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ARTICLE

Effect of Aging on Solar Reflectance of White Cool Roof Coatings: Natural Weathering and the Influence on Building Energy Needs for Different Climate Conditions in Brazil

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ABSTRACT

The use of cool materials on the building envelope is one of the most cost-effective ways to increase indoor thermal comfort conditions in hot climates and decrease the cooling energy needs. Despite the benefit of reducing cooling loads, researches have demonstrated that aging of roof coatings changes the initial solar reflectance (SR), which influences the long term building thermal and energy performance. Thus, this work presents preliminary natural weathering tests performed on samples of nine white coatings exposed to natural weathering for one year in the city of Sao Carlos, Brazil. Solar reflectances were measured with a spectrophotometer before and after exposure, every 3 months, for identifying the effect of aging along the time. The findings showed changes of 13% to 23% on SR after one year of natural weathering, with higher decrease on SR for rougher surfaces. The cleaning process restored from 90% to 100% of the original SR, which means maintenance can be an effective solution to restore the initial SR. Simulations indicated that roofs with higher solar reflectance increase indoor thermal comfort conditions and decrease the cooling energy need for buildings in hot climates, but the aging of white coatings increased the cooling energy needs along the time.

1. Introduction

The continuous population growth and urban sprawl directly influence the negative effects of global warming and climate change, with the increase of buildings and paved surfaces, and the reduction of vegetation in urban areas. In this case, the predominance of impermeable surfaces contributes with the rise on solar energy absorption by different materials, with direct impact on surface and ambient temperatures, given rise to the microclimate phenomena called urban heat islands (UHI) [1-4].

The UHI is mainly characterized by urban areas with higher temperature when compared to their surrounding rural environment. This phenomenon can be more intense in cities with hot climate conditions, located mainly in latitudes from 15° North to 15° South, where the solar radiation is an important issue regarding building heat gains [5]. In Brazil, for example, solar radiation is one of the most important contributors with the thermal load

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of buildings. According to the Brazilian standard NBR 15220-3 [6], the country is mainly characterized by tropical and hot conditions, with solar radiation levels sufficiently high and no active heating required for buildings even during the winter season. In contrast, the summer overheating usually adversely influences indoor comfort conditions in the built environment and increases energy need for cooling systems [7].

It is already known that the building sector is responsible for more than 40% of the global energy consumption [8]. Considering the energy needs mainly related to HVAC systems, this effect is increased primarily in countries with predominance of hot climate conditions. The Brazilian Energy Balance for 2019 [9] demonstrated that buildings account for 52% of the electric energy use, with 26.1% for the residential sector and 25.9% for non-residential buildings, mainly related to HVAC systems. More specifically, the cooling energy need has increased considerably in the last decades, as the use of cooling systems has been more intense to control the overheating in the built environment, associated primarily to climate change and urban development [10]. Furthermore, Ascione [11] demonstrated a worldwide increase of cooling degree days through a large literature review concerning building envelope, HVAC systems and renewables.

Over the years, different solutions were suggested to control the negative effects of global warming and urban heat islands on buildings thermal-energy performance, including building design strategies [12-14]. One of this solution is the use of cool coatings on the building envelope in order to decrease cooling energy needs in buildings and improve indoor thermal comfort in summer conditions. Cool materials are characterized by high solar reflectance and thermal emittance, which can maintain a lower surface temperature, reducing the solar heat gains by the building envelope [15,16]. However, building envelopes in the urban environment are subject to weather and the deposition of particulate matter present in the air, with direct effects on the solar reflectance of these surfaces [17]. Results from several researches indicated that natural weathering of roof surfaces decreased the original solar reflectance over time [18-23]. By this way, durability has become an important issue for new materials considering the potential of preserving high SR over time, since the higher initial investment must be paid back by cooling energy savings [24].

According to Bretz and Akbari [25], the high initial solar reflectance of surfaces likely to decrease mainly due to material degradation and surface materials accumulation as dirt and microbial growth. In this case, the surface accumulations may not be permanent, depending on their water solubility. According to the authors, microbial growth is more common in humid areas. Degradation, however, induces chemical changes in the material with permanent alteration of the solar reflectance. Previous researches have indicated that degradation of roof coatings is mainly related to insolation (particularly UV radiation), temperature variation of the roof (daily time-averaged), moisture (humidity, rain, and dew), and natural and anthropogenic pollutants [19,20,23]. Furthermore, the solar reflectance degradation of coatings occurred primarily within the first year of application, and even within the first two months of exposure [18-20]. However, an accurate maintenance procedure can reduce albedo changes by natural aging, as presented by Levinson *et al.* [26].

The effect of natural weathering on solar reflectance has been continuously analyzed [27-31]. Alchapar and Correa [27] assessed the influence of natural weathering on the thermal behavior of 19 roof tiles and roof paint. They concluded that all materials tend to reduce their reflectance capacity after three years of weathering exposure, and identified that morphological characteristics of color, composition, and finish (for new materials) and color, finish, and shape (for aged materials) impact the thermal performance. Ferrari *et al.* [28] investigated the effect of natural aging on the solar reflectance for clay roof tiles exposed to natural weathering in Arizona for three years. The results indicated that Arizona weathering condition affects the solar reflectance up to 0.05. On the other hand, De Masi *et al.* [29] found that the solar reflectance of a white cool roof coating decreased from 0.67 to 0.48 after 1 year of outdoor natural weathering in Benevento, Italy, under Mediterranean climatic conditions. Dornelles *et al.* [30] analyzed the effect of natural aging for 20 coatings after 18 months of exposure in tropical climate conditions, in Brazil. The results confirmed a reduction on the solar reflectance mainly related to dust and soot deposition for most of the samples. Two coatings with dark colors ($SR<0.15$) presented an increase on the SR, probably associated to degradation from UV radiation.

