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Characterization and Durability of Cool Materials: Standard Methodologies for the Evaluation of Thermal Performance of New and Aged Products

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Abstract: This study highlights how the analysis of the long-term performance of solar reflective materials used both as roofing and flooring solutions to mitigate urban overheating has recently become more important. European and Italian legislations focus just on initial properties, but actual energy efficiency depends on durability over time. The objective is the development and the validation of characterization methodologies that consider performance degradation due to aging, providing reliable guidance for designers and policy makers. This study integrates standard thermophysical characterization methods with natural and accelerated aging protocols. Solar reflectance (SR) measurements can be performed by using ultraviolet-visible-near-infrared spectrophotometer, solar spectrum reflectometer and pyranometer/albedometer, while thermal emissivity can be measured with infrared emissometers. Natural aging was implemented at the Energy Efficiency Laboratory structure of the University of Modena and Reggio Emilia, operational since 2017. Accelerated methods include the standard protocol for surface soiling and an innovative method for biological growth. The analysis reveals significant degradations in SR, with reductions of between 10% and 40% after three years of natural exposure. Bituminous membranes show the most marked degradation, while ceramic materials present the best stability. Accelerated methods show interesting correlations with natural aging. The doubling of the standard accelerated cycle, designed on North American climatic conditions, is more representative of European climatic conditions characterized by greater air pollution. It must be recalled that evaluation based just on initial performance significantly underestimates long-term behaviour. The results suggest the need to update regulations by introducing requirements based on post-ageing performance. New materials design should be focus on durability by integrating into new materials both self-cleaning properties and improved stability over time. While, during design process, materials with certified long-term stability, analyzed through durability and degradation analysis should be considered in energy and economic assessments.

Keywords: Solar reflective materials; Solar reflectance; Thermal emissivity; Cool roof; Natural aging; Artificial aging; Thermophysical properties

1 Introduction

Urban Heat Island (UHI) represents one of the most significant challenges of modern cities regarding both the energy and environmental sustainability. The increase in urban temperatures, often 2–5°C higher than the surrounding rural areas, is mainly caused by the absorption and retention of solar heat by artificial surfaces, in particular roofs and floors. This phenomenon determines a significant increase in energy needs for the summer air conditioning of buildings, with consequent increases in electricity consumption, greenhouse gas emissions and operating costs. The adoption of effective mitigation strategies is becoming more urgent due to the increasing urbanization and intensification of extreme climate events. High solar reflectance (SR) materials, commonly referred to as "cool materials", appear to be a promising technological solution for passive control of surface temperatures and reducing urban overheating in this context [1–6].

"Cool" materials are characterized by two fundamental thermophysical properties that determine their effectiveness in controlling overheating: high SR (or albedo) and high thermal emissivity in the infrared wavelength range. Thanks to these properties they are often referred to as solar-reflective materials [7, 8]. SR represents the fraction of incident solar radiation reflected from the surface, reducing the energy absorbed and converted into heat, while thermal emissivity measures the ability of the material to return to the atmosphere, through infrared thermal radiation, the fraction of solar energy absorbed. The surface heat balance of a material exposed to solar radiation depends critically on these two parameters: while reflectance reduces energy input, emissivity favors the dissipation of accumulated heat.

Solar Reflectance Index (SRI) was developed, according to ASTM E1980 [9], to quantify the combined effect of these properties. It compares the surface temperature of the material under examination with that of two reference surfaces: one black (SR 0.05, emissivity 0.90) and one white (SR 0.80, emissivity 0.90), both analyzed under the same irradiation conditions. An SRI of 0 corresponds to the black reference surface, while an SRI of 100 corresponds to the white one. Materials with optimal properties can reach SRI values above 100. Knowing of the importance of cool materials in energy and environmental, policies has led to the progressive introduction of specific regulatory requirements. For the first time in 2009, the Leadership in Energy and Environmental Design program included SRI among the criteria for building sustainability certification, significantly influencing market development and research in the sector [10].

In Italy, the requirement for solar reflective materials was introduced with the Interministerial Decree of June 26th 2015 regarding "Minimum requirements" on new buildings [11]. Thermophysical properties should be certified for high SR for roofs, setting minimum reflectance values of 0.65 for flat roofs and 0.30 for pitched roofs. These obligations apply to new buildings, expansions, demolitions and reconstructions, first level renovations and energy requalification affecting the roof.

The regulatory framework was further strengthened by the Ministerial Decree of 11 October 2017 on $Criteri$ $Ambientali$ $Minimi$ (Minimum Environmental Criteria, CAM), the Italian implementation of European Green Public Procurement [12]. CAMs introduce more stringent requirements based on SRI: at least 29 for covers with a slope greater than 15% and at least 76 for covers with a slope less than or equal to 15%. Similar performances are required for external paved surfaces.

However, both Italian legislation and most international standards still focus on the initial properties of materials, neglecting the crucial aspect of performance durability over time. This limitation represents a significant gap, since performances of cool materials can degrade considerably due to natural aging and exposure to atmospheric agents and pollutants.

2 Methodology

2.1 Solar Reflectance

The accurate determination of SR (ρ_{sol}) constitutes the fundamental parameter for the characterization of cool materials [13–15]. SR represents the fraction of solar radiation reflected from the surface in the spectral range 300–2500 nm weighted by the irradiance spectrum, according to the relationship (1):

$$\rho_{sol} = \frac{\int_{300}^{2500} \rho(\lambda) I(\lambda) \mathrm{d}\lambda}{\int_{300}^{2500} I(\lambda) \mathrm{d}\lambda} \tag{1}$$

where, $\rho(\lambda)$ is the spectral reflectivity, defined as the fraction of incident light a surface reflects at different wavelengths of the electromagnetic spectrum; $I(\lambda)$ is the irradiance spectrum selected for the calculation.

