Natural weathering rack for evaluating solar reflectance degradation of exterior building coatings

Conference Paper · December 2023

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ABSTRACT

The use of reflective materials is recommended as one of the alternatives to mitigate the negative effects of global warming, especially in hot climates. However, once these surfaces are exposed to weathering, their reflective capacity may change due to natural aging. In this context, monitoring the optical properties of reflective materials has become essential for understanding the long-term performance of such surfaces. This paper describes the design, construction, and operation of a natural aging rack to evaluate the degradation of solar reflectance of coatings over time. Results from 36 months of exposure of 25 types of tiles are presented to validate the operation of the rack and to comparatively understand the effect of natural aging on reflective and non-reflective roofs. The novelty of this study is the continuous monitoring of the surface temperatures of the samples exposed to weathering. The rack has proven to be a viable, simple, inexpensive, and reliable method to evaluate the effects of solar reflectance degradation of coatings over 36 months of weathering. According to the results, 1) the reflective tiles suffered the greatest impact of natural weathering, with 32.14% and 27.39% reduction in reflectivity, respectively; 2) a very strong correlation (R^2_{0month} = 0.879; $R^2_{36month}$ = 0.888) was found between the maximum surface temperatures of the tiles and their solar reflectance values; and 3) the surface temperature, which was continuously monitored throughout the weathering, serves as an important indicator of the thermal performance of the tiles. Therefore, the rack can potentially be used for joint analyses of solar reflectance degradation and thermal performance of coatings.

Keywords: solar reflectance, weathering rack, natural aging, roof tile, thermal performance.

Introduction

Urban growth, coupled with the lack of trees, heightens solar radiation absorption by buildings and paved surfaces, contributing to the formation of urban heat islands - UHI (SANTAMOURIS *et al.*, 2011; ROMERO *et al.*, 2019). The phenomenon may be more intense in hot climates, such as between 15° North and 15° South latitudes, where solar radiation is a relevant issue for thermal gains in the built environment (JAYASINGHE *et al.*, 2003). Brazil, being a vast country with a part of its territory falling within the aforementioned latitude range, experiences significant solar radiation, which becomes a major contributor to the thermal loads of its buildings (ABNT, 2005). Numerous studies aimed at mitigating undesirable heat accumulation in buildings have proposed the use of cool or reflective materials on urban surfaces. Cool materials, characterized by high solar reflectance and high thermal emittance,

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maintain lower temperatures in sunlight, reducing artificial cooling need and enhancing occupant comfort in naturally ventilated buildings, especially during hot summers. However, the reflective property is dynamic and can change over time due to the action of natural weathering (PEREIRA, 2014; FERRARI *et al.*, 2017; TSOKA *et al.*, 2018).

Bretz and Akbari (1997) found an average 20% reduction in solar reflectance of 26 roofs during the first year of weathering in different regions of the United States. Alchapar and Correa (2016) evaluated 19 roofing materials in Mendoza, Argentina, and found more than 20% SRI degradation in 75% of the samples, increasing surface temperatures by 12°C to 24°C. Tsoka *et al.* (2018) reported up to 40% reflectance loss in some coatings due to aging. De Masi *et al.* (2018) observed an absolute decrease of 0.19 (0.67 to 0.48) in the reflectance of white roofs in Benevento, Italy, after 1 year of exposure. Araujo (2022) found a 21.42% decrease in solar reflectance of white glazed ceramic tiles after 2 years in São Carlos, Brazil. These changes occur mainly in materials with initially high solar reflectance (SLEIMAN *et al.*, 2015) and in samples whose surface finishes are acrylic paints (REVEL *et al.*, 2013). Such natural aging of the building envelope can significantly increase the unwanted thermal gain absorbed by roofs, mainly due to the darkening of their surfaces (CHENG *et al.*, 2012; ALCHAPAR *et al.*, 2014; ALGARNI *et al.*, 2015), and has therefore become a fundamental factor to be studied (AKBARI *et al.*, 2005).