In addition, some studies also assessed the influence of natural aging of coatings on buildings thermal-energy performance. Mastrapostoli *et al.* [31] found a decrease of 72% on cooling energy demand with the application of a new cool roof coating when compared to the aged cool roof, through simulations with Energyplus. Aoyama *et al.* [32] conducted a study to evaluate the potential of increasing the durability of a high-reflectance coating due to its self-cleaning capability when exposed to natural aging tests at Kobe University. After one year of exposure, the results indicated differences of 0.09 on SR from the self-cleaning (0.70) and conventional (0.79) roofs, and the energy saving of the self-cleaning coating and the cool roof was great during the year. Paolini *et al.* [33] investigated the performance of wall finishes with high solar reflectance and thermal emittance after four years of aging in Milan, Italy. The authors find a reduction on the solar reflectance of 0.20 for white coats and 11% increase in cooling energy need for a typical residential building with aged white walls without exterior insulation. In a previous study of natural aging in Roma and Milan, Italy, Paolini *et al* [17] identified a reduction of 0.14 on the initial SR of white roof membranes in Rome and 0.22 for samples aged in Milano after two years of exposure. For a typical commercial building highly insulated in Milan, an aged white roof may reach a surface temperature 16°C higher than a new white roof. The study confirmed that the decrease on SR after natural aging influences the energy needs of buildings and the surface temperature of the roofing membrane.

Based on the above, this work presents preliminary natural aging tests for samples of cool white coatings exposed to natural weathering for one year in São Carlos, SP, Brazil. Spectral and solar reflectances were measured with a spectrophotometer before and after exposure, every 3 months, for identifying the effect of aging along the time. A cleaning process was also conducted to identify the ability of the coatings to restore the initial solar reflectance after the period of natural weathering. Computer simulations were performed to assess the cooling and energy need for a residential building located in different climate conditions in Brazil, considering new and aged solar reflectances of samples analyzed in this research.

2. Methodology

Specimens were prepared for the characterization of the material properties (solar reflectance and thermal emittance) in laboratory, according to specific standards. Natural weathering exposure procedure was conducted for 12 months to identify the effects of aging and cleaning on the solar reflectances of 9 cool white roof coatings. As a case study, computer simulation for a single-story residential building located in 4 different climate conditions in Brazil estimated the thermal performance and energy need to restore indoor comfort conditions, considering different roof's reflectance. Procedures and instruments are following described.

2.1 Selected Materials

In this work, nine coatings available in the market were selected: three standard white acrylic coatings (STD) and six white coatings formulated with ceramic microspheres (CER), according to information provided in Table 1. Samples were prepared with ceramic specimens with smooth surface (80 x 80 mm) to minimize the roughness effect on the solar reflectance results.

Table 1. Characteristics of analyzed coatings

Sample	Coating description	Type	Color
S1-STD	Acrylic, elastomeric coating	Standard	White
S2-CER	Acrylic, elastomeric coating with ceramic microspheres	Ceramic microspheres	White
S3-CER	Acrylic, elastomeric coating with ceramic microspheres	Ceramic microspheres	White
S4-CER	Acrylic, elastomeric coating with ceramic microspheres	Ceramic microspheres	White
S5-CER	Acrylic, elastomeric coating with ceramic microspheres	Ceramic microspheres	White
S6-CER	Acrylic, elastomeric coating with ceramic microspheres	Ceramic microspheres	White
S7-CER	Acrylic, elastomeric coating with ceramic microspheres	Ceramic microspheres	White
S8-STD	Styrene acrylic coating	Standard	White
S9-STD	Styrene acrylic coating	Standard	White

2.2 Laboratory Measurements

2.2.1 Spectral Reflectance Measurements

In this work, spectral reflectance laboratory measurements for optical analyses were conducted according to the ASTM E903-20 standard [34]. The equipment is a double-beam spectrophotometer (Varian CARY 5G), fitted with an integrating sphere of 150 mm diameter. The spectral reflectance was measured from 300 to 2500 nm, at wavelength intervals of 1 nm. The solar reflectance was calculated by weighted averaging, based on a standard solar spectrum provided by ASTM G173-20 [35] as the weighting function.

2.2.2 Thermal Emittance Measurements

Thermal emittance measurements were performed with the emissometer model AE1 from Devices and Services, according to the standard ASTM C1371-15 [36]. This equipment measures the total thermal emittance when compared to standard materials with low and high emittance (0.06 and 0.87, respectively), calibrated before each measurement. The thermal emittance was conducted for the nine white coatings for initial conditions, before exposure to natural weathering.

2.3 Natural Weathering Procedure

The samples with 9 acrylic cool coatings were exposed to natural weathering conditions for 12 months in the city of São Carlos, SP, Brazil (22°S, 48°W, 860 m). The

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specimens were positioned on a low sloped roof surface (8°) to avoid standing water and to maximize the effect of soiling in a short testing period (Figure 1).

