reflectancia solar de los morteros de cemento para producir teja de concreto frías coloridas

Thermal performance of the built environment

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Abstract

This paper determines the optimal amount of pigment for the production of Brazilian cool concrete tiles. Spectral reflectance measurements were conducted on 60x60x11 mm pigmented mortar samples, and the Solar Reflectance Index (SRI) was calculated for them. White, yellow, red, brown, and black pigments were added to the mortars at 1%, 5%, and 10% of the cement weight. Solar reflectance (SR) increased with the addition of white pigments, showing a very strong correlation (r=0.952). On the other hand, yellow, red, brown, and black pigments reduced the SR as their concentration increased. Although no mortar had an SRI > 78 to be classified as a cool roof, it is recommended to use 10% and 1% of the cement weight for white and colored pigments, respectively, to achieve higher SR rates in colored concrete tiles.

Keywords: Cool roof. Solar absorptance. Cement-based materials. Titanium dioxide. Iron oxide.

Resumo

Este artigo buscou determinar a quantidade adequada de pigmento para a produção de telhas de concreto frias brasileiras. Medições de refletância espectral foram realizadas em amostras de argamassa pigmentada (60x60x11 mm) e o Índice de Refletância Solar (SRI) foi calculado. Pigmentos nas cores branco, amarelo, vermelho, marrom e preto foram adicionados nas concentrações 1%, 5% e 10% em relação à massa do cimento. A refletância solar (RS) aumentou com o incremento de pigmentos brancos com uma correlação muito forte (r=0,952). Por outro lado, pigmentos coloridos reduziram a RS com o incremento de pigmento. Apesar de nenhuma amostra apresentar SRI > 78 para classificá-la como telhado frio, recomenda-se adicionar 10% para pigmentos brancos e 1% para pigmento coloridos, ambas em relação à massa do cimento, para alcançar maiores RS em telhas de concreto coloridas.

Palavras-chave: Cobertura fria. Absortância solar. Materiais cimentícios. Dióxido de titânio. Óxido de ferro.

Resumen

Este trabajo tiene como objetivo determinar la cantidad óptima de pigmento para producir tejas brasileñas de hormigón frío. Se realizaron mediciones de reflectancia espectral en muestras de mortero pigmentado de 60x60x11 mm y se calculó el Índice de Reflectancia Solar (SRI). Se agregaron pigmentos blancos, amarillos, rojos, marrones y negros a los morteros en concentraciones de 1%, 5% y 10% de la masa de cemento. La reflectancia solar (RS) aumentó con el aumento de la cantidad de pigmentos blancos com uma correlación muy fuerte (r=0.952). Por otro lado, los pigmentos de color redujeron la RS con el aumento de pigmento. Aunque ninguna muestra presentó SRI > 78 para clasificarla como un techo frío, se recomienda adicionar 10% para pigmentos blancos y 1% para pigmentos de color, ambos en relación a la masa de cemento, para lograr una RS más alta en tejas de hormigón coloreadas.

Palabras clave: Techo frío. Absorbancia solar. Materiales a base de cemento. Dióxido de titânio. Óxido de hierro.

1. Introduction

The use of cool materials, i.e., materials with high solar reflectance - particularly in the near-infrared region of the solar spectrum - and high thermal emittance, is a well-documented cooling strategy for the built environment. Cool roofs and walls are a cost-efficient and easy solution for cooling buildings and pavements (Alhazmi; Sailor; Levinson, 2023) once 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 of new concrete products (Levinson; Akbari, 2002; Marceau; Vangeem, 2008). Therefore, the incorporation of cool pigments or reflective materials into the cement mix or their application as a coating is recommended for increases in solar reflectance (Levinson *et al*., 2010).