Assessments of natural aging, especially for cool coatings, have been conducted in North America and Europe since the 1990s (ANDERSON, 1992; BYERLEY *et al.*, 1994; BRETZ *et al.*, 1997). In Brazil, it was not until 2021 that an amendment to the Building Performance Standard NBR 15575-1 (ABNT, 2021) recommended that the effects of degradation on the solar reflectance of exterior walls and roofs be monitored for thermal performance analysis of buildings. Regarding degradation analysis, the amendment suggests a) study of products in use, with a systematic inspection of a representative sample, or b) study of natural aging of small samples exposed in weathering racks for 36 months.

This paper describes the construction of an aging rack, entirely built in Brazil (located in São Carlos, SP), whose novelty is the possibility of constantly monitoring the surface temperatures of the samples throughout the weathering period. Given the novelty of analyzing the natural aging of coatings in Brazil, the design of this aging rack was influenced by North American systems known as Weathering Racks, used to evaluate the effect of natural degradation on the solar reflectance of building materials. The presented aging rack has been in operation since July 2019, and provides the results of the first 36 months of solar reflectance degradation for 25 different types of tiles.

Materials and weathering

Location and Climate

The weathering rack was installed in the outdoor experimental area of the Laboratory of Environmental Comfort (LCA) of the Institute of Architecture and Urbanism of University of São Paulo, in São Carlos (IAU-USP). São Carlos is at 22º01'04" (S) and 47º53'27" (W), around 856 m above sea level. The city is medium-sized by Brazilian standards, with approximately 257,000 inhabitants (IBGE, 2021). The site is sparsely wooded, which prevents leaf accumulation and excessive shading. It's near a busy road, exposed to airborne particles, a stream, and university buildings. Overall, this site mimics urban roof wear in mid-sized cities.

However, each location is specific in terms of climate, airborne particulate matter, and solar radiation exposure, impacting surface aging based on the area. Araujo (2022) divides the climate of São Carlos into two primary groups, rather than four distinct seasons: 1) humid, with lower temperatures (Nov - Mar), and 2) dry, with a wider temperature range (May - Sep).

Materials and Sample Preparation

The 25 selected tiles were purchased from local building material stores (São Carlos, SP, BR) and divided into 3 groups based on their raw materials (Figure 1. and Table 1). The colors of the glazed ceramic tiles are fixed by an acrylic resin after firing, while concrete tiles are pigmented directly in the mass and colored as a whole and not only on the surface. The colored ceramic tiles (19, 20 and 21) are pigmented by a layer of powder paint obtained by heating at high temperatures. Ceramic tiles 23 and 24 are the only ones that have had a transparent resin applied to their surface for waterproofing, and tiles 22 and 25 have no differentiated finish. Among all samples, only tiles 1 and 9 meet the cool roof criteria (Table 2), with an initial solar reflectance (SR) higher than 0.65 (CASINI, 2016).

A portable reflectometer, model SSR-ER version 6.4 (Devices & Services Co.), from the Laboratory of Microstructure and Eco-Efficiency of Materials (LME) of the Polytechnic School (POLI-USP), was used to measure the SR of the samples. The measurement procedure followed the method described in ASTM C1549-16 (ASTM, 2016), as explained by Shirakawa *et al.* (2020, 2022). According to the author, results obtained with a portable reflectometer are as reliable as those obtained with a spectrophotometer using an integrating sphere.

Figure 1. Selected tiles. 1 to 12 - glazed ceramics; 13 to 18 – concrete; and 19 to 25 - pigmented or conventional ceramic.

Table 1. Tiles characteristics.

Type tile	Size (cm)	Thickness (cm)	Weight (kg)	Size (cm)
Glazed ceramic	25,3 x 42,6 x 41,5	1,0	2,1	25,3 x 42,6 x 41,5
Concrete	42 x 33	2,5	4,4	42 x 33
Colored ceramic	25,7 x 42,4	1,2	3,0	25,7 x 42,4
Ceramic	25,3 x 44,5	1,2	3,0	25,3 x 44,5

Table 2. Initial solar reflectance (SR_0) of selected tiles.

