Performance of self-cleaning mortar using TiO_2

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Abstract
Building facades suffer degradation due to environmental factors, leading to aesthetic issues like staining. This study investigated self-cleaning mortars produced by the surface application of titanium dioxide (TiO_2) suspensions. The mortar was prepared with a 1:1:6 volumetric ratio (cement: lime: sand) and a water/binder ratio of 0.125 (considering sand moisture). To confer self-cleaning properties, aqueous suspensions of TiO_2 were applied to the surface at concentrations of 1%, 5%, and 10%. Tests included fresh state characterization and hardened state mechanical properties. Stain removal efficiency was evaluated under natural weathering for 90 days, testing different orientations (north, south, east, west, horizontal) and staining agents. An Analysis of Variance (ANOVA) was used to identify the most influential factors. Results showed that the mortar met normative requirements for consistency and density. In the hardened state, it achieved an average compressive strength of 14.07 MPa. Statistical analysis revealed that surface orientation and TiO_2 concentration significantly influenced performance. The best stain removal was observed on horizontal surfaces and north-facing facades, where UV activation was maximized. Higher TiO_2 concentrations (5% and 10%) were more effective, particularly for removing organic stains like coffee and ash. The study concludes that surface-applied TiO_2 effectively promotes self-cleaning without compromising the mortar's mechanical properties.
Keywords: building facades; mortars; photocatalysis; self-cleaning; titanium dioxide.

Desempenho da argamassa autolimpante utilizando TiO_2

Resumo
As fachadas das edificações sofrem degradação devido a fatores ambientais, levando a problemas estéticos como o manchamento. Este estudo investigou argamassas autolimpantes produzidas pela aplicação superficial de suspensões de dióxido de titânio (TiO_2). A argamassa foi preparada com um traço volumétrico de 1:1:6 (cimento:cal:areia) e uma relação água/aglomerante de 0,125 (considerando a umidade da areia). Para conferir propriedades autolimpantes, suspensões aquosas de TiO_2 foram aplicadas à superfície nas concentrações de 1%, 5% e 10%. Os testes incluíram a caracterização no estado fresco e propriedades mecânicas no estado endurecido. A eficiência na remoção de manchas foi avaliada sob intemperismo natural por 90 dias, testando diferentes orientações (norte, sul, leste, oeste, horizontal) e agentes manchantes. A Análise de Variância (ANOVA) foi empregada para identificar os fatores mais influentes. Os resultados mostraram que a argamassa atendeu aos requisitos normativos de consistência e densidade. No estado endurecido, alcançou uma resistência média à compressão de 14,07 MPa. A análise estatística revelou que a

orientação da superfície e a concentração de TiO_2 influenciaram significativamente o desempenho. A melhor remoção de manchas foi observada em superfícies horizontais e fachadas voltadas para o norte, nas quais a ativação UV foi maximizada. Concentrações mais altas de TiO_2 (5% e 10%) foram mais eficazes, particularmente para a remoção de manchas orgânicas como café e cinzas. Conclui-se que o TiO_2 aplicado superficialmente promove efetivamente a autolimpeza sem comprometer as propriedades mecânicas da argamassa.
Palavras-chave: *autolimpeza; argamassas; dióxido de titânio; fachadas das edificações; fotocatálise.*

1 Introduction

Facade claddings cover the entire exterior of buildings, playing a crucial role in protecting and complementing seals and structural elements. They meet requirements for durability, air and water tightness, thermal and acoustic insulation, and fire resistance. Additionally, they serve as a finishing touch, enhancing the aesthetic appearance, economic value, and various functional aspects related to the building's use (Ferreira *et al*., 2021).

The exterior claddings of buildings degrade over time, requiring maintenance to ensure their proper performance. However, maintaining facades faces challenges such as height and high costs of materials and labor. In Brazil, traditional mortar claddings are typically applied in two layers. These claddings often face issues with staining and porosity, which lead to a high incidence of building defects. Methods such as water repellents and biocides have shown low efficiency and the need for continuous maintenance. Managing facade maintenance involves interdisciplinary technical considerations and the formulation of public policies for building restoration. This highlights the importance of innovative methods to improve both the durability and aesthetics of constructions.

Recent advances in construction materials have sought to address the persistent challenge of maintaining clean and aesthetically pleasing building facades. Among various solutions, photocatalytic materials have emerged as a promising strategy due to their ability to degrade organic pollutants under light exposure (Bersch *et al*., 2023). In this context, titanium dioxide (TiO_2) has been extensively studied for its photocatalytic properties, particularly in its anatase crystalline form, which exhibits high efficiency under ultraviolet (UV) radiation (Kotzias, 2024).

Currently, the incorporation of TiO_2 into external coatings has gained significant attention. It is an excellent photocatalyst that is effective in creating self-cleaning surfaces. The self-cleaning mechanism of TiO_2 is based on two simultaneous processes under UV irradiation: photocatalytic oxidation and photo-induced super-hydrophilicity.

When activated by UV light, electron-hole pairs are generated on the TiO_2 surface, producing reactive oxygen species (ROS) such as hydroxyl radicals and superoxide ions. These species decompose organic pollutants into simpler substances like water and carbon dioxide. Simultaneously, the surface becomes super-hydrophilic. This allows water to spread in a thin film rather than forming droplets, which facilitates the washing away of accumulated dirt and prevents the adhesion of new contaminants (Wang *et al*., 2022).

There is a hypothesis that this material could be used in mortars and concretes to reduce staining on facades. This would delay the need for surface maintenance of buildings, reducing costs and improving the visual aesthetics of urban landscapes.

According to Ghosh *et al*. (2025), the use of a thin layer of titanium dioxide in material coatings is increasing. This trend is due to the unique property of TiO_2 to attract rather than repel water, which makes the surface super-hydrophilic. Additionally, exposure of TiO_2 to UV radiation leads to the formation of powerful agents capable of oxidizing and decomposing many types of bacteria, organic, and inorganic materials. This oxide is an industrially produced pigment that is the whitest and brightest, with a global production of around 4.5 million tons per year. Its primary uses are in paints and coatings, plastics, papers, printing inks, toothpastes, among others.

According to Ramalingam *et al*. (2023), grease, grime, and organic pollutants disintegrate when TiO_2 is exposed to light and are simply swept away by water (rain). Ink and vehicle smoke are utilized to evaluate the self-cleaning properties of TiO_2-containing concretes, and the oxidation of carbons, gaseous atmospheric pollutants responsible for acid rain and photochemical smog, is explored using nano titanium dioxide.