The addition of pigments to the cement mix is a usual technique for the production of colored composite materials, such as concrete tiles. However, the amount of pigment can influence the concrete´s physical, mechanical, and optical properties – as such an amount increases, the slump, i.e., the test method that evaluates the consistency or workability of fresh concrete decreases, but the compressive strength can be improved (Li *et al*., 2024). Although solar and visible reflectance of concrete samples with black, blue, and red pigments decreases with increased pigment amount (Rosso *et al*., 2017), Brazilian Standard NBR 13858 – Concrete tile (ABNT, 2009) and ASTM C1492 – Standard specification for concrete roof tile (ASTM, 2022) do not limit the addition of pigment to concrete tiles. Therefore, this paper determines the optimal amount of pigment needed for the production of cool colored concrete tiles.

2. Materials and methods

2.1 Pigments

Market Brazilian concrete tiles are available in natural color (i.e., gray), white, and in shades of yellow, red, brown, and black (Tégula, 2022; Vilhena, 2024). Pigments in those colors, namely, titanium dioxide rutile, white 6, yellow 42, IOX yellow, iron oxide III, IOX red, brown M1260, and IOX black, were selected through a literature review conducted for this study (Table 1).

Table 1: White, yellow, red, brown, and black pigments.

Pigment description		Comment
TiO_2 Titanium dioxide	White powder, pure reagent, 98% concentration. CAS 13463-67-7.	Cool pigment and between 0.87 and 0.88 near-infrared reflectance (LBNL, 2024; Levinson; Berdahl; Akbari, 2005).
PW6 White 6	Water-based pigment dispersion with 60% titanium concentration. Commercial name: Aquatint Branco 6.	Cool and commercial pigment. Near-infrared reflectance of 0.87-0.88 over a white background and 0.24-0.65 over a black background (Levinson; Berdahl; Akbari, 2005).
PY42 Yellow 42	Water-based pigment dispersion. Commercial name: Aquatint Amarelo Óxido 42.	Cool and commercial pigment. Near-infrared 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 (300 - 2500 nm) 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 Red 101 of near-infrared 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 (300 - 2500 nm) 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 (300 - 2500 nm) 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 (300 - 2500 nm) not reported in the literature.

Note: CAS is the identification number of a chemical substance provided by Chemical Abstracts Service (CAS).

Source: Elaborated by the authors, 2025.

2.2 Mortar samples

The pigments were added to the cement mix (1:4:0.7 - 1 part of gray Portland Cement CP-V ARI from Liz Cimentos®, 4 parts of fine sand of <1.2mm grain size, and 0.7 water-cement ratio) for the production of colored composite mortars. The amounts of pigment were 1%, 5%, and 10% of the cement weight since ASTM Standard C979/C979M (ASTM, 2016) has set a limit of 10% of pigment addition for avoiding changes to the physical and mechanical performance of concrete. ASTM Standard was assumed since no regulations for pigmented mortar had been found. The production process of all 25 different mortar samples (1 natural sample and 24 pigmented ones) of 60mm x 60mm x 11mm dimensions (Figure 1) was similar to the real one of concrete tiles, i.e.,

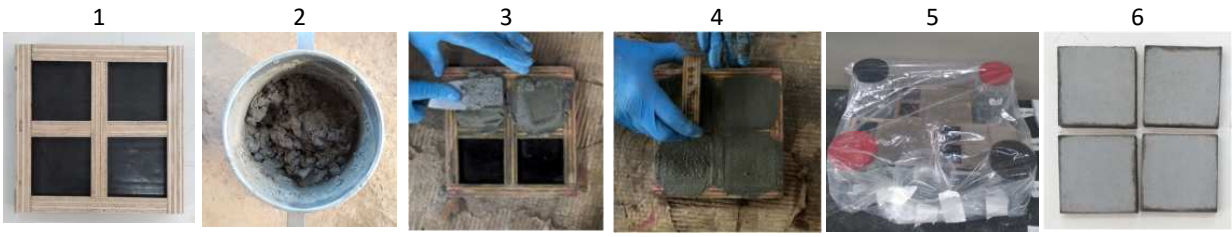
application of a demolding agent in molds, mixing of raw materials, filling of molds with the use of vibration for the removal of air bubbles, molding by extrusion, curing for unmolding of tiles, and natural drying for 7 days (Figure 2).