Tile	1	2	3	4	5	6	7	8	9	10	11	12
SR_0	0.84	0.64	0.60	0.38	0.44	0.56	0.61	0.29	0.73	0.53	0.27	0.23

13	14	15	16	17	18	19	20	21	22	23	24	25
0.35	0.26	0.28	0.09	0.49	0.27	0.65	0.56	0.44	0.45	0.42	0.43	0.43

Weathering Rack Construction

According to the Weathering Testing Guidebook developed by Atlas Weathering Material Testing Solutions (AEDC, 2001), natural aging testing is defined as the direct exposure of the coatings to be tested to sunlight. The process is performed using an anodized aluminum exposure rack facing south (in the northern hemisphere) at a fixed angle - the average size of the samples to be exposed is 150 x 305 mm. In order to evaluate the natural degradation of building materials exposed to weathering, the conditions under which aging would occur naturally should be simulated (WYPYCH, 2018). In addition, both the exposed samples and the exposure site must be carefully maintained to ensure that external factors do not disturb the exposure conditions.

In order to regulate and standardize material degradation studies, specialized institutions propose certain procedures. ASTM G7/G7M (ASTM, 2021) is an international standard that outlines these procedures for natural aging testing of nonmetallic materials in outdoor environments. The guidelines cover a) test site, specimen arrangement in the fixed structure, and exposure orientation, b) exposure rack construction, c) instrumentation, d) test procedure, e) reporting of results, and f) accuracy and reliability of results. When selecting an outdoor exposure method from several options, it's important to consider the one that best mimics natural weathering degradation. Method recommendations may vary, depending primarily on the type of material and the local climate.

The weathering rack constructed in this study aims to replicate a typical Brazilian roofing system for ceramic tiles, glazed or not, and concrete tiles. Figure 2 and Table 3 show an overview of the rack with details of all its components. Two types of samples were used: a) laboratory samples, obtained from the most linear part of the tile, used to measure the solar reflectance with a portable reflectometer, and b) thermocouple samples, representing the uncut part of the tile, used to measure its undersurface temperature.

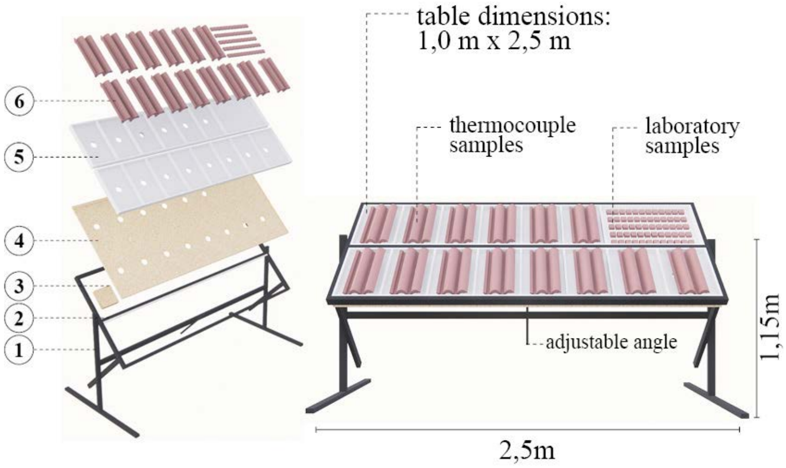

Figure 2. Weathering rack project.

Table 3. Elements of the weathering rack

Item	Part name	Function	Material
1	Structure	Exposes the samples, allowing rotation from 0º-80º	Metalon brand galvanized steel tube, 30 x 40 - 1.25 mm
2	Channel	Organizes the thermocouple distribution	Aluminum channel
3	Box	Organizes the arrival of thermocouples from the data acquisition system	OSB (oriented strand board)
4	Table	Supports samples to be analyzed	OSB (oriented strand board)
5	Partitions	Isolate samples from any surface that might interfere with temperature monitoring	15 mm thick polystyrene boards
6	Samples	Object of analysis	25 different types of tiles

As mentioned above, the rack design was based on international references such as Weathering Testing Guidebook (ATLAS-MTS), Outdoor Weathering (Q-LAB) and ASTM G7/G7M (ASTM, 2021). The angle of the table was set according to the manufacturers of the tiles analyzed. The rack was oriented to the north, which is more exposed to solar radiation throughout the year in the southern hemisphere. In addition, the design included continuous monitoring of the undersurface temperatures of the tiles throughout the weathering period, allowing the thermal performance of the coatings to be evaluated over the course of the experiment. This feature is a significant innovation over commonly used aging stations.