Khannyra *et al*. (2022) investigated a self-cleaning nanostructured TiO_2-based coating with the capacity to mitigate the adverse effects of air pollution. In addition to reducing the deterioration of building materials, the coating also showed potential to prevent pollution-related health issues. To achieve this, mesoporous TiO_2/SiO_2 photocatalysts were synthesized to produce durable, self-cleaning coatings suitable for outdoor environments. The materials were spray-applied onto concrete substrates and evaluated for self-cleaning (via methylene blue and soot degradation) and air depollution (via nitrogen oxides reduction). The coatings exhibited high photocatalytic activity, with efficiency increasing as TiO_2 content rose. After 60 minutes of UV-vis irradiation, photocatalysts ST1 and S4T degraded 79% and 95% of methylene blue, respectively. Furthermore, after 104 hours of irradiation, they converted 38% and 49% of total NO. In contrast, the commercial photocatalyst E503 produced cracked coatings, achieved only 50% dye degradation, and 35% NO conversion. The TiO_2/SiO_2 coatings retained their photocatalytic performance and structural integrity after four months of real-life exposure and three degradation cycles.

The article by Rabajczyk *et al*. (2021) systematizes information on materials with self-cleaning surfaces, focusing on the photocatalytic process with titanium dioxide (TiO_2). They studied additives that decompose impurities, using TiO_2 in forms of anatase, rutile, or a combination of both. They concluded that building materials modified with TiO_2 improve air quality and extend the lifespan of buildings, providing self-cleaning capabilities.

Chavarry Vallejos *et al*. (2021) determined the influence of titanium dioxide (TiO_2) addition on Portland Type I cement mortars. A reference mixture and three mixtures with 5%, 7.5%, and 10% TiO_2 as volumetric replacement of cement were prepared. To evaluate the self-cleaning properties, rhodamine tests and weathering exposure were conducted. The addition of TiO_2 led to reduced compressive strength, increased workability, and water absorption rate. The rhodamine test indicated that the mixture without TiO_2 showed no photocatalytic activity, as it did not meet the R4 and R26 photodegradation criteria. Weathering exposure enhanced the self-cleaning property in panels containing 5% TiO_2.

The study by Enea *et al*. (2019) evaluated the effects of atmospheric conditions on three commercial photocatalytic paints (white, yellow, and red) containing 4% to 6% TiO_2, applied to fiber-reinforced cement mortar. The durability of the paints was tested according to standards, comparing samples subjected to accelerated and natural aging over two years. Surface color was measured using a spectrophotometer, and the tests included electron microscopy, optical microscopy, UV-vis spectrophotometry, and X-ray diffraction characterizations. Results indicated color retention, increased hydrophilicity, and preservation of photocatalytic performance, despite a decrease in self-cleaning after natural aging, with more noticeable color variations in the yellow and red samples.

The study by Dantas *et al*. (2019) investigated the impact of degradation agents and ultraviolet radiation on facades, evaluating the effect of adding different concentrations of TiO_2 (1%, 5%, and 10%) to mortars applied on concrete substrates. The mortars were compared with surfaces without TiO_2, both with and without paint, exposed for 16 months to the climate of São Paulo. The results indicated that the mortar without TiO_2 but with paint maintained better reflectance, showing smoother and less permeable surfaces, which reduced the retention of dirt and microorganisms. In contrast, the mortars with TiO_2 showed greater dirt accumulation, which negatively affected their reflectance.

Given the issue of facade maintenance, this research aimed to explore the process of developing self-cleaning mortars by applying titanium dioxide (TiO_2) to their surfaces. Thus, the characteristics of the self-cleaning mortar were analyzed, along with the effect of sample exposure on self-cleaning capability and the influence of different TiO_2 concentrations on self-cleaning effectiveness and stain resistance. Various staining agents were used, and the test specimens were exposed to the natural climate of Itajubá—a city in the state of Minas Gerais (MG), Brazil—for evaluation.

Despite the breadth of literature on photocatalytic materials, there is a paucity of investigations regarding TiO_2 applied exclusively to the surface, especially when subjected to real-world exposure and diverse angles of solar incidence. To bridge this gap, the present study evaluates the performance of surface-treated mortars, specifically examining how facade orientation and the nature of the stain influence photocatalytic efficiency.

This article is structured into four main sections, in addition to this introduction. Section 2 (Materials and Methods) details the characterization of raw materials, the mix design, and the experimental procedures adopted for the production and analysis of mortars. In Section 3 (Results and Discussion), the data obtained from fresh-state, mechanical performance, and self-cleaning efficiency tests under environmental exposure are presented and discussed. Section 3 also includes a statistical analysis to deepen the understanding of the results through a factorial regression model, identifying the most impactful variables on photocatalytic performance. Finally, Section 4 (Conclusions) synthesizes the main research findings, discussing the technical viability of surface-applying TiO_2 to rendering mortars.

2 Materials and methods

The experimental program was designed to evaluate the physical, mechanical, and photocatalytic properties of rendering mortars. The topic was divided into five main stages: (i) physical and chemical characterization of the raw materials; (ii) definition of the mix design and mixing procedures; (iii) assessment of mortar properties in both fresh and hardened states; (iv) evaluation of self-cleaning efficiency through real-world environmental exposure; and (v) statistical analysis of the governing variables.

2.1 Characterization of materials

The coating mortar, as seen earlier, consists of several layers. According to ABNT NBR 13281 (ABNT, 2023), mortar for external coating is classified as a leveling layer. This layer is commonly known as rendering, plaster, or a single layer. For the preparation of the rendering mortar with photocatalytic properties, the following materials were used: a fine aggregate consisting of washed natural sand; titanium dioxide (TiO_2); CH-III hydrated lime; CP II-E 32 Portland cement and potable water for mixing. The specific mass test was conducted on the cement, following the recommendations of the current standards.

The fine aggregate used was sand, dried in an oven for 24 hours, and the tests performed to characterize it were particle size distribution (sieve analysis) and specific gravity determination.

Hydrated lime was also used as a binder, whose main function is to efficiently and durably bond the masonry units, both in laying and in rendering applications. Unlike cement, sand, and lime, titanium dioxide was not used in the mortar composition. Instead, it was diluted in water and applied to the surface of the rendering mortar in order to evaluate its performance with respect to staining.

Table 1 summarizes the physical and chemical characteristics of titanium dioxide.