Figure 1: Pigmented mortar samples.



Source: Elaborated by the authors, 2025.

Figure 2: Production of mortar samples.



1 Application of the demolding agent to the molds
2 Mechanical mixing of raw materials and pigments
3 Filling of molds
4 Extrusion process
5 Curing for 24h (sealed plastic bag with water container)
6 Unmolded and dried samples (N-Natural)

Source: Elaborated by the authors, 2025.

2.3 Solar Reflectance and Solar Reflectance Index

Although cool materials are characterized by high solar reflectance and high thermal emittance, the thermal emittance is high for nonmetallic building materials (e.g., concrete, tiles, wood, paint, and others), i.e., around 0.90, without expressive changes for different materials. According to

Pereira (2015), the thermal emittance for mortar can vary from 0.87 to 0.94. Therefore, the solar reflectance was measured in this study, and thermal emittance was assumed to be 0.90 for the calculation of the **Solar Reflectance Index** (SRI) for 5, 12, and 30 $Wm^{-2}K^{-1}$ convective coefficients, following ASTM Standard E1980 (ASTM, 2019). SRI is a relative steady-state surface temperature between a standard white (SRI=100) and a standard black (SRI=0) (ASTM, 2019).

Solar reflectance was obtained by integrating spectral reflectance measured over the standard spectral irradiance distribution of ASTM Standard G173 (ASTM, 2023), following ASTM Standard E903 (ASTM, 2020), and Brazilian Standard NBR 17162 (ABNT, 2024). Reflectance for separated ranges of the solar spectrum (ultraviolet: 300 nm - 380 nm, visible: 380 nm - 780 nm, and near-infrared: 780 nm - 1900 nm) was calculated towards identifying the uniformity of the samples' reflectance for different amounts of pigment. A Varian Cary 7000 UV-Vis-NIR spectrophotometer measured spectral reflectance on the samples with 5 nm step and from 300 nm to 1900 nm wavelength. 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 from ASTM Standard G173 (ASTM, 2023). Therefore, the lack of spectral reflectance from 1900 nm to 2500 nm does not invalidate the data analysis. Only one measurement of spectral reflectance was performed on the center spot of each sample. Measurements were made at least after 42 days of age, since six weeks are required for stabilizing the reflectance of cement (Levinson; Akbari, 2002; Marceau; Vangeem, 2008). Person's correlation test checked the relationship between pigment amount and mortars' solar reflectance using a desktop version of the Jamovi 2.3 software (Jamovi, 2024).