The structure was made of galvanized steel tubes coated with synthetic enamel paint to prevent metal oxidation. OSB type wood panels were fixed to the galvanized steel to support the polystyrene panels (15mm) in contact with the tiles. The adaptable locking system (0° - 80°) allows reusability for different material analyses (Araujo and Dornelles, 2022). After assembly, circular cuts facilitate rainwater drainage and allow the passage of the thermal monitoring data system. Designed not only for sample exposure, but also for continuous surface temperature monitoring of the tiles, a rail was positioned on the back of the system near the OSB panel to guide wires, with a protective box for thermocouples. Construction was completed and operations began in July 2019 (Figure 3).

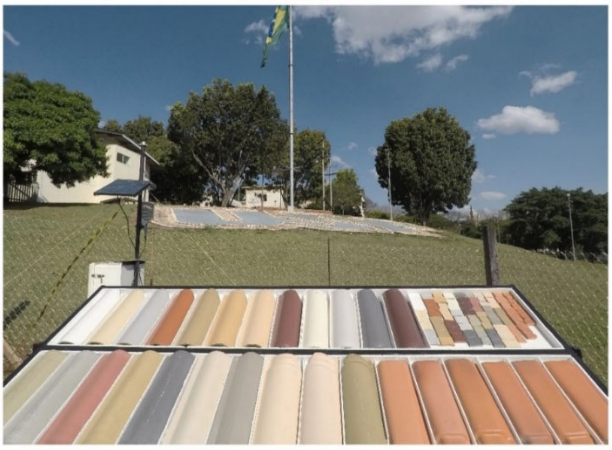

Figure 3. Weathering rack finished and in operation.

Surface Temperature Monitoring

Undersurface temperatures of the tiles on the weathering rack were continuously monitored to assess the effect of solar reflectance degradation on heat absorption. Monitoring was performed using Testo S30-T1 infrared thermometers with a resolution of 0.1°C and T-type thermocouple sensors (copper-constantan; 0.51 mm; Teflon/Teflon insulation; ANSI standard) glued to the underside of the samples. Contact between the thermocouple and the underside of the tile was made through one of the circular openings, ensuring weather protection and data integrity. Thermal paste and low-emissivity metal adhesive tape were used to attach the thermocouple to the underside of the sample to minimize external disturbances to data monitoring (Figure 4a).

The data storage unit contains a UPS battery (12V, 7Ah), a CR10X data logger for data acquisition and storage, and two multiplexers that amplify the data logger outputs for simultaneous sample measurements. The fiberglass unit is painted white to reduce the effect of external solar radiation on the experiment. Power for the data acquisition system comes from a 21-volt solar panel that powers the temperature monitor. Two additional instruments, measuring relative humidity (HMP 35C, Vaisala) and irradiance (Pyranometer SP Lite, Kipp & Zonen), complement the aging station assembly. These are connected to the data acquisition system along with the 25 thermocouples on the exposed tiles. The data logger, programmed using PC400 software (Campbell), records tile temperature and local climate data every minute and calculates averages every 30 minutes (Figure 4b).

The equipment monitored the surface temperatures of all tiles and collected the specified data for 36 months. Comparative data were compiled for three different intervals (0, 24, and 36 months) during the exposure period, allowing a combined analysis of the effects of natural degradation on solar reflectance and its influence on the thermal performance of the tiles. Due to the Covid-19 pandemic, data for the 12-month exposure phase couldn't be obtained due to limited access to the weathering rack location and inability to use laboratory equipment.

Figure 4. a) Thermocouple position b) Supplementary measuring system and rack feed.

