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Natural aging of cool walls: Impact on solar reflectance, sensitivity to thermal shocks and building energy needs

Riccardo Paolini[a,b,*], Andrea Zani[a], Tiziana Poli[a], Florian Antretter[c], Michele Zinzi[d]

[a] Politecnico di Milano, Department of Architecture, Built environment and Construction Engineering, Italy
[b] The University of New South Wales, UNSW Built Environment, Australia
[c] Fraunhofer Institute for Building Physics, Department of Hygrothermics, Germany
[d] ENEA – UTEE-ERT Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Italy

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ABSTRACT

Wall finishes with high solar reflectance and thermal emittance, commonly known as cool walls, can reduce the exterior surface temperatures of façades, and consequently the building cooling energy needs and power demand, and lower the sensitivity to degradation. Aging, though, may affect their performance. To investigate this risk, we exposed for four years in Milan, Italy, two series of façade finish coats, white and beige, facing north and south, in vertical and vertical-sheltered position, and we measured their solar spectral reflectance and thermal emittance before and after aging. The solar reflectance of the white finish coats drops from 0.75 to 0.55 in four years, and from 0.46 to 0.38 for the beige coats, while the thermal emittance is unchanged. Then, for a typical residential building with white walls, we computed that the cooling energy needs increase with walls aging by 5% and 11%, respectively, with or without exterior wall insulation. The exterior surface temperature is increased even by 6 °C, and the number of sudden surface temperature variations in one hour is boosted. Finally, the moisture content in the external layers is reduced, showing the impact on the heat and mass balance because of the uncertainty in solar absorption due to aging.

1. Introduction

Worldwide, the cooling energy consumption of buildings currently represents only 4.4% of the total consumption for heating and cooling. However, this figure is expected to increase to 35% by 2050, and up to 61% by 2100, because of the combination of global warming and higher market penetration of air conditioning [1]. In some countries, such as India, the outlook is of a tenfold residential cooling energy consumption in 2050, with respect to current levels.

To reduce the cooling loads of buildings, several passive techniques have been pursued, including the exploitation of thermal storage, and night ventilation [2]. Moreover, it was soon understood that to tackle effectively the cooling loads it is necessary to act both on the building and the local urban climate scale. Therefore, during the last three decades, a wide range of building envelope technologies has been developed and tested with these objectives [3,4]. Among these technologies, highly reflective and emissive surfaces, widely known as cool surfaces, were proven to be an effective option, easy to be implemented [5–7]. Initially, the research on cool materials applications mostly concerned cool roofs [6,8], while more recent studies focused on applications for shading devices [9,10] and walls [11–14]. For instance, for a reference residential building in Mediterranean climate, an increase of the solar reflectance of the walls by 0.1 can provide cooling energy savings up to 2.9 kWh m^{-2}, and reduce the indoor operative temperature by 1.1 °C of unconditioned buildings [12]. However, these documented benefits could be compromised by weathering and soiling [15–17], and biological growth [18,19]. There are some materials that exhibit self-cleaning features also over long periods, such as anatase added photoactive materials [20] or those that employ fluoropolymers [21,22]. In some cases, degradation causes the detachment of particles from the material surface, producing an apparent self-cleaning effect [23]. While there is information on the evolution over time of the optical-radiative response of roofing materials, it is not so for façade materials, for which the published data mostly concern their visual performance [24].

Here we show the results of a four-year natural exposure campaign of white and beige finish coats. We measured their solar reflectance (ρ_s) and thermal emittance (ε) before and after aging,

* Corresponding author at: UNSW Built Environment, Red Centre West Wing, UNSW Sydney 2052, Sydney, Australia.
E-mail address: r.paolini@unsw.edu.au (R. Paolini).

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Table 1
Building envelope features and surface area.

Building components	Orientation and area (m^2)	Case 1: No insulation	Case 2: Insulated
Wall	Tot. 2014 N/E/S/W: 504	$U = 0.49\,W\,m^{-2}\,K^{-1}$ $\rho_{s,new}$ and $\rho_{s,aged}$ from experiment	$U = 0.22\,W\,m^{-2}\,K^{-1}$ $\rho_{s,new}$ and $\rho_{s,aged}$ from experiment
Roof	412	$U = 0.56\,W\,m^{-2}\,K^{-1}$ $\rho_s = 0.25$	$U = 0.23\,W\,m^{-2}\,K^{-1}$ $\rho_s = 0.25$
Floor	Tot. 3709 412	$U = 0.51\,W\,m^{-2}\,K^{-1}$	$U = 0.51\,W\,m^{-2}\,K^{-1}$
Floor over cellar	412	$U = 0.52\,W\,m^{-2}\,K^{-1}$	$U = 0.29\,W\,m^{-2}\,K^{-1}$
Window	Tot. 419 N: 109 E: 106 S: 98 E: 106	$U = 2.9\,W\,m^{-2}\,K^{-1}$ g-value = 0.75 + external shading system (roller shutter)	$U = 1.4\,W\,m^{-2}\,K^{-1}$ g-value = 0.57 + external shading system (roller shutter)

and we computed the impact of aging of façades on (i) the heating and cooling loads of a typical residential building in Milan, Italy, (ii) the sensitivity to thermal shocks, and (iii) the moisture content within the wall layers.