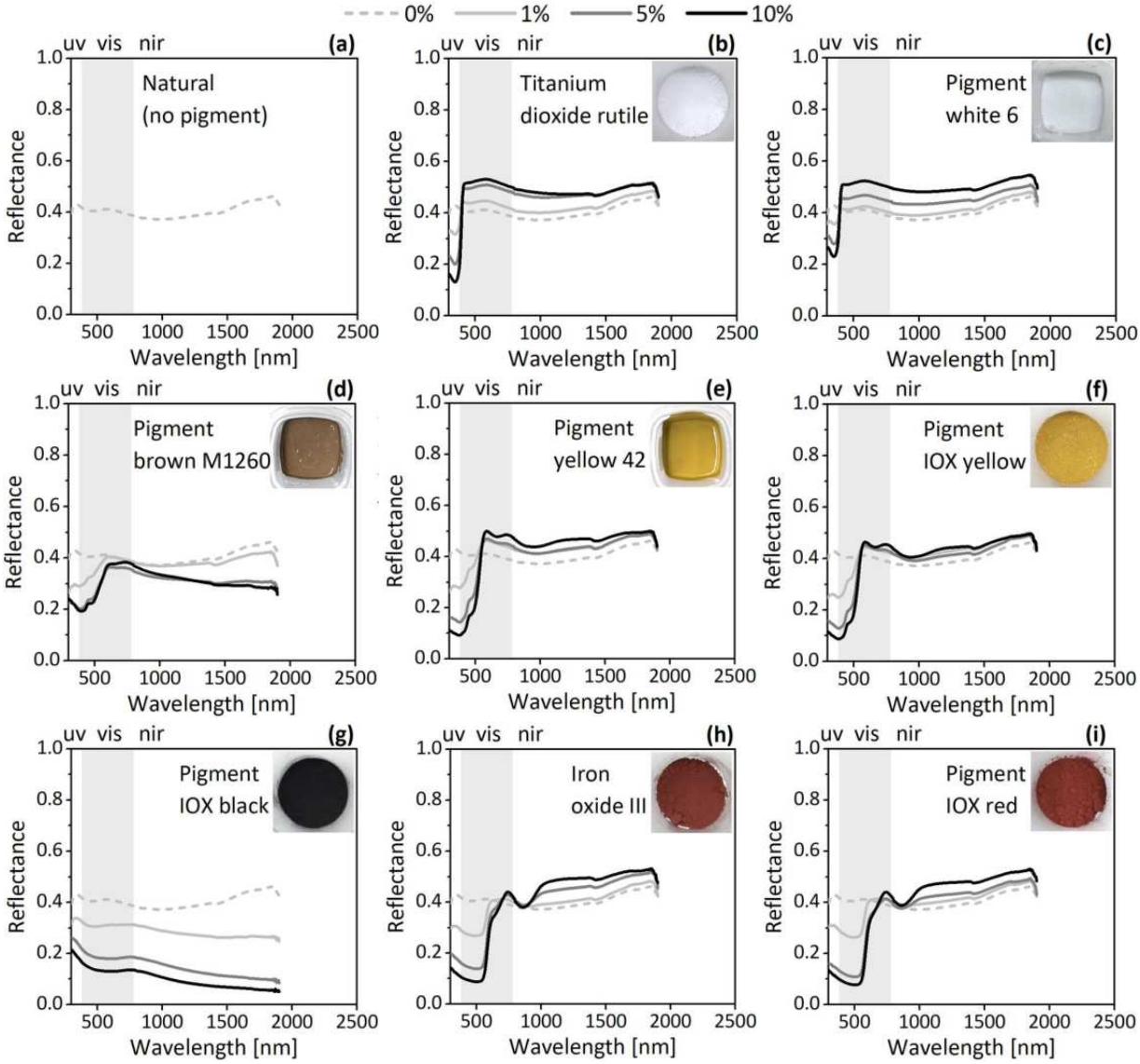
3. Results and discussion

3.1 Solar Reflectance and Solar Reflectance Index results

The amount of pigment affects the spectral reflectance of pigmented mortar samples from 300 nm to 1900 nm wavelength, varying across each spectral region (i.e., ultraviolet, visible, and near-infrared) in function of pigment color. However, no mortar produced for concrete tile could be classified as a cool roof because they did not achieve an SRI of 78 (ASHRAE, 2019). Figures 3