Figure 1. Low sloped roof with exposed specimens and detail of investigated samples

A weather station continuously monitored air temperature, relative humidity, global solar radiation, and precipitation) on site. The main assessment criteria for durability were the variation on solar reflectance and appearance along the time. The solar reflectance is related to the thermal performance of materials and the appearance is associated to the aesthetic condition. Soiling was supposed to have the major effects on solar reflectance loss, and this result must be differentiated from the contribution from other weathering agents like insolation, air temperature, and relative humidity. In this research, the natural aging considering both weathering and soiling actions was quantified through the reflectance loss over time for specimens exposed to natural weathering conditions. Solar and spectral reflectance for the cool coating samples were measured in laboratory before the exposure (new specimens), and every three months for aged specimens.

Finally, reflectances of each soiled specimen was remeasured followed by a cleaning process of washing with dishwashing detergent, water, and natural air drying, until the appearance of the coating stabilized. This procedure was intended to simulate an artificial cleaning mechanism.

2.4 Building Energy Simulation

The numerical analysis was carried out to assess the impact of cool white coatings on the indoor thermal comfort conditions and building energy needs of residential buildings located in 4 different climate conditions in Brazil. Computer simulations were conducted with EnergyPlus simulation software, based on solar reflectance data (new and aged) obtained for nine different white coatings considered in this work. Table 2 presents the latitude, longitude, and altitude of selected cities, with different climate conditions according to the Brazilian National Standard NBR 15220 [6].

Table 2. Latitude, longitude, and altitude of selected cities with different climates in Brazil.

Climate Zone	City / State	Latitude (°)	Longitude (°)	Altitude (m)	Climate Classification
1	Curitiba, PR	-25.52	-49.18	934	Subtropical
4	Brasília, DF	-15.78	-47.92	1171	Tropical (dry winter)
7	Petrolina, PE	-9.35	-40.55	376	Hot Semi-Arid
8	Belém, PA	-1.38	-48.48	10	Humid tropical

Meteorological data were based on the weather database of the US Department of Energy for Energyplus Software [37], typically used also for dynamic thermal-energy simulation of buildings. The building considered as a base case for simulation is a single story with a flat roof (Figure 2). This building is a real example of residential buildings currently built in Brazil in the last decade, mainly for low-cost houses. Its height is assumed to be 2.7 m, with walls and ceiling made of 10 cm of concrete. The solar reflectance of walls was assumed 0.5 and window area of 1.44 m² each one with clear 3 mm glass. The roof is covered with a 6 mm fibrocement tile, with solar reflectance according to the laboratory measurements of the selected white coatings. Bathroom has one window with 0.36 m² of clear 3 mm glass.

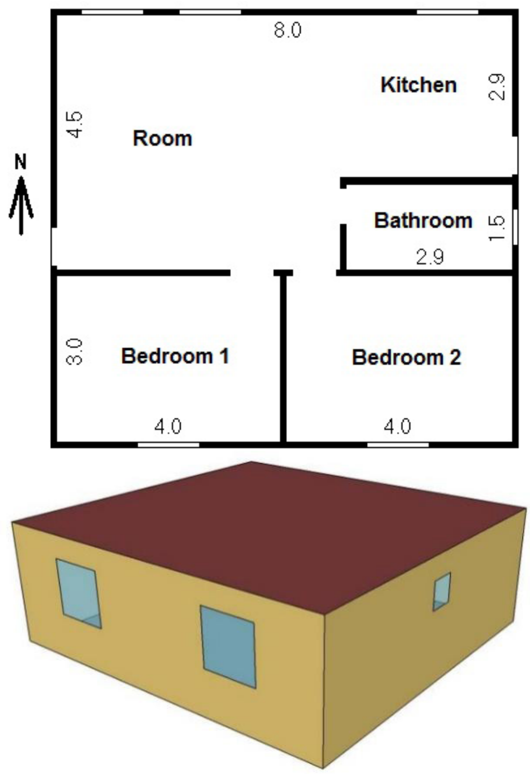

Figure 2. Case study – reference building

Infiltration and ventilation rates were set as 1/hour, according to the Brazilian standard NBR 15575 [38]. Regarding internal gains, simulations considered thermal

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loads from the rooms' occupancy (people, lighting, and equipment), according to a typical Brazilian family [7] for which this kind of buildings are designed for (low-cost houses): 2 adults (100 W/person) and 2 children (60 W/person) in sedentary activities; lighting (18 h-24 h, 100 W) and TV (15 h-24 h, 50 W); kitchen equipment (lighting: 2 h/day, 100 W/hour; refrigerator: 24 h/day, 90 W/h; stove: 8 h/day, 60 W).

This building configuration may not necessarily be representative of houses in different tropical and hot climates. However, the purpose of this work was to assess the influence of roof reflectance on indoor thermal comfort conditions and energy use for different climate conditions in Brazil. In addition to the solar reflectance obtained in this study for the nine different samples (new and aged white coatings), it was included in the simulation procedure one fibrocement tile widely used for roofing in developing tropical countries. The new and aged solar reflectance for the fibrocement tile was obtained from earlier study [39].