Table 1 – Physical and chemical characteristics of titanium dioxide

Formula	TiO_2
Molecular mass	79.9
Boiling point	2,600 ºC – 3,000 °C
Melting point	1,855 °C
Shape	White powder

Source: Degussa (2023)

2.2 Dosage and mixing method

Mortar mix design can be conducted through various methodologies. However, the absence of a universally established procedure at the national level often leads the construction industry to rely on pre-fixed ratios derived from technical standards. In this context, Reis *et al*. (2024) emphasize the importance of adopting mix design methods that prioritize eco-efficiency and performance-based requirements. Following this approach and a review of common practices in literature, a volumetric ratio of 1:1:6 (cement: lime: sand) was selected. This proportion was chosen for its widespread application in rendering mortars and its compliance with normative guidelines.

The mixing process for preparing coating mortar should follow the steps outlined in ABNT NBR 16541 (ABNT, 2016b) (Table 2). This method takes into account the specifications of ABNT NBR 7200 (ABNT, 1998), which states that the mixing time for mechanized processes should be no less than 3 minutes and no more than 5 minutes.

Table 2 – Mixing process

Time	Materials	Procedure
1 minute	Cement, sand, lime	Manual
30 seconds	75% water	Low speed
1 minute	–	High speed
1 minute and 30 seconds	–	Manual
1 minute	25% water	Low speed

Source: adapted from ABNT NBR 16541 (ABNT, 2016b)

2.3 Mortar properties

The control of mortar, in both its fresh and hardened states, is of utmost importance to ensure that pre-established properties, such as consistency and minimum strength, are achieved. In the fresh state, it is recommended to evaluate several properties that directly affect the final quality of the mortar.

The fresh state properties were assessed through consistency and mass density tests. Following ABNT NBR 13276 (ABNT, 2016a), a spread of 260 (±5) mm was targeted to optimize workability and application. Mass density was measured according to ABNT NBR 13278 (ABNT, 2005) by correlating the compacted mortar mass to its volume.

In the hardened state, the mechanical performance of the mortar was evaluated through flexural tensile strength and axial compressive strength tests. Three cylindrical specimens (5 cm in diameter and 10 cm in height) and three prismatic specimens (4 cm × 4 cm × 16 cm) were prepared. After 24 hours, the specimens were demolded and cured in a calcium hydroxide solution for 28 days. Flexural tensile strength and axial compressive strength were determined in accordance with current technical standards. The specimens identified as CP1, CP2, and CP3 correspond to three independent samples produced with the same composition and under identical preparation, compaction, and curing conditions, ensuring result reliability and comparability.

2.4 Staining test

For the staining test, 144 specimens were produced in the form of circular plates with a diameter of 4 cm and a thickness of 20 mm. These specimens were made using 50 mL disposable plastic cups.

It is important to note that the 20 mm thickness was determined based on the recommendations of ABNT NBR 13749 (ABNT, 2013), which specifies acceptable thicknesses for wall and ceiling coatings.

To ensure the 20 mm thickness, the specimens were weighed using a precision balance (SHIMADZU UX62000H) and compacted with the help of a Solotest vibrating table. After a 48-hour curing period and demolding, the self-cleaning layer was created by applying TiO_2 aqueous suspensions (0%, 1%, 5%, and 10% by weight) to the surface with a bristle brush. With the specimens prepared, we proceeded to the staining test. The staining test was conducted following the guidelines of ABNT NBR ISO 10545 (ABNT, 2017).

After the application of the diluted titanium dioxide, the coated specimens were stabilized in a controlled environment for 24 hours and subsequently subjected to staining tests using tomato sauce, red wine, coffee, spray paint, and coal ash.

For the test, the plates were positioned facing north, south, east, and west, with six plates of each percentage of titanium dioxide dissolved in water (0%, 1%, 5%, and 10%) allocated to each cardinal point (north, south, east, and west) at a 90° inclination. An additional six plates of each percentage were placed at a 0° position, simulating the external coatings of buildings.

Once stained, the plates were placed in an urban environment at the Federal University of Itajubá (UNIFEI) campus, located in Itajubá, state of Minas Gerais (MG), to conduct the visual analysis tests.

The visual analysis tests were carried out 7, 14, 28, 56, and 90 days after the staining. To complement this analysis, a portable radiometer (Cole-Parmer Series 356 nm 9811-50) was used to monitor the radiation at the location. Radiometer readings were taken on the same days, both in the morning at 9:00 AM and in the afternoon at 3:00 PM.

The choice of 9:00 AM and 3:00 PM for measurements in studies of photoactivated materials is not arbitrary. These hours were selected to measure the solar radiation striking the walls of the buildings. This is because, at noon, solar radiation primarily strikes the roofs rather than the facades.

2.5 Statistical analysis

To quantitatively evaluate the influence of experimental variables on self-cleaning performance, a statistical analysis was conducted using Minitab® software. A General Factorial Regression model was employed to process the data obtained from the visual assessment after 90 days of exposure. The experimental design considered three independent factors:

- TiO_2 Concentration: 4 levels (0%, 1%, 5%, and 10%);
- Position/Orientation: 5 levels (north, south, east, west, and horizontal);
- Staining Agent: 5 levels (spray paint, charcoal ashes, wine, tomato sauce, and coffee).

The response variable was the stain removal score, measured on a visual scale from 1 to 5. Due to the unreplicated nature of the full factorial design (n = 1 per combination), a saturated model was obtained. Consequently, the significance of the factors and their interactions was evaluated based on the magnitude of the Adjusted Sum of Squares (Adj SS) and the analysis of Main Effects and Interaction Plots, rather than traditional p-values derived from residual error. This approach allowed for the identification of the most influential variables and the synergistic effects between TiO_2 content and solar

3 Results and discussion

Table 3 presents the physical properties of the materials, including the specific gravity of the cement, as well as the maximum diameter, fineness modulus, and specific gravity of the sand.