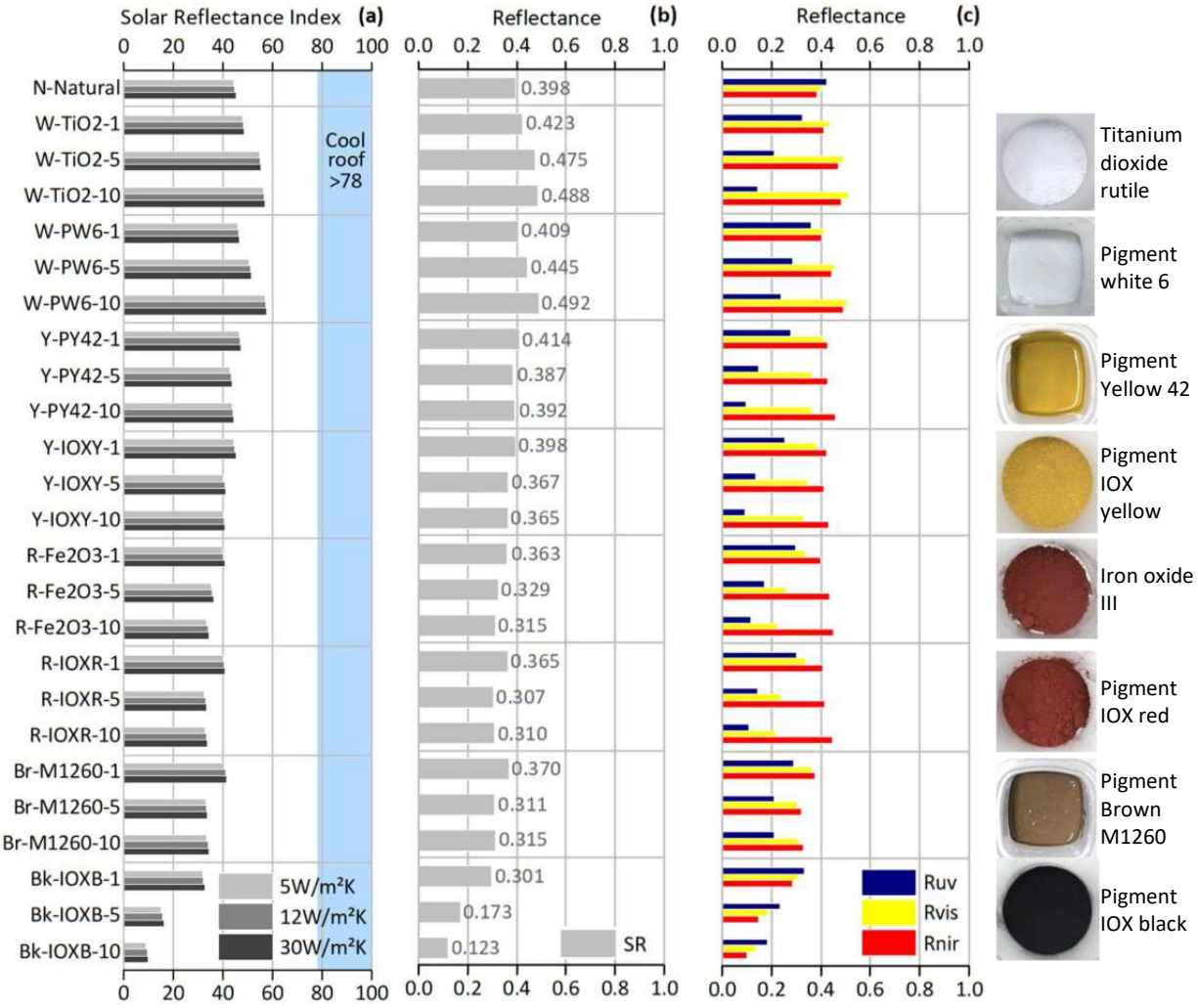
and 4 show, respectively, the spectral reflectance, SRI, solar reflectance (SR) value, and reflectance calculated for ultraviolet (Ruv), visible (Rvis), and near-infrared (Rnir) regions.

Figure 3: Spectral reflectance of (a) natural (dashed light gray) and (b – i) pigmented mortar samples, with 1% (solid light grey), 5% (solid dark grey), and 10% (solid black) pigment addition.



Source: Elaborated by the authors, 2025.

Figure 4: (a) Solar Reflectance Index for 5, 12, and 30 $Wm^{-2}K^{-1}$ convective coefficients, (b) solar reflectance (300 – 1900 nm, SR) and (c) reflectance for ultraviolet (300 – 380 nm, Ruv), visible (380 – 780 nm, Rvis), and near-infrared (780 – 1900 nm, Rnir) regions of natural and pigmented mortars.



Source: Elaborated by the authors, 2025.