In order to assess indoor thermal comfort conditions, comfortable temperature intervals were considered according to Equation 1, from ASHRAE 55-2017 [40] for natural ventilated buildings. The main advantage of this standard is its adaptative nature, which means that this standard recognizes that occupants used to living in warm climates prefer higher temperatures than those in cold climates, and vice versa.

$$Tc = 17.9 + 0.31 * To \quad (1)$$

Where:

Tc: temperature for comfort conditions (ºC);

To: Arithmetic average of the mean daily minimum and mean daily maximum outdoor (dry bulb) temperatures per month (ºC). Equation 1 is valid for 10.0 ºC ≤ *To* ≤ 33.5 ºC.

ASHRAE [40] indicates comfortable temperature range with *upper limit* calculated from Equation 2 and *lower limit* from Equation 3.

$$\text{Upper limit} = Tc + \text{tolerance} \quad (2)$$

$$\text{Lower limit} = Tc - \text{tolerance} \quad (3)$$

Where:

Tc: temperature for comfort conditions (ºC);

Tolerance: in this work it was considered a tolerance of 2.4 °C, which satisfies 90% of the occupants according to ASHRAE 55 [40]. For 80% of the occupants, standard ASHRAE 55-2017 indicates a tolerance of 3.4 °C.

Table 3 presents the temperature intervals (upper and lower limits) for indoor thermal comfort conditions, in order to obtain the degrees-hour of discomfort for summer (December) and Winter (June) design days, for each selected climate zone in Brazil.

Table 3. Comfortable limits for indoor air temperatures analyzed in building simulations.

Zone	City	To (°C)		Tn (°C)		Lower limit (°C)		Upper limit (°C)	
		Jun	Dec	Jun	Dec	Jun	Dec	Jun	Dec
1	Curitiba	14.82	19.78	22.49	24.03	20.09	21.63	24.89	26.43
4	Brasília	18.44	21.26	23.62	24.49	21.22	22.09	26.02	26.89
7	Petrolina	24.32	27.08	25.44	26.30	23.04	23.90	27.84	28.70
8	Belém	26.24	26.29	26.03	26.05	23.63	23.65	28.43	28.45

The indoor thermal discomfort was quantified in degrees-hour (Kh) of heat or cold conditions. Each degree-hour (1 K/h) relates to the discomfort due to dry-bulb temperature once this is under the lower limit (cold) or when it is above the upper limit (heat). Daily, monthly, or annual discomfort levels are the sum of these during the corresponding period.

For the building energy performance, Szokolay [41] presents a simplified method to estimate the cooling or heating energy required to restore indoor thermal comfort, according to Equation 4:

$$E = DH * q \quad (4)$$

where *E* is the energy for cooling or heating the building (Wh/day), *DH* is the daily degrees-hour of discomfort (Kh/day), and *q* is the heat flux by conduction (*qc*) and convection (*qv*), according to Equations 5. *qc* and *qv* are calculated according to Equations 6 and 7:

$$q = qc + qv \quad (5)$$

$$qc = \sum_{i=1}^{n} (A \times U)_i \quad (6)$$

$$qv = 0.33 * V * N \quad (7)$$

qc is the heat flux by conduction (W/K), *A* is the total area of the envelope (walls, roof, windows, floor - m²); *U* is the thermal transmittance (W/m²K), *n* is the number of external parts of the building envelope. *qv* is the heat flux by convection (W/K), *N* is the ventilation rate (volumes/h) and *V* is the room volume (m³).

3. Results and Discussion

3.1 Laboratory Measurements for New and Aged Samples

Spectral reflectances measured in laboratory for

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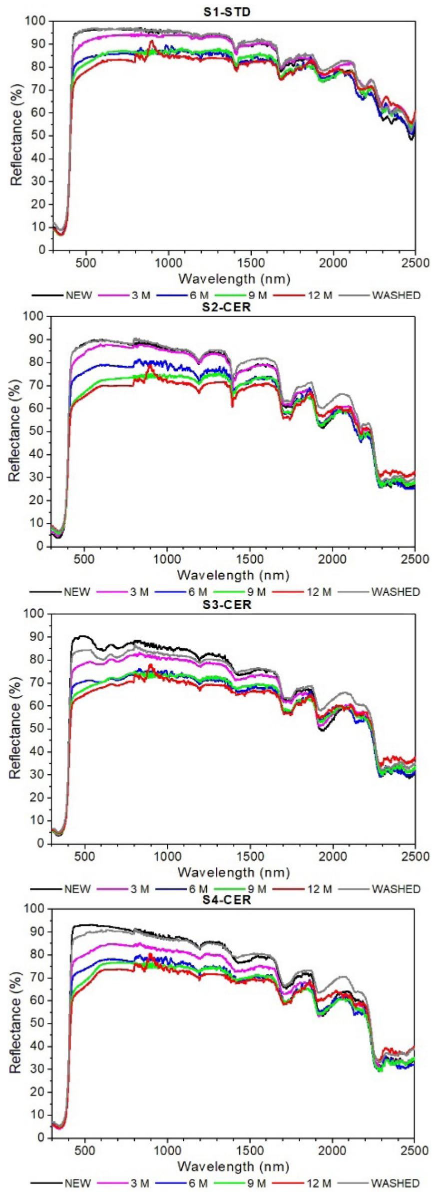
new and aged samples are presented in Figure 3. Solar reflectance and thermal emittance are presented in Table 4, for the 9 coatings considered in this research. The thermal emittance was measured only for conditions before natural weathering (new). The measurements show that all the cool white coating samples have high thermal emittance, ranging from 0.89 to 0.91, which confirm the non-metallic material characteristics.