Table 3 – Particle size distribution of fine aggregate

Characteristic maximum diameter (D max)		2.40 mm
Fineness modulus (FM)		2.20
Material	**Specific gravity (g/cm³)**	**Unit mass (g/cm³)**
Cement CPIIE32	2.94	1.05
Lime	2.30	0.50
Fine aggregate	2.54	1.46

Source: research data

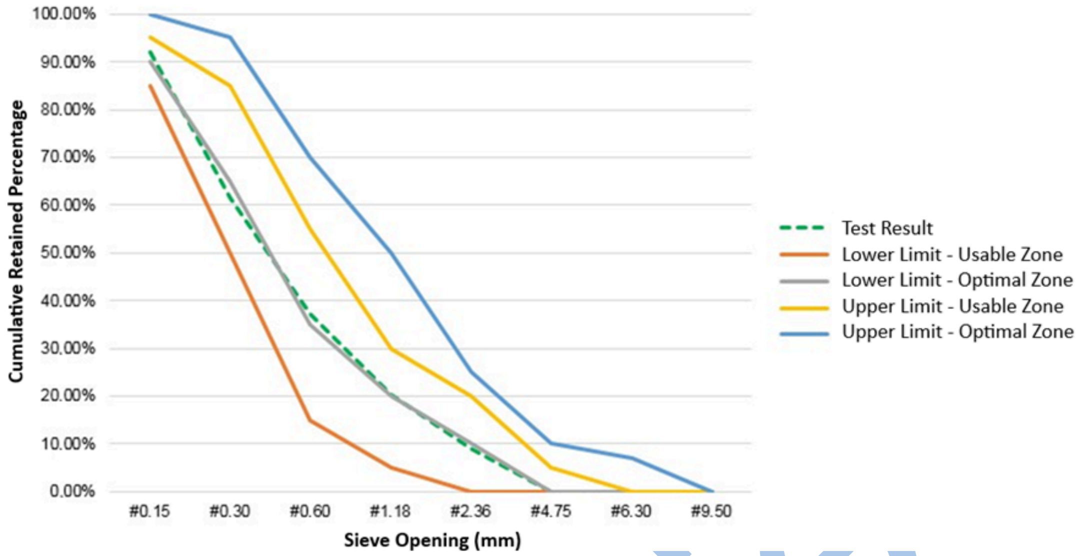
The fineness modulus (FM) determined for the fine aggregate was 2.20. According to the Brazilian standard ABNT NBR 7211 (ABNT, 2022), this value falls within the range that characterizes the material as fine sand. Based on the data presented in Table 3, the characteristic maximum diameter (Dmáx) was determined to be 2.40 mm, corresponding to the sieve opening where the cumulative retained percentage is less than 5%. This indicates that the material is suitable for use as fine aggregate in mortar applications.

The specific gravity values for both the cement and the fine aggregate are within expected ranges for Portland cement and quartz-based natural sands, respectively. The unit mass of the aggregate (1.46 g/cm³) is also consistent with values found in similar studies using natural river sands (Lazorenko *et al*., 2024).

Figure 1 shows the particle size distribution curves of the fine aggregate analyzed, highlighting the cumulative percentage distribution of the particles as a function of sieve openings. The distribution curve shows that the sand contains a significant proportion of fine particles (over 90% passing the 0.15 mm sieve), which may improve cohesion and reduce segregation in fresh mixtures (Martins *et al*., 2024). However, excessive fines content could also lead to higher water demand and reduced permeability in hardened systems (Reis *et al*., 2024; Gaspar *et al*., 2024). Therefore, the use of this material should be carefully balanced with the binder content and water-to-cement ratio to optimize performance.

These curves allow for the assessment of the material's uniformity and gradation key aspects for the classification of fine aggregates according to the specifications of ABNT NBR 7211 (ABNT, 2022).

Figure 1 – Particle size distribution curve of fine aggregate



Source: adapted from ABNT NBR 7211 (ABNT, 2022)

Figure 1 shows the particle size distribution curve of the fine aggregate, along with the lower and upper limits for both the usable and optimal grading zones. The experimental curve (green dashed line) demonstrates a well-graded fine aggregate, with most of the data points falling within the optimal grading zone defined by the standard.

The grading curve indicates a continuous and smooth distribution, suggesting a low likelihood of segregation and good workability in mortar or concrete mixes.

Furthermore, the proximity of the curve to the center of the optimal zone implies a favorable balance between fine and coarse particles within the fine aggregate, which can enhance packing density and reduce void content Finally, the sand moisture test was conducted using the speedy method to determine the amount of water present.

3.1 Dosage and fresh and hardened state tests

The mix ratio used is shown in Table 4, already accounting for the sand's moisture content.

Table 4 – Corrected unit mix ratio used

Corrected Mix Ratio	Cement (g)	Lime (g)	Sand (g)	Water (g)
1:1:6	1,066.11	1,066.11	6,727.2	266.44

Source: research data

The mortar was formulated based on a traditional 1:1:6 volumetric ratio (cement:lime:sand), converted into a precise mass-based mixture (Table 4) to ensure experimental reliability. This conversion yielded a water-to-binder (w/(c+lime)) ratio of approximately 0.125 and a sand-to-binder ratio of 3.15. Although the low (w/(c+lime)) ratio is intended to enhance packing density and reduce porosity, such mixtures typically present workability challenges. However, the use of corrected mass-based dosing provided strict control over the composition, ensuring that the observed results in subsequent photocatalytic tests are attributable to the investigated variables rather than uncontrolled variations in the mixture. Fresh-state properties were evaluated through the consistency index test following ABNT NBR 13276 (ABNT, 2016a).

The mixture achieved an average spread of 262 mm, complying with the standard requirement of 260 (±5) mm. This satisfactory workability, despite the low water content, is attributed to the optimized granulometric distribution of the aggregates (Figure 1), which promotes particle packing and reduces water demand (Martins *et al.*, 2024). The minimal variation among measurements confirms the high reproducibility of the preparation process, a critical prerequisite for evaluating advanced functional modifications in cementitious materials (Gaspar *et al.*, 2024).

Therefore, the results of the consistency index test confirm that the proposed formulation not only complies with technical standards but also provides a reliable basis for evaluating the advanced functional properties investigated in this work.

Next, the bulk density test of the mortar was conducted. The values for the mass of the empty cylindrical container (mv = 97.91 g), the mass of the cylindrical container with the test mortar (mc = 415.50 g), and the volume of the cylindrical container (Vr = 162.50 cm^3).

By substituting the values, the bulk density of the mortar is calculated to be 1,954.4 kg/m^3.

According to ABNT NBR 13281 (ABNT, 2023), the tested mortar is classified as DF3 (1,800 to 2,000 kg/m^3). The term DF refers to the density requirement in the fresh state. Furthermore, as per Dębska (2022), the mortar is classified as normal (Table 5), which means it is suitable for conventional applications.