Increases in white pigments in the mortar also increase its solar reflectance. The difference in solar reflectance between 1% and 10% of pigment addition was 0.064 and 0.084 for titanium dioxide and pigment white 6, respectively. Although reflectance in visible and near-infrared regions follows the same trend of solar reflectance, in ultraviolet it decreases 0.181 for titanium

dioxide and 0.119 for pigment white 6 from 1% to 10% pigment addition. Both white pigments contain titanium dioxide, which scatters, reflects, and absorbs ultraviolet radiation (Barbosa, 2017). Increases in the amount of white pigment decrease the mortar's reflectance in the 300 nm to 380 nm wavelength interval, i.e., the ultraviolet region. Yellow, red, and brown pigments achieved their highest solar reflectance with 1% of pigment addition: 0.414 (Y-PY42-1), 0.398 (Y-IOXY-1), 0.363 (R-Fe2O3-1), 0.365 (R-IOXR-1), and 0.370 (Br-M1260-1) for yellow 42, IOX yellow, iron oxide III, IOX red, and brown M1260, respectively. Those values are at least 0.028 and 0.022 higher than solar reflectance with 5% and 10% of pigment addition, but not greater than 0.059 and 0.055, respectively. However, no significant difference was observed between samples with 5% and 10% pigment addition, for the solar reflectance values differ by a maximum value of 0.014 for those colored pigments, and up to ±0.02 is an acceptable variation (ASTM, 2020).

Yellow and red pigments lead to a decrease in Ruv, with values ranging from 0.161 to 0.184 for yellow and from 0.183 to 0.193 for red, as the amount of pigment increased from 1% to 10%. Similarly, both pigments reduced Rvis, with decreases from 0.051 to 0.056 for yellow and from 0.112 to 0.116 for red. In contrast, the amount of pigment increased Rnir at least 0.041 for red pigments and 0.008 for yellow ones, with maximum increases of 0.050 and 0.031, respectively. Rosso *et al*. (2017) reported similar decreases in Rvis and increases in Rnir for colored pigments, especially red ones. Regarding the brown pigment, the differences in Ruv, Rvis, and Rnir between 5% and 10% pigment additions were smaller than 0.008. However, the sample with 1% of pigment addition showed mean differences of 0.079, 0.060, and 0.052 for Ruv, Rvis, and Rnir, respectively, from samples with 5% and 10% of pigment addition, which has not been fully understood, since the supplier does not inform the pigment composition.

The black pigment showed an inverse performance in comparison to white pigments. The amount of black pigment decreased 0.178 solar reflectance from 1% (Bk-IOXB-1) to 10% (Bk-IOXB-10) of pigment addition. Ruv, Rvis, and Rnir followed the same trend, decreasing with increases in the amount of IOX black in the mortar. Rosso *et al*. (2017) reported similar decreases in optical characteristics for black samples since the addition of pigments darkened the color.

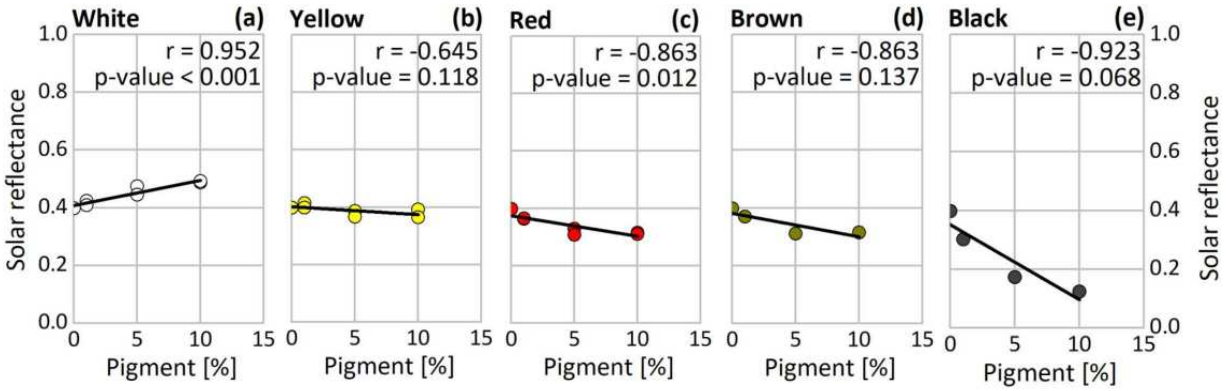
A common observation is the decrease in Ruv as the amount of pigment increases, which is attributed to the higher titanium dioxide concentration in the mortar for white pigments. However, no additional titanium dioxide was included in the cement mix for yellow, red, brown,