Results showed that the standard white coating S1-STD presented higher solar reflectance (0.91) when compared to cool white coatings with ceramic microspheres, or to standard white coatings S8 and S9 (Table 4). Actually, all coatings presented high rsolar (higher than 0.74) when new, before natural exposure, once conventional white based colors are characterized by the high near-infrared reflectance due to the intrinsic properties of the titanium dioxide (Figure 3).



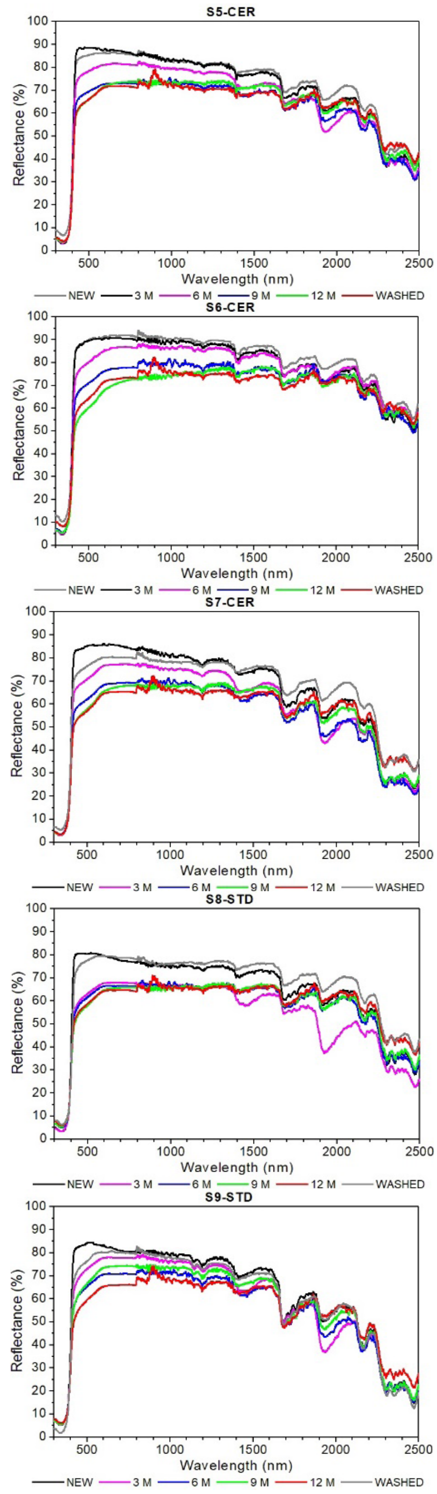


Figure 3. Spectral reflectance for new and aged coatings (3, 6, 9, 12 months) and after a cleaning process.

Figure 4 indicates solar reflectance ranges over time for weather conditions of São Carlos, SP, Brazil. During the first six months of natural weathering, a significant decrease on solar reflectance was observed, mainly related to the specimens weathering. Reflectance modifications are

Table 4. Thermal emittance (ε) and solar reflectance (ρ_{solar}) of the selected samples.

Sample	Thermal Emittance (ε)	Solar Reflectance (ρ_{solar})							
		New	3 months	6 months	9 months	12 months	Washed	$\Delta\rho_{new-12m}$ (-)	$\Delta\rho_{new-12m}$ (%)
S1-STD	0.90	0.91	0.89	0.82	0.82	0.79	0.92	0.12	13
S2-CER	0.91	0.82	0.80	0.73	0.68	0.66	0.83	0.16	19
S3-CER	0.90	0.81	0.75	0.68	0.68	0.66	0.78	0.15	19
S4-CER	0.90	0.85	0.77	0.72	0.70	0.69	0.84	0.16	19
S5-CER	0.91	0.81	0.75	0.68	0.68	0.67	0.80	0.14	17
S6-CER	0.90	0.85	0.81	0.73	0.67	0.69	0.87	0.16	19
S7-CER	0.89	0.78	0.70	0.63	0.62	0.61	0.75	0.18	23
S8-STD	0.91	0.74	0.62	0.62	0.61	0.61	0.74	0.12	17
S9-STD	0.90	0.76	0.71	0.65	0.67	0.62	0.73	0.14	19

mostly due to dust accumulation during the dry period in São Carlos (months 3 to 6), with dust removal as a result of precipitation after the winter (months 6 to 9). The cleaning process restored the solar reflectance for all specimens to a range very similar to the initial solar reflectances (Table 4).

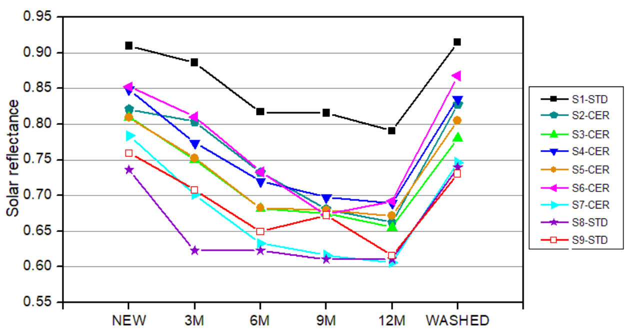


Figure 4. Solar reflectance vs. time and for washed condition after 1 year of natural weathering exposure.