Table 5 – Unit mix ratio used

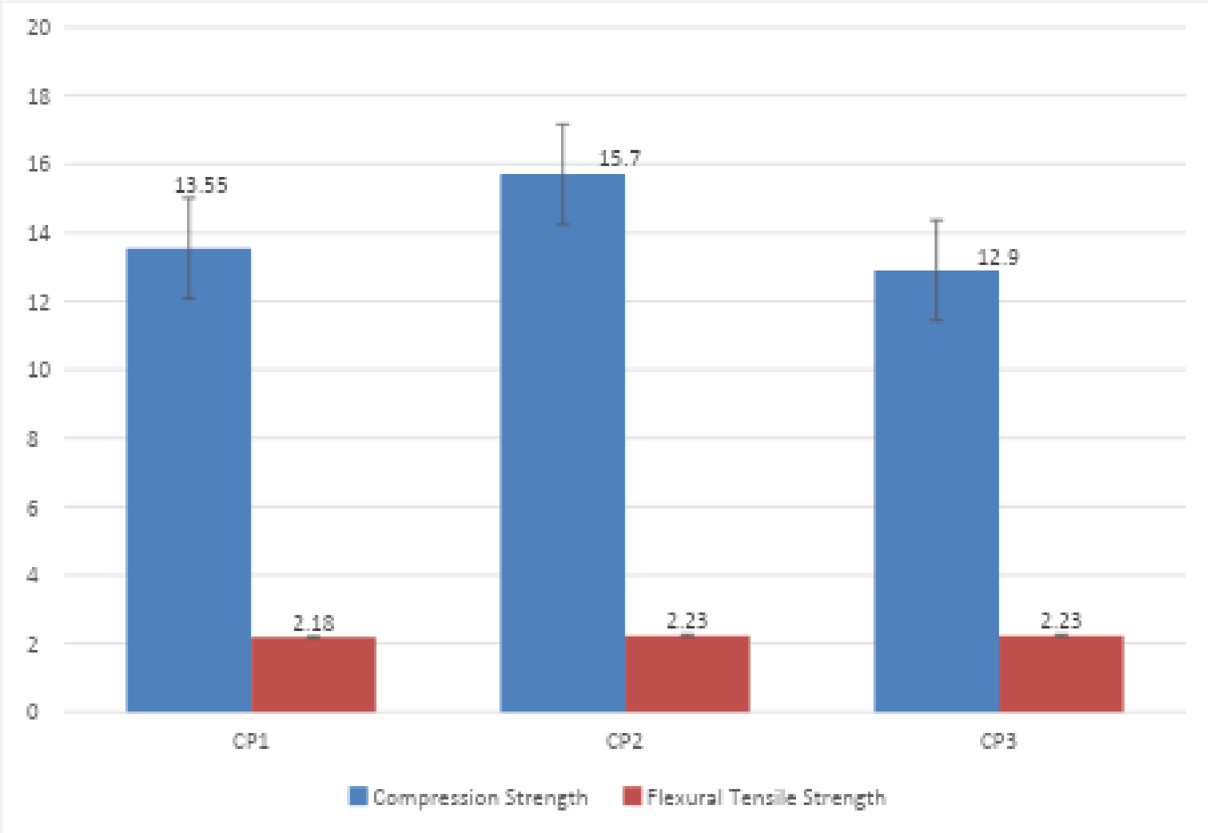
Mortar	**Bulk Density (g/cm^3)**	**Main Aggregates Used**	**Uses/observations**
Light	< 1.40	Vermiculite, perlite, expanded clay	Thermal and acoustic insulation
Normal	2.30 ≤ A ≤ 1.40	River sand (quartz) and crushed limestone	Conventional applications
Heavy	> 2.30	Barite (barium sulfate)	Radiation shielding

Source: adapted from Dębska (2022)

It is important to note that the higher the bulk density, the heavier the mortar, which can impact its workability.

After 28 days, axial compressive strength and flexural tensile strength tests were performed. The results of the compressive strength test are shown in Figure 2, with the mortar strength being the average of the three specimens.

Figure 2 – Compression strength (MPa)



Source: research data

The compressive strength values ranged from 12.9 MPa (CP3) to 15.7 MPa (CP2), with specimen CP1 presenting an intermediate value (13.55 MPa). The higher average value observed for CP2 indicates a slightly superior mechanical performance compared to the other specimens. The error bars denote a moderate experimental variability, typical of tests on cementitious materials, suggesting good repeatability of the molding and testing procedures.

Regarding flexural tensile strength, results were highly consistent, ranging from 2.18 MPa (CP1) to 2.23 MPa (CP2 and CP3). This minimal variation demonstrates the material's homogeneity and stable tensile performance, suggesting that any microstructural variations were insufficient to significantly impact this property.

Overall, the results demonstrate consistency among the test specimens, with variations compatible with those expected within a single experimental batch. The slightly higher compressive strength of CP2 may be related to improved compaction, lower void content, or subtle local microstructural differences. Finally, the explicit identification of CP1, CP2, and CP3 as experimental replicates in the methodology reinforces data reliability, demonstrates experimental control, and supports the reproducibility of the study.

The limited variation among CP1, CP2, and CP3, with a slight superiority of CP2 in compression and nearly identical values in flexural tensile strength, is consistent with the experimental variability typically reported for cementitious materials, in which differences of up to approximately 5% between specimens are considered normal and do not compromise result representativeness (Cangussu *et al.*, 2024). Moreover, the compressive and flexural strength values obtained fall within recent empirical correlations between these properties, further reinforcing the mechanical consistency of the material studied (Abubakar *et al.*, 2025).

Recent literature suggests that incorporating TiO_2 at levels up to 5% by binder mass does not significantly compromise mechanical properties and may even improve compaction and reduce porosity (Fleck; Polesello; Leão, 2025). However, unlike their study, which focused on bulk incorporation, the TiO_2 in this study was applied as a surface coating. Consequently, the photocatalytic agent did not influence the mortar's internal mechanical performance, as the core composition remained unaltered.

3.2 Stain removal efficiency test

To evaluate self-cleaning efficiency, TiO_2 aqueous suspensions at concentrations of 1%, 5%, and 10% were applied to the mortar surfaces. A more pronounced whitish opacity was observed at higher concentrations due to the pigment's inherent characteristics. After 24 hours, specimens were marked with common urban stains (spray paint, charcoal ash, wine, tomato sauce, and coffee) alongside a clean control sample (Figure 3). The samples were exposed to outdoor urban conditions for 90 days to assess photocatalytic performance under real-world environmental stressors.

Recent studies have shown that TiO_2, when activated by UV radiation, promotes oxidation reactions that break down organic compounds deposited on the surface. TiO_2 based photocatalysts are novel materials that exhibit excellent absorption behavior toward organic compounds in wastewater due to their outstanding properties including nontoxicity, high photocatalytic degradation ability, and excellent thermal and chemical stabilities. However, several challenges exist regarding TiO_2 applications for organic effluents such as particle aggregation, mass transfer limitation, poor affinity, high band energy, scattering conditions, and difficulty of recovery (Chen *et al*., 2020).