Results and discussion

Effect of Natural Aging on Solar Reflectance

Figure 5 and Table 4 present data on the change in solar reflectance of the tiles. The T1 reflective tile experienced the greatest impact from natural weathering, with a 32.1% reduction in its initial solar reflectance. In general, natural weathering has a greater impact on reflective surfaces than on conventional surfaces (Akbari *et al.*, 2005; Synnefa *et al.*, 2007; Mastrapostoli *et al.*, 2016; Shi *et al.*, 2019). However, despite suffering the greatest reductions in their initial reflectances, T1 and T9 consistently maintained the highest solar reflectance of all samples even after 36 months of weathering. The rate of reflectance change in the samples was more pronounced in the first 2 years of exposure compared to the last year of aging. This pattern is consistent with the findings of Akbari *et al.* (1997) that solar reflectance changes tend to be gradual after the first year of exposure.

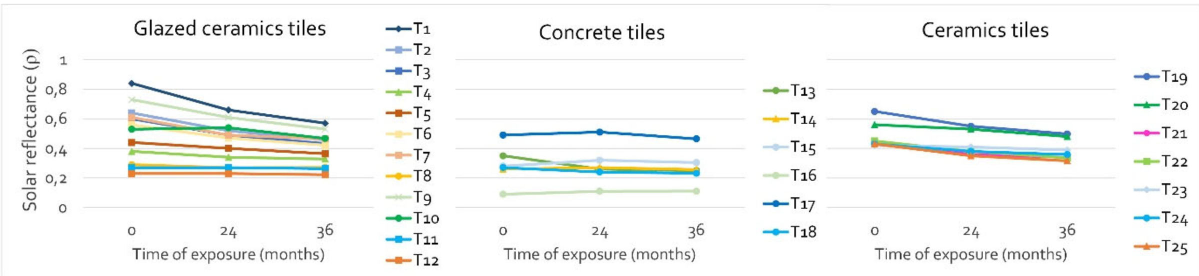

Figure 5. Change in SR (ρ) of roof tiles over time.

Table 4. Solar reflectance (SR_0, SR_{24}, SR_{36}) of selected tiles over 36 months of exposure

Tile	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
SR_0	**0.84**	0.64	0.60	0.38	0.44	0.56	0.61	0.29	**0.73**	0.53	0.27	0.23
SR_{24}	**0.66**	0.52	0.49	0.34	0.40	0.47	0.49	0.27	**0.61**	0.54	0.27	0.23
SR_{36}	**0.57**	0.46	0.43	0.33	0.36	0.42	0.46	0.27	**0.53**	0.47	0.26	0.22
$\%_{36-0}$	**-32,1**	-28,5	-27,9	-13,6	-17,3	-24,7	-23,8	-6,6	**-27,3**	-11,8	-2,6	-3,5

13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
0.35	0.26	0.28	0.09	0.49	0.27	0.65	0.56	0.44	0.45	0.42	0.43	0.43
0.26	0.27	0.32	0.11	0.51	0.24	0.55	0.53	0.36	0.38	0.41	0.38	0.35
0.25	0.26	0.30	0.11	0.46	0.23	0.50	0.48	0.34	0.34	0.39	0.36	0.32
-28,6	-1,0	8,6	22,6	-5,2	-14,2	-23,4	-14,2	-23,0	-25,5	-7,5	-16,7	-26,6

Figure 6 shows the correlation between the experimental data obtained in this study and the estimated values from the latest update of the Brazilian standard NBR 15575-1 (ABNT, 2021). The Pearson correlation coefficient shows a highly significant relationship between the empirical NBR equation and the experimentally measured data ($R^2 = 0.92$). Thus, we confirm that the tiles on the weathering rack followed an expected degradation curve, establishing the reliability of the weathering rack developed in this study for assessing solar reflectance degradation over a 36-month weathering exposure.