Sample S1 (standard) presented higher solar reflectance reduction after month 6 (from 0.91 to 0.82), with a small reduction from month 6 to 12 of exposure. The SR for sample S1 presented a total reduction of 13% for one year of natural weathering exposure, the lower reduction from all the coatings analyzed in this work. The reduction of solar reflectance during the first 6 months was similar for samples S3 and S4 (with ceramic microspheres), but with a total decrease of 19% after one year. For samples S5, S6, and S7, the reduction was also significant during the first 6 months, with higher difference during the total period of 12 months for sample S7 (23%, rsolar from 0.78 to 0.61).

Sample S2-CER had a significant decrease in the SR after 9 months of exposure (from 0.82 to 0.68), keeping it in this range after 12 months (0.66), with a final reduction of 19%. Sample S8 had a very significant decrease in solar reflectance since the first 3 months (0.74 to 0.62) and kept this range of SR for the next 9 months, with a final solar reflectance of 0.61. On the other hand, sample S9 presented a gradual reduction during all the period of exposure, from 0.76 to 0.62 (total decrease of 19%).

After one year of natural weathering, the coatings' solar reflectance decreased 13% to 23% (respectively for specimens S1 and S7). In addition to weather conditions, soiling (dust and soot deposition, biological growth, etc.) has a large effect on white coatings. Combined actions of weathering and soiling on the specimens can be mainly observed on the spectral reflectance curves in the visible range (380-780 nm) from the solar spectrum (Figure 3). This decrease validates the influence of soiling on the surface appearance [10,24,26,27]. The average decrease about 19% for the samples analyzed in this work are very similar with results obtained by Bretz and Akbari [25]. The authors found 20% solar reflectance reduction for 26 different roofs during the first year of natural weathering.

On the other hand, the surface roughness of specimens with coatings with ceramic microspheres is higher than in smooth standard acrylic coatings. For this reason, the soiling accumulation on the surface is increased according to the surface roughness, which decreases the specimen's solar reflectance. As rougher is the roof surface, higher is the dust deposition, and then the decrease in the long-term solar reflectance [42]. This condition was mainly observed for sample S7, the rougher from all the samples analyzed in this work, as can be noticed in Figure 4, which compares the appearance of the sample for two different conditions: new and after 12 months of natural weathering exposure.

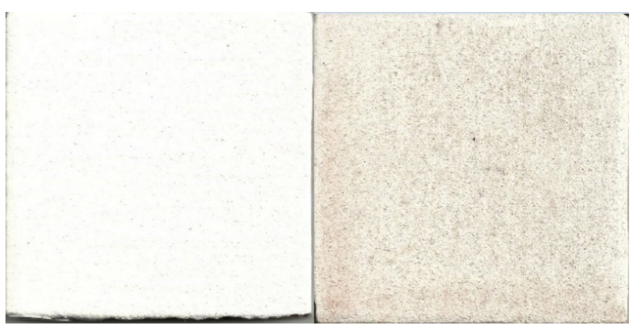


Figure 4. Sample S7-MEC, new and after 12 months of natural weathering exposure

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The cleaning process restored from 90% to 100% of the original solar reflectance, which means the cleaning process is a very efficient approach to keep the good thermal performance of white roofs, mainly in hot climates. Similar results were achieved by Bretz and Akbari in earlier study [25] and Levinson *et al.* [26].

3.2 Building Simulation Results

3.2.1 Indoor Thermal Comfort for Summer and Winter Conditions

Table 5 presents the degrees-hour/day (Kh/day) of heat discomfort for the simulated building with 9 different solar reflectances (new), and after 12 months of exposure (aged). The results showed that as higher is the roof solar reflectance, the lower is the heat discomfort for buildings located in cities with hot climate (ZB4 and ZB8).

Furthermore, the degrees-hour/day of cold discomfort are presented in Table 6. In this case, the results indicate that as higher is the solar reflectance of a roof surface, the higher is the heating need for colder climates (ZB1 and ZB4), considering the Brazilian scenario. Furthermore, no heating energy was needed for hot climates of ZB7 and ZB8.

The results confirmed that using cool white coatings for cooling roof surfaces are efficient to decrease the indoor heat discomfort for buildings located in tropical/hot climates. According to the findings, a building with fibrocement roofing (FIBCIM) with solar reflectance of 0.48 presents 70.6 Kh/day of heat discomfort for Belem (ZB8). If this roof was covered with cool white coatings (solar reflectance higher than 0.8), the heat discomfort could be more than 50% reduced in this building, offering indoor thermal comfort conditions for users. And this condition would directly influence the cooling energy needs in buildings, as mentioned in the next analyses.