Figure 3 – Staining of test specimens

Source: authors' archive

The self-cleaning performance was monitored over a 90-day urban exposure period (July to September 2023), with measurements taken at 7, 14, 28, 56, and 90 days. This strategic schedule, supported by Reddy and Panchangam (2024), prioritizes frequent early-stage observations to capture initial photocatalytic effects while monitoring long-term stability and potential performance decline. Complementing this, Table 6 details the solar radiation intensity recorded at 9:00 AM and 3:00 PM. These measurements were conducted using a portable radiometer with the specimens positioned in five orientations: vertical (north, south, east, and west) and horizontal (0°), providing a comprehensive temporal and environmental framework for the analysis.

Table 6 – Measurements with portable radiometer

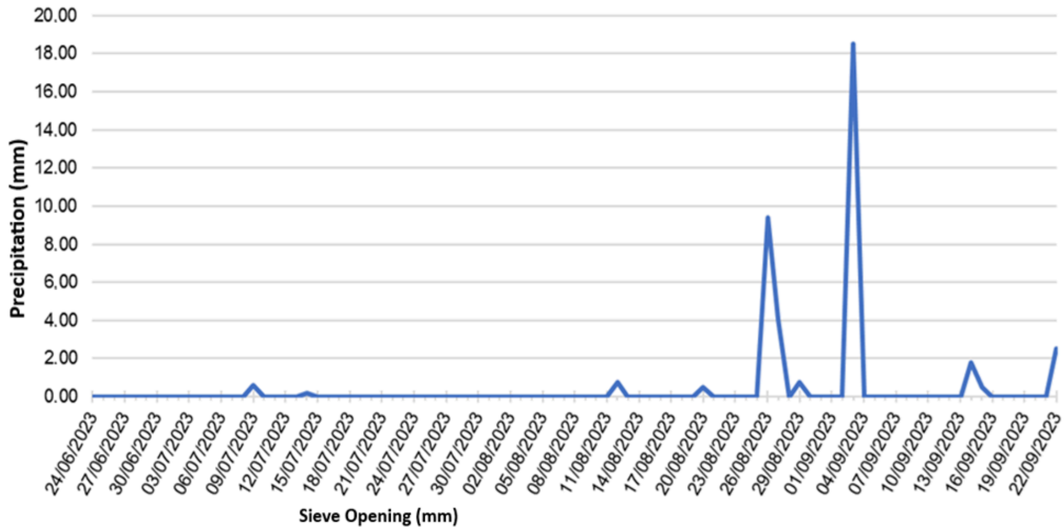
Measurement	**Date**	**Time**	**Plates at 90°**				**Plates at 0°**	
			North	**South**	**East**	**West**	**North-South**	**East-West**
1	07/01/2023	9:00	0.14	0.09	0.14	0.09	0.31	0.31
		3:00	0.58	0.06	0.58	0.06	0.31	0.31
2	07/08/2023	9:00	0.11	0.10	0.21	0.05	0.32	0.28
		3:00	0.30	0.09	0.18	0.09	0.22	0.32
3	07/22/2023	9:00	0.03	0.06	0.08	0.06	0.19	0.14
		3:00	0.06	0.04	0.06	0.05	0.12	0.10
4	08/19/2023	9:00	0.09	0.10	0.09	0.10	0.32	0.31
		3:00	0.10	0.07	0.10	0.07	0.17	0.17

5	09/22/2023	9:00	0.29	0.14	0.10	0.26	1.51	1.30
		3:00	0.46	0.05	0.16	0.05	0.51	0.40

Source: research data

Solar radiation intensity was monitored on five dates between July and September 2023 at 9:00 AM and 3:00 PM using a portable radiometer. The TiO_2 coated plates were evaluated at two inclinations: 90° (facing north, south, east, and west) and 0° (horizontal, aligned north-south and east-west). Overall, the horizontal plates (0°) received the highest incident radiation, peaking on 09/22/2023 at 9:00 AM with values of 1.51 (N-S) and 1.30 (E-W). Diurnal variations were evident, with generally higher radiation levels recorded at 3:00 PM, particularly for north and west orientations, reflecting the solar trajectory. Conversely, lower intensities recorded on specific dates (e.g., 07/22/2023) suggest overcast conditions that may temporarily attenuate photocatalytic activity. These results confirm that incident radiation is sufficient to activate the photocatalytic process, with horizontal surfaces such as rooftops and pavements likely benefiting most from self-cleaning action. This analysis, coupled with the visual measurements recorded over 90 days (Figure 4), is essential for understanding the real-world efficiency of TiO_2 coatings under varying environmental conditions.

Figure 4 – Precipitation in Itajubá-MG during the measurements



Source: UNIFEI (2023)

The performance of the self-cleaning mortar was evaluated under real climatic conditions in Itajubá-MG, from June 24 to September 22, 2023, with particular focus on precipitation data.

Meteorological records (Figure 4) indicate that the period was characterized by low rainfall and predominantly dry weather, typical of the winter season in southeastern Brazil. Most days exhibited either no precipitation or levels below 2 mm. Only three significant rainfall events were recorded, with the highest on September 2, 2023 (~18 mm), followed by ~9 mm on August 26.

The limited rainfall reduced the natural washing effect on the mortar surfaces, potentially constraining the visual evidence of the self-cleaning effect induced by TiO_2. Nonetheless, photocatalytic degradation of organic contaminants likely occurred under solar radiation. However, the physical removal of surface residues, which is essential for achieving visible self-cleaning effects, is generally more effective during periods with higher precipitation frequency.

After 90 days of exposure, distinct differences were observed between specimens positioned horizontally and those inclined at 90°. Horizontally positioned specimens exhibited more pronounced stain discoloration, attributed to prolonged exposure to solar radiation. Furthermore, an increase in titanium dioxide (TiO_2) content correlated with greater stain discoloration in the horizontal samples. Solar orientation analysis showed that north-south facing plates (Figure 5) achieved higher decolorization rates, especially those with a 10% TiO_2 layer evaluated at 7, 14, 56, and 90 days.

Figure 5 – Visual measurement – 7, 14, 56 e 90 days (north – south)

Source: elaborated by the authors

As illustrated in Figure 5, after 90 days of exposure, nearly complete decolorization was observed for most contaminants, including charcoal ash, wine, tomato sauce, and coffee. This high degradation efficiency is attributed to the presence of complex organic compounds in these stains, such as polyphenols in wine and coffee and carbonaceous species in ash, which are readily susceptible to oxidation by hydroxyl radicals generated on the TiO_2 surface (Chen *et al*., 2020; Szczepanik, 2017). In contrast, the spray paint exhibited minimal degradation. This resistance can be chemically rationalized by the stable polymeric matrix of the paint, typically composed of synthetic resins and long-chain polymers, whose robust chemical bonds are generally much less reactive toward photocatalytic oxidation than low-molecular weight organics under comparable conditions. Overall, these findings indicate that, while TiO_2 is highly effective for the remediation of many organic contaminants, its performance is selectively constrained by the intrinsic chemical stability of the target pollutant (Chen *et al*., 2020; Szczepanik, 2017).