2. Experiment

We selected from the market two standard finish coats (i.e., without self-cleaning features) that are commonly used for walls exterior insulation systems, one beige and another white, respectively with initial ρ_s equal to 0.46 and 0.75. The siloxane-based finish coat (with 0/1 mm sand) is 2 mm thick and it was applied onto a 4 mm thick base coat (i.e., cement mortar with 0/1 mm sand, with ~ 2% of acrylic resin as plasticizer). The two-coat system was laid on top of 10 cm × 10 cm fiber reinforced concrete slates used as a substrate (5 mm thick). From April 2012 to April 2016, we exposed in Milan, Italy (45°28′48″N; 9°13′46″E; 123 m above mean sea level), three replicates per product and per exposure condition, namely north and south, and vertical and vertical sheltered. The latter exposure condition refers to positioning the samples vertically underneath an overhang of 10 cm, which simulates a windowsill or roof gutter.

The exposure site is located on a rooftop, at 35 m above the street level and is equipped with a complete weather station [25]. During the aging campaign, the average ambient temperature was of 15.39 °C (with 2nd and 98th percentiles equal to 1.6 °C and 31.2 °C, respectively), average wind speed of 1.6 m s^{-1}, never exceeding 9 m s^{-1}, and average yearly rainfall of 1176 mm. Milan's climate is cold during the winter and hot during summer, considerably drier than its surrounding non-urban adjacent areas [26].

The samples were retrieved, measured in the laboratory, and re-exposed on the metal racks at 3, 6, 12, 18, 24, 36, 42, and 48 months of natural aging. The spectral reflectance (ρ) was measured with a PerkinElmer Lambda 950 spectrometer, equipped with a 150 mm integrating sphere, in the 300–2500 nm wavelength range, with a spectral resolution of 5 nm (with 25 samplings per wavelength). Each sample was measured in its center, characterizing an area of approximately 1 cm^2. Then the average spectral curve was computed and broadband values measured in the laboratory, and re-exposed on the metal racks at 3, 6, 12, 18, 24, 36, 42, and 48 months of natural aging. The spectral reflectance (ρ) was measured with a PerkinElmer Lambda 950 spectrometer, equipped with a 150 mm integrating sphere, in the 300–2500 nm wavelength range, with a spectral resolution of 5 nm (with 25 samplings per wavelength). Each sample was measured in its center, characterizing an area of approximately 1 cm^2. Then the average spectral curve was computed and broadband values were calculated starting from the spectral data, according to ISO 9050 [27]. The interlaboratory measurement uncertainty of this technique is equal or less than 0.020 [28,29]. The thermal emittance (ε) was measured with the TIR 100-2 emissometer by Inglas, according to EN 15976 [30], performing five measurements per replicate. Thermal emittance measurements, considering all measurement methods, have an average uncertainty of ± 0.02 [29,31]. Given the thickness of the samples and their not perfectly smooth surface, the ASTM C 1371 method was not applicable neither in the original version nor in the 'slide method' variant [32,33]. We processed the average spectral curve, for each exposure condition, in the CIELab color space, composed by three color coordinates: L*, lightness; a*, hues from red to green; and b*, hues from yellow to blue [34,35].

The capillary water absorption coefficient by partial immersion was measured on new and aged samples, after four years of exposure, according to ASTM C 1794 [36]. As the scope of this test is to observe changes with aging, to avoid known problems in repeatability and reproducibility [37,38], we performed the tests on all the samples in the same experimental session. In particular, for materials offering low water absorption, the deviation from interlaboratory median values may be even of 40% [39], while within-laboratory deviations account for less than 10% [37]. For the hygrothermal simulations, instead, we performed capillary water absorption tests of the same finish and base coat on a substrate of expanded polystyrene.

Finally, on a subset of three white coat replicates, exposed facing north, we performed two cleaning steps, similarly to the experiment by Levinson et al. on PVC roofing membranes [40]. We rinsed and brushed the samples, measured their ρ, and then brushed and washed them with a common soap based on sodium carbonate, measuring again ρ afterward.

3. Simulations

As a case study, we selected a residential isolated tower building (i.e., not surrounded by other buildings), that is representative of buildings with high solar access in Milan, Italy [41], namely those that could be mostly benefited by cool walls. Since the purpose of this study is to assess the impact of weathering and soiling of cool walls on the building hygrothermal and energy performance, we selected an isolated building, providing the upper bound of this variation. The ten-story building is 30 m high and 20.3 m × 20.3 m in plan, with a total net floor area of 3307 m^2, façades perpendicular to the cardinal directions and four windows per floor of 1.6 m × 1.7 m on each façade. We considered two case studies: non-retrofitted and retrofitted, the latter compliant with the current energy regulations in Italy [42] (Table 1). In both cases, we considered an aged roofing felt as a waterproofing layer on the flat roof (data from [16]). For the retrofitted case, we selected an External Thermal Insulation Composite System with rendering (ETICS), applied onto the existing wall substrate (Table 2).

The capillary water absorption coefficient of the walls finish coat and the solar reflectance and thermal emittance are the values achieved with the experimental activity of this study. The other material properties are from the WUFI database, derived from mea-