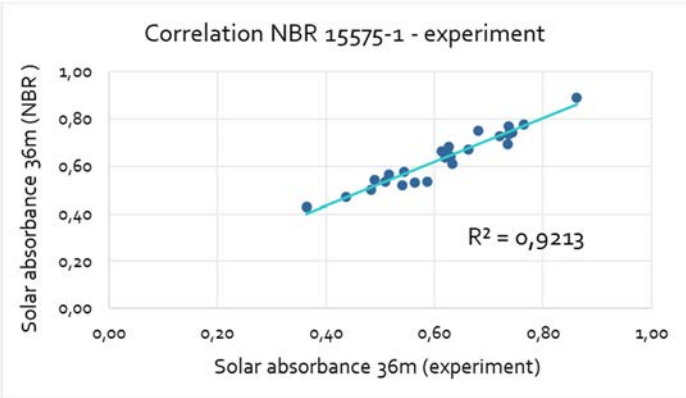

Figure 6. Correlation NBR 15575-1- experiment (NBR empirical equation: $\alpha_{t=3} = 0{,}07 \cdot (\alpha_{t=0})^2 + 0{,}59 \cdot \alpha_{t=0} + 0{,}27$; where $\alpha_{t=3}$ is the solar absorbance of the external surface after 3-year degradation; $\alpha_{t=0}$ is the initial solar absorbance of the external surface; and t is the surface exposure time, expressed in years).

Effect of Solar Reflectance on Surface Temperature

Figure 7 and Table 5 show the maximum and average surface temperatures of the exposed tiles. Surface temperatures varied due to solar reflectance, material type, thickness, and related properties that affect transmittance (U) and thermal capacity (CT). Intrinsic material properties, beyond our scope, weren't investigated; our focus was solely on the effect of aging on solar reflectance to validate the weathering rack. Reflective tiles T1 and T9 had the lowest maximum surface temperature and thermal range, while T17, with the lowest solar reflectance, had the highest maximum surface temperature. Figure 8 shows the correlation between maximum temperatures and solar reflectance for all samples. Pearson's coefficient shows a strong correlation between these parameters ($R^2_{0month}= 0.879$ and $R^2_{36month}= 0.888$). Since these variables are inversely proportional (higher solar reflectance, lower surface temp), the line is plotted in a descending fashion.

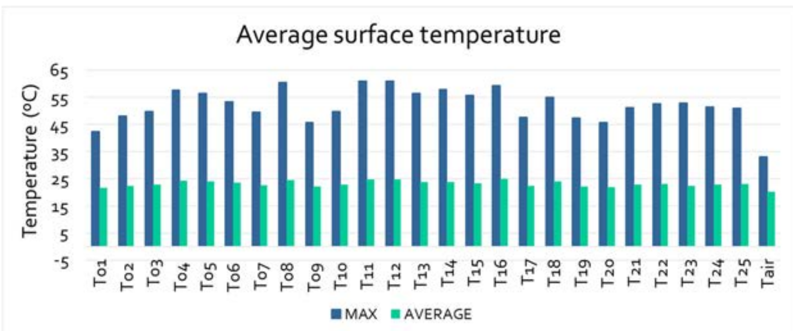

Figure 7. Variations in maximum and average surface temperatures (°C) over 36 months.

Table 5. Maximum temperature (T_{MAX}) of tiles over 36 months of weathering (°C).

Tile	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	9	**10**	**11**	**12**
T_{MAX}	42,46	48,15	49,68	57,7	56,39	53,37	49,49	60,38	45,69	49,84	60,93	60,94

13	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
56,47	57,93	55,8	59,18	47,64	55,05	47,33	45,79	51,27	52,65	52,83	51,48	51,05

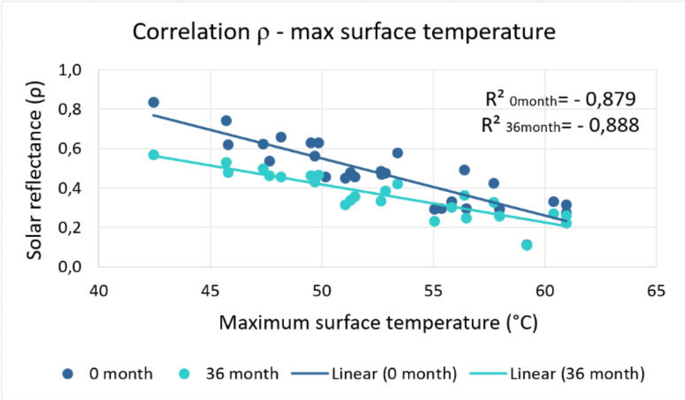

Figure 8. Correlation SR_0 and SR_{36} (ρ) - Maximum temperature of tiles (°C).