The use of titanium dioxide (TiO_2) in cement-based materials has been extensively studied over the past decades due to their photocatalytic properties, which enable the degradation of organic compounds and impart self-cleaning effects to surfaces exposed to solar radiation. Recent studies have shown that the incorporation of TiO_2 into rendering mortars can not only improve the aesthetics and durability of surfaces but also contribute to the mitigation of urban air pollutants.

The efficiency of these systems depends on multiple factors, such as the TiO_2 content, the application method (blended or surface-coated), the type of incident radiation (UV or visible), and the environmental conditions during exposure, including temperature and precipitation (Kuk-Dzul *et al*., 2024). Studies such as that by Bersch *et al.* (2023) highlight that the combined action of solar radiation and rainfall is essential for the visible manifestation of the self-cleaning effect, as photodegradation is driven by the action of TiO_2, but the physical removal of residues relies on the presence of water.

Recent studies support the observations regarding the influence of climatic conditions, especially precipitation, on the self-cleaning efficiency of cementitious materials containing titanium dioxide (TiO_2).

For example, according to Reddy and Panchangam (2024), the self-cleaning performance of TiO_2-containing cement mortars under natural sunlight was evaluated. The results indicated that rainfall contributes to the physical removal of degraded residues, thereby enhancing the visible self-cleaning effect. In contrast, during periods of low precipitation—such as the winter season in southeastern Brazil—the visual effectiveness of the self-cleaning property may be limited, despite the occurrence of photocatalytic degradation of organic contaminants under solar radiation.

To quantitatively assess the visual observations and evaluate the influence of the input variables on the self-cleaning performance, an Analysis of Variance (ANOVA) model was employed using the General Factorial Regression tool in the Minitab software. The analysis considered the concentration of TiO_2 (0%, 1%, 5%, and 10%), the sample position (north, south, east, west, and horizontal), and the type of staining agent as factors. The response variable was the stain removal score (on a scale of 1 to 5) assigned after 90 days of exposure.

The unreplicated nature of the experimental design (n = 1) led to a saturated model (R-sq = 100.00%), with zero degrees of freedom for the error term. Thus, the significance of the factors was evaluated by the magnitude of their effects, expressed by the Adjusted Sum of Squares (Adj SS), as shown in Table 7, and by graphical analysis.

Table 7 – Analysis of variance

Source	DF	Adj SS	Adj MS	F-value	p-value
Model	99	156.110	1.5769	*	*
Linear	11	136.490	12.4082	*	*
% TiO_2	3	74.670	24.8900	*	*
Position	4	25.360	6.3400	*	*
Staining Agent	4	36.460	9.1150	*	*
2-Way Interactions	40	12.900	0.3225	*	*
% TiO_2*Position	12	2.480	0.2067	*	*
% TiO_2*Staining Agent	12	3.380	0.2817	*	*
Position*Staining Agent	16	7.040	0.4400	*	*
3-Way Interactions	48	6.720	0.1400	*	*
% TiO_2*Position*Staining Agent	48	6.720	0.1400	*	*
Error	0	*	*		
Total	99	156.110			

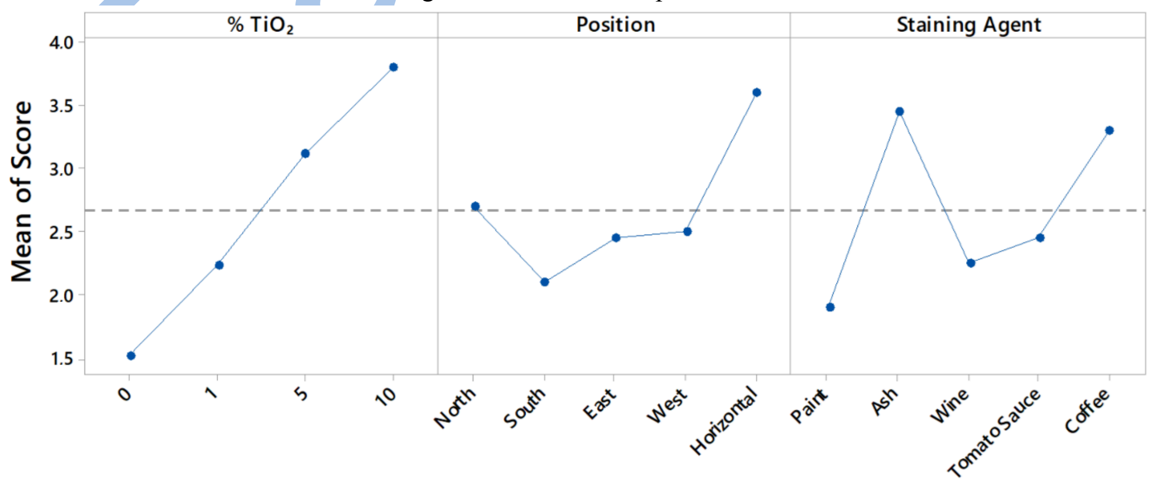
Source: research data

Given the unreplicated experimental design (n = 1), the ANOVA resulted in a saturated model with zero degrees of freedom for the error term, precluding the calculation of F-values and p-values. However, the numerical reliability of the model can be assessed by the magnitude of the Adjusted Sum of Squares (Adj SS), which quantifies the variation explained by each factor.

As shown in Table 7 and illustrated in Figure 6, the Linear model accounts for the vast majority of the total variability (Adj SS = 136.490 out of 156.110), representing approximately 87.4% of the observed variance. This dominance of main effects over interactions (which account for only ~12.6%) indicates that the identified factors are robust predictors of performance.

Among the factors, TiO_2 Concentration exerts the greatest influence (Adj SS = 74.670), explaining nearly half of the total variance alone. This confirms that the dosage of the photocatalyst is the primary driver of the self-cleaning mechanism. Staining Agent (Adj SS = 36.460) and Position (Adj SS = 25.360) follow as significant secondary factors. Therefore, despite the absence of replication, the large disparity in Adj SS values allows for a safe interpretation that the observed improvements are due to the experimental treatments rather than random noise.