3.2.2 Building Energy Needs

Based on the degrees-hour of heat (Table 5) and cold discomfort (Table 6), the following cooling and heating energy needs were obtained from Equation 4, as presented in Figure 5 and Figure 6. The results indicated that aging

Table 5. Degrees-hour/day of heat discomfort

Sample	Solar Reflectance		Degrees-hour of discomfort (Kh/day) - Heat							
	rsolar		ZB1		ZB4		ZB7		ZB8	
	New	Aged (12M)	New	Aged	New	Aged	New	Aged	New	Aged
S1-STD	0.91	0.79	0	0	0	0.9	35.4	50.0	27.5	40.1
S2-CER	0.82	0.66	0	0.3	0	3.4	45.6	64.2	36.2	51.8
S3-CER	0.81	0.66	0	0.3	0.2	3.4	46.8	64.2	37.3	51.8
S4-CER	0.85	0.69	0	0	0	1.6	42.5	58.1	33.5	46.5
S5-CER	0.81	0.67	0	0.2	0.3	3.3	47.0	64.0	37.4	50.7
S6-CER	0.85	0.69	0	0	0	1.6	41.9	58.1	33.1	46.5
S7-CER	0.78	0.61	0	1.4	0.8	5.4	49.8	70.0	39.8	57.0
S8-STD	0.74	0.61	0	1.4	1.9	5.4	55.3	70.0	44.5	57.0
S9-STD	0.76	0.62	0	1.1	1.3	4.8	52.7	68.4	42.3	55.5
FIBCIM	0.48	0.39	5.9	9.9	11.2	16.1	84.5	94.7	70.6	79.9

Table 6. Degrees-hour/day of discomfort by cold

Sample	Solar Reflectance		Degrees-hour of discomfort (Kh/day) - Cold							
	rsolar		ZB1		ZB4		ZB7		ZB8	
	New	Aged (12M)	New	Aged	New	Aged	New	Aged	New	Aged
S1-STD	0.91	0.79	104.9	97.7	7.1	4.3	0	0	0	0
S2-CER	0.82	0.66	99.8	55.0	5.1	1.4	0	0	0	0
S3-CER	0.81	0.66	99.2	55.0	4.8	1.4	0	0	0	0
S4-CER	0.85	0.69	101.3	57.1	5.7	2.5	0	0	0	0
S5-CER	0.81	0.67	99.1	56.0	4.8	2.1	0	0	0	0
S6-CER	0.85	0.69	101.6	57.1	5.8	2.5	0	0	0	0
S7-CER	0.78	0.61	97.7	53.3	4.3	1.0	0	0	0	0
S8-STD	0.74	0.61	95.0	53.3	3.4	1.0	0	0	0	0
S9-STD	0.76	0.62	96.3	53.8	3.9	1.1	0	0	0	0
FIBCIM	0.48	0.39	49.15	46.3	0.24	0	0	0	0	0

of white coatings after 1 year of natural weathering increased the cooling energy needs, and this difference is very significant for white coatings with higher initial SR, when compared to the fibrocement tile.

The highest cooling energy need was for the fibrocement roof, when compared to the white coatings, mainly for hot climates (ZB7 and ZB8). The effect of using cool materials (white coatings) can contribute significantly for the reduction of cooling energy needs, as confirmed for some earlier studies [4,43,44].

The simulations showed that, for the climate of Petrolina (ZB7), with very hot and dry conditions, and for the city of Belem (ZB8) with hot and humid climate, the building system considered for simulation demonstrated weak thermal performance, despite the use of white roofs, with high solar reflectance. On the other hand, the use of white roofs decreased the cooling energy needs in these climates, when compared to the fibrocement tile with SR of 0.48 or 0.39.

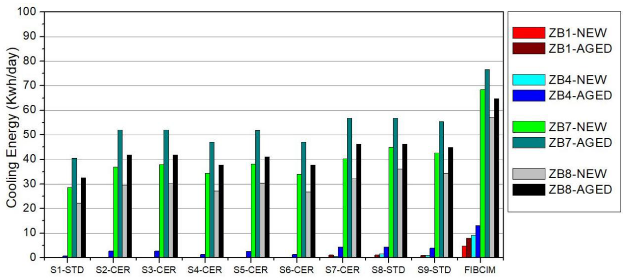

Figure 5. Cooling energy needs estimated for new and aged coatings in different climate conditions

Considering the city of Curitiba (ZB1), subtropical climate with cold winter, the heating energy needs is high for all the solar reflectances considered in the simulation, once the building characteristics are not appropriate for the climate conditions of this zone. However, the difference between energy needs is significant when compared to new and aged roofs, after one year of natural weathering exposure (Figure 6). These results confirm the importance of the maintenance during the lifecycle of roofs, in order to restore the solar reflectance of coatings near to initial condition.

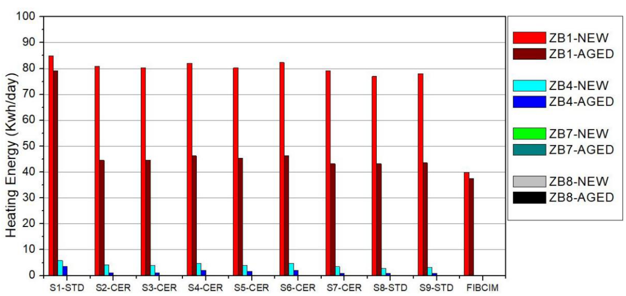

Figure 6. Heating energy needs estimated for new and aged coatings in different climate conditions

Figure 7 presents the correlations between the roof solar reflectance and the energy needs for cooling and heating, according to the outdoor climate conditions. The results showed that, as higher is the solar reflectance of roofs, for the base case analyzed in this work, lower is the cooling energy needs, mainly in hot climate conditions (ZB7 and ZB8). Considering subtropical climates with cold winter in Brazil (ZB1), the heating energy need is higher, but these results are directly related also to the building constructive system simulated. Furthermore, the heating energy need is negligible for tropical and hot climates in Brazil.