The final analysis presented shows surface temperature variations in 6 tiles over a full day. Temporal segments were selected to compare aging stages on days with similar insolation and cloud cover. These tiles represent samples with the most contrasting initial solar reflectances within each of the 3 groups studied. Specifically, T1 and T12 belong to the glazed ceramic category, T16 and T17 represent the concrete group, and T19 (colored) and T25 (uncolored) belong to the ceramic group (Figure 9).

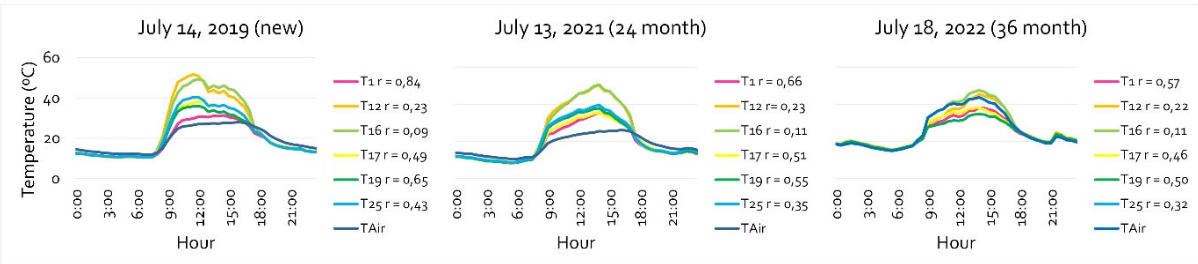

Figure 9. Surface temperature variations in tiles when new, at 24 and 36 months of exposure (°C).

T1 initially had the lowest surface temperature, with a significant difference from the other tiles. However, as the weathering period progressed, the surface temperature difference between T1 and the other tiles decreased. By the end of the period, the surface temperature of T1 was not significantly different from T17 and T19 throughout the day. T12 and T16, which had the lowest initial solar reflectances among the 6 selected samples, consistently maintained the highest surface temperatures even after 36 months. These results confirm the robust correlation between solar reflectance values and surface temperature of the 25 tiles.

Conclusions

The Weathering Rack is a cost-effective, reliable method for evaluating solar reflectance degradation over 36 months. It offers weather resistance, equipment protection, self-sufficiency, ease of use, adjustable table angle, rainwater drainage, and continuous monitoring of sample surface temperature. The rack was built entirely at IAU-USP and can be easily replicated and used in similar studies. In addition, the data collected over the 36-month period were compared with estimates from NBR 15575-1. The empirical equation in the standard and the data measured in the laboratory showed a very strong correlation, confirming the successful achievement of the objectives of the rack.

A limitation of this rack is that the OSB panel needs to be replaced for extended exposures due to moisture-related deterioration. Larger rainwater drainage holes are required, and the use of polystyrene panels between sections proved unnecessary as they deteriorated rapidly due to weather and bird-related factors, but their absence did not significantly affect the measurements as the analysis performed was comparative in nature.

In terms of the effect of natural aging on thermal performance, T1 and T9 exhibited the most significant effects of natural weathering, with a decrease in reflectance of 32.14% and 27.39%, respectively. Despite this, both tiles consistently exhibited the lowest solar reflectance, resulting in the lowest surface temperatures, even after 36 months of exposure. A very strong correlation ($R^2 0_{month}$= 0.879; $R^2_{36month}$= 0.888) was found between maximum surface temperatures and solar reflectance, highlighting the need for continuous surface temperature monitoring as a critical performance indicator. Thus, the rack has the potential to be used for integrated solar reflectance degradation and thermal performance analysis of coatings.

Acknowledgments

The authors are grateful to the Brazilian agency CAPES for the grant awarded for this research (funding code 001), and to the IAU-USP staff.

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