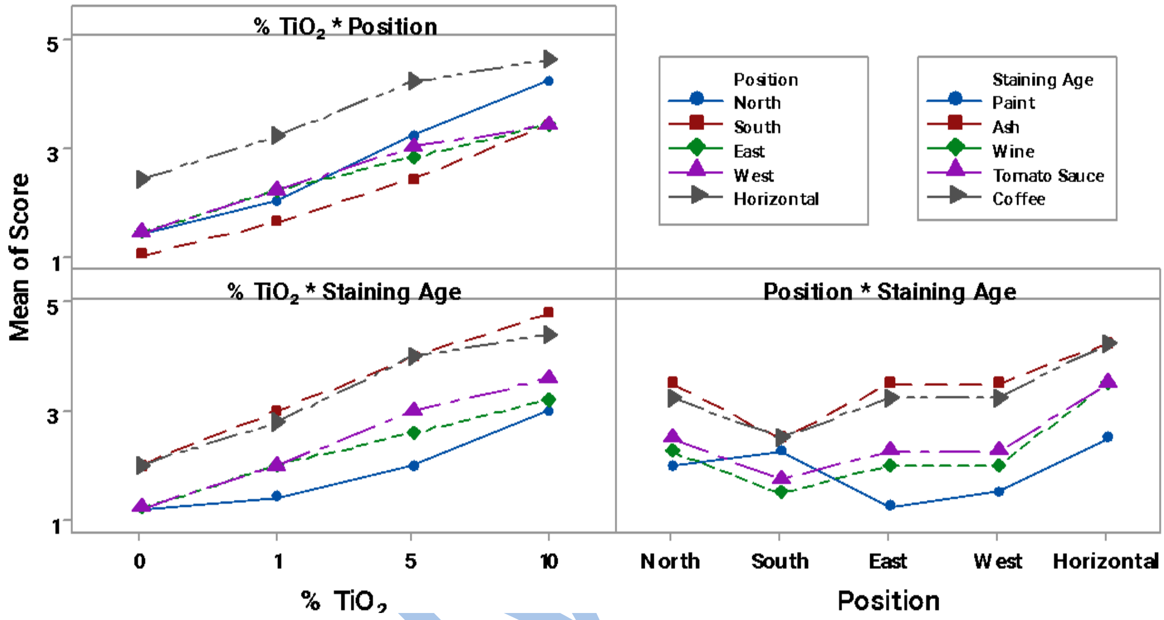
Figure 6 – Main effects plot for score



Source: research data

However, for a more in-depth understanding, the analysis is not limited to isolated effects. The assessment of the interactions between factors, detailed in the Interaction Plot (Figure 7), is crucial for revealing synergistic effects. The most relevant interaction for this study is highlighted: % TiO_2 * Position. The non-parallelism of the lines in the corresponding graph demonstrates that the photocatalytic efficacy of TiO_2 is dependent on the sample's position. It is observed that the magnification of the cleaning effect, as the TiO_2 concentration is increased, is substantially greater in the Horizontal position compared to the vertical positions. This result corroborates the hypothesis that optimizing exposure to solar radiation is a prerequisite for maximizing the potential of the TiO_2 treatment.

Figure 7 – Interaction plot for score



Source: research data

In summary, the statistical analysis validates and quantifies the experimental observations, confirming TiO_2 concentration, sample position, and stain type as determinant factors and revealing the synergistic interaction between the photocatalyst concentration and the sample's position as a primary condition for optimizing the coating's self-cleaning efficiency.

4 Conclusion

Self-cleaning mortars were successfully developed through the surface application of titanium dioxide (TiO_2) and evaluated under real environmental exposure conditions. Regarding their fresh-state properties, the treated mortars maintained adequate performance, with a consistency of 262 mm and a bulk density of 1,954.4 kg/m³, thus meeting the requirements for conventional rendering mortars. Furthermore, the mechanical performance was not adversely affected by the TiO_2 application, yielding an average compressive strength of 14.07 MPa and a flexural tensile strength of 2.22 MPa.

The results indicated that surface orientation significantly influenced stain removal, with horizontally positioned specimens showing superior performance compared to vertical specimens inclined at 90°. Higher TiO_2 concentrations (5% and 10%) resulted in enhanced stain removal efficiency, particularly in specimens oriented toward the north. Statistical analysis confirmed that TiO_2 concentration, sample orientation, and stain type are determinant factors governing self-cleaning performance, with concentration identified as the most impactful variable.

Additionally, a strong synergistic interaction between TiO_2 concentration and surface orientation was observed, demonstrating that photocatalytic efficiency is maximized under conditions of increased solar exposure. It is important to note, however, that effectiveness depended on the nature of the contaminant; higher efficiency was observed for organic stains, such as coffee, wine, and tomato sauce, while lower effectiveness was recorded for spray paint and ash, especially on vertical surfaces. Overall, the surface application of TiO_2 proved to be an effective and viable strategy for imparting self-cleaning functionality to rendering mortars, provided there are favorable solar exposure conditions.

4.1 Limitations of the study

Despite the promising results, this study presents some limitations that should be acknowledged. The self-cleaning performance was evaluated under natural weathering conditions over a 90-day period, which, although representative of real exposure, was characterized by low precipitation, potentially limiting the visual manifestation of the self-cleaning effect. In addition, experimental design adopted an unreplicated full factorial approach (n=1 per condition), resulting in a saturated ANOVA model and preventing conventional statistical significance testing. Furthermore, the assessment of stain removal relied primarily on visual scoring, which, although supported by statistical analysis, may introduce a degree of subjectivity when compared to instrumental colorimetric methods.

4.2 Future research directions

Future investigations should focus on long-term exposure campaigns covering different seasons and climatic conditions, particularly periods with higher rainfall, to better capture the combined effects of photocatalysis and natural washing. The inclusion of replicated experimental designs and objective colorimetric measurements (e.g., ΔE analysis) would strengthen statistical robustness and result reliability. Additionally, future studies may explore alternative TiO_2 formulations, visible-light-active doped photocatalysts, and different application techniques to enhance efficiency under lower UV availability. Evaluating durability aspects, such as abrasion resistance, adhesion of the TiO_2 layer, and long-term photocatalytic stability, will also be essential for practical implementation in building facades.

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Conflict of interests

The authors declare no conflicts of interest.

Note

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Contributions to the article

SIQUEIRA A. C. M.; RODRIGUES S. P.: study/research design and conception; **SOUZA M. H. B.; KONDO M. M.; RIBEIRO, V. A. S.; SANTOS, V. C.:** final revision with critical and intellectual contribution to the manuscript. All authors participated in the writing, discussion, review, and approval of the final version of the article.

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