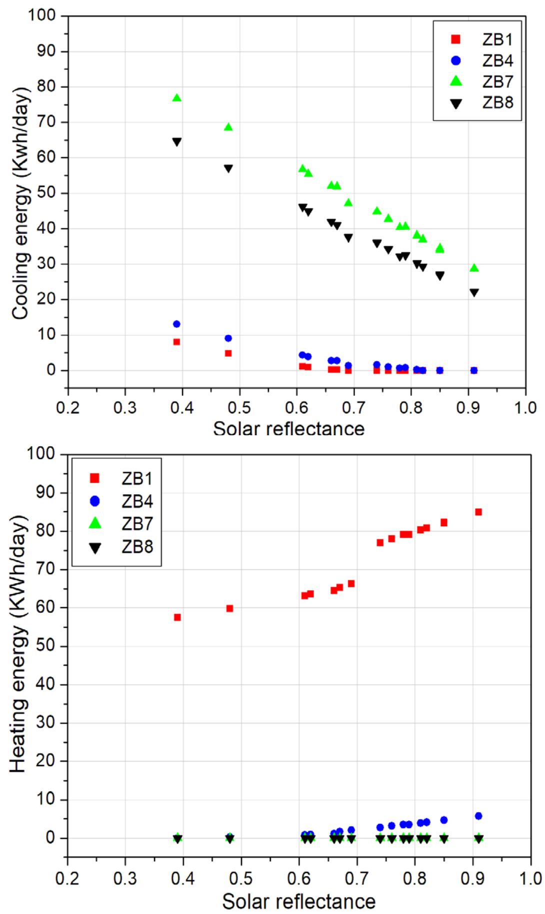

Figure 7. Correlation between roof solar reflectances and the cooling and heating energy needs for different climate conditions in Brazil

4. Conclusions

Cool roofs are effective in maintaining indoor thermal comfort conditions and decreasing the cooling energy needs of buildings, mainly in hot climates. However, solar reflectance may be strongly affected by weathering and soiling after a long period of natural exposure. In this work, nine commercially available white coatings with

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high solar reflectance were analyzed. Specimens were exposed to natural weathering conditions in a middle-size city in Brazil (São Carlos, SP) for one year. Solar and spectral reflectances were measured in laboratory before exposure (new) and after 3, 6, 9 and 12 months (aged samples). The results indicated that changes on the solar reflectance of cool white specimens were mainly affected by weathering and soiling, even within the first 6 months. After one year of natural weathering, the coatings' solar reflectance decreased 13% to 23%. The average decrease in solar reflectance about 19% for the samples analyzed in this work are very similar with results from earlier studies.

Considering the roughness of the samples, the results indicated that the soiling accumulation on the specimens are higher for rough surfaces, and as rougher is the coating surface, higher is the dust deposition. In consequence, there is a significant decrease in the long-term solar reflectance, mainly observed for sample S7 in this study. A cleaning process was also conducted to identify the capability of the coatings to restore the initial solar reflectance after the period of natural weathering. The cleaning process restored from 90% to 100% of the original solar reflectance, which means the maintenance is a very efficient approach to keep the good thermal performance of white cool roofs, mainly in hot climates.

Computer simulations were conducted to assess the cooling and heating energy needs for a residential building located in different climate conditions in Brazil, considering new and aged solar reflectances of samples analyzed in this research. The results indicate that as higher is the solar reflectance of roof surfaces, the lower is the heat discomfort and the cooling energy need for buildings located in hot climate cities (ZB7 and ZB8). On the other hand, as higher is the solar reflectance, the heating energy need increases for buildings located in subtropical climates with cold winters, considering the Brazilian scenario. The results also indicated that the aging of white coatings increased cooling energy needs, and this difference is very significant for white coatings with higher initial SR, when compared to the fibrocement tile with initial SR of 0.48.

In conclusion, the proposed analysis showed how the use of cool coatings on roofs could be a passive solution for buildings in tropical and hot climates, which contribute to increase indoor thermal comfort conditions and decrease cooling energy needs. In particular, the weathering and soiling of roof surfaces may be considered in these analyses once the effect on the solar reflectance over time cannot be neglected. In this case, maintenance through cleaning processes can be an effective solution to restore the initial solar reflectance. The effect of aging on the thermal performance of materials from the building envelope is significant and cannot be ignored in the design of green buildings. The results emphasized the importance of developing a new generation of cool coatings, relatively easy to clean and also able to maintain the initial solar reflectance for a long period.

The findings presented in this work apply to a particular building configuration under to specific climate conditions. Future research is needed to account for the aging of the coatings after 3 years of natural weathering exposure, as recommended by the Cool Roofing Rating Council [45] and earlier studies [20,24]. Different building systems may also be analyzed to identify the influence on the cooling and heating energy needs according to the aging of roofs solar reflectance.

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