and black pigments. The reasons behind such a phenomenon have not been fully understood and will be further investigated, since radiation is highly energetic and can degrade materials and their surfaces, leading to color loss and fading in coatings (Dornelles, 2008).

3.2 Statistical analysis

Color plays an important role in pigment performance. Figure 5 shows the statistical analysis for the pigments grouped by color. Pigment amount and solar reflectance showed > 0.05 p-value in Shapiro-Wilk normality test; therefore, they have a normal distribution and parametric tests can be applied for data analyses. Pearson's correlation coefficient (r) measured a linear correlation between pigment amount and solar reflectance, showing the following classification: no correlation (r = 0), very weak (0.01 < r < 0.20), weak (0.21 < r < 0.40), moderate (0.41 < r < 0.60), strong (0.61 < r < 0.80), very strong (0.81 < r < 0.99), and perfect correlation (r = 1).

Figure 5: Person's correlation between solar reflectance and amount of (a) white, (b) yellow, (c) red, (d) brown, and (e) black pigments in the mortars.



Note: N-Natural is the mortar with 0% pigment addition, which showed a 0.308 solar reflectance.

Source: Elaborated by the authors, 2025.

Only white and red pigments showed a significant correlation in function of the < 0.05 p-value. Pearson's correlation was very strong (r = 0.952) for white pigments and directly proportional to the amount of pigment. It was also very strong (r = 0.863) for red ones, but inversely proportional to the amount of pigment. Yellow, brown, and black pigments showed strong (0.61 < r < 0.80) to very strong (0.81 < r < 0.99) correlations, with p-values greater than 0.05, thus showing no

significant statistical correlation between pigments and their amounts in the mortar. The number of brown and black pigments, or the percentages analyzed, may have been insufficient for statistically demonstrating the observed correlation. Figure 5e clearly shows a decrease in solar reflectance with the addition of black pigment. Additionally, the p-value for Pearson's correlation was 0.068 for that pigment, which is very close to the significance threshold of 0.05.

4. Concluding remarks

The amount of pigment affects the solar reflectance of mortars differently in function of pigment color. The amount of white pigment and mortar's solar reflectance had a very strong directly proportional correlation (p-value < 0.001 and r = 0.952 for Pearson's correlation). From 1% to 10% of pigment addition, titanium dioxide rutile and pigment white 6 increased 0.064 and 0.084, respectively, from 1% to 10% of pigment addition in the mortar. Yellow, red, and brown pigments decreased their solar reflectance when more pigment was added to the mortar. However, only red pigments (iron oxide III and IOX red) had an inversely proportional correlation between the amount of pigment and solar reflectance, confirmed by the statistical analysis (p-value = 0.012 and r = -0.863 for Pearson's correlation). Black pigment also showed a decrease in solar reflectance for high amounts of IOX black. Rosso *et al*. (2017) reported similar decreases in optical characteristics for black samples, but the data were insufficient to prove the correlation.

Although no mortar produced for concrete tile could be classified as a cool roof since they did not achieved SRI of 78 (ASHRAE, 2019), the use of 10% of the cement weight for white pigments and 1% for yellow, red, brown, and black pigments achieved higher solar reflectance rates for concrete tiles. A high number of pigments, mainly in brown and black colors, and distinct pigment additions should be investigated to confirm the trends observed.

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