2.1.1 UV-Vis-Nir spectrophotometer

The use of UV-Vis-NIR spectrophotometer represents the most accurate methodology for measuring SR and it is described by ASTM E903 [16], EN 410 and ISO 9050 standards. The instrument measures spectral reflectivity between 300 and 2500 nm, from which the integrated SR is calculated. For measurements of diffuse reflectors, an integrating sphere with a minimum diameter of 150 mm, coated with highly reflective material, is required. This methodology allows the characterization of flat samples with homogeneous surface; for variegated surfaces it is possible to carry out mediations on multiple measurements.

An important critical issue concerns the choice of the reference solar spectrum on which to integrate the spectral reflectivity curve. Different standards specify different solar spectra (AM1.5 beam normal for performance comparisons, AM1GH for scientific analyses) which may result in slightly different SR values for the same material.

2.1.2 Solar spectrum reflectometer

The ASTM C1549 [17] method uses a multiband solar reflectometer that illuminates the sample via internal sources and directly measures reflectance by weighting measurements from sensors operating at different wavelengths. Comparison with certified reference samples guarantees the traceability of the measurements. This methodology offers advantages in terms of speed and practicality, while maintaining adequate accuracy for engineering applications.

2.1.3 Albedometer/pyranometer

The ASTM E1918 [18] standard describes how in situ measurements can be made on large surfaces using an albedometer or double pyranometer. The instrument, composed of two opposing pyranometers, simultaneously measures the solar radiation incident from above and that reflected from below using a thermopile shielded from the currents thanks to a glass dome. Measurements require clear sky conditions and solar elevation above 45°. At 0.50 m from the target, the surface to be measured must be at least 4 × 4 m to ensure adequate statistical representativeness. This method allows you to measure the actual reflectance of a material in the real conditions in which it is placed.

2.2 Thermal Emissivity

Thermal emissivity represents how effectively a surface emits thermal radiation, defined as the ratio of energy radiated by a surface to the energy radiated by a perfect blackbody at the same temperature quantifies the material' ability to emit infrared radiation, a crucial parameter for the dissipation of absorbed heat. Two standard methodologies are available for this characterization.

2.2.1 Infrared emissivity (ASTM C1371)

This methodology [19] uses an electrically heated thermopile that detects heat exchanged with the sample by infrared radiation. The measurement takes place by comparison with two reference samples with high and low emissivity. For non-conductive samples it is necessary to implement the "slide method", continuously moving the probe (manually or robotized) to avoid heating the material and the consequent disturbance of the measurement.

2.2.2 Infrared thermal emissivity (EN 15976)

The European method EN 15976 [20] operates in the spectral range 2.5–40 μm using a hemispherical radiant source at 100°C. A detector measures the IR radiation emitted by the source and reflected by the sample, kept at room temperature. The measurement for comparison with reference samples guarantees the accuracy of the method.

2.3 Solar Reflectance Index

The SRI is calculated according to the ASTM E1980 [9, 21] standard using the Eq. (2):

$$\text{SRI} = 100 \cdot \frac{T_{\text{black}} - T_{\text{surf}}}{T_{\text{black}} - T_{\text{white}}} \tag{2}$$

where, T_{surf} is the surface temperature of the material under examination, T_{black} is the surface temperature of the reference black surface (SR = 0.05, emissivity = 0.90) and T_{white} is the surface temperature of the reference white surface (SR = 0.80, emissivity = 0.90). The calculation assumes standard conditions of radiation (1000 W/m^2), air temperature (37°C), wind speed (3 m/s) and clear skies.

3 Aging and Durability Issues

3.1 Degradation Mechanisms

It is known that the performance of cool materials degrades significantly over time, making durability assessment more important than characterization on new materials. The degradation mechanisms can be classified into three main categories [22].

Regarding chemical-physical degradation, most of solar reflective solutions are represented by paint, membranes and bitumen layers. Exposure to UV rays, overheating and thermal cycling induces degradation in polymeric materials and pigment formulations. Photo-oxidative processes alter the surface chemical structure, modifying the optical properties. Moreover, thermal cycles induce mechanical stresses that can cause surface microfractures, increasing roughness and reducing specular reflectance.

The deposition of atmospheric particulates (surface soiling) represents one of the most relevant causes of reduction in SR. Dust, soot and carbon deposits accumulate on the surface, creating an absorbent layer that reduces significantly the albedo of solar reflective materials. The intensity of soiling depends on local environmental conditions, the concentration of air pollutants and the surface microstructure.

The growth of microorganisms (bacteria, algae, fungi), under conditions of high relative humidity, on the surface of solar reflective materials, can significantly alter the optical properties. The dark colored biofilms, formed by these microorganisms, drastically reduce the SR. This phenomenon is particularly critical in humid climates and for materials with nutritional properties favorable to microbial growth.

3.2 Natural Aging

The US Cool Roof Rating Council has developed the most established protocol for the natural aging of solar reflective materials, requiring exposure for at least 3 years at three climatically representative sites: Arizona (hot-dry climate), Florida (hot-humid climate) and Ohio (cold-temperate climate). This multi-site approach allows characterizing the behavior of materials under different climatic conditions [23].

There is no single "test farm" for cool roofs in Europe, but several organizations and projects conduct testing and research. According to Paolini et al. [24], European pollution conditions, particularly Italian ones, are more intense than those in the American territory [25]. The Po valley contains many of the climatic conditions (pollution, thermal cycles, UV exposure, humidity) that most test the properties of solar reflective materials. Since 2017 there has been a test farm working according to the ASTM G7 standard for natural aging in European climatic conditions. The facility includes south-facing displays at an inclination of 45°, a comprehensive weather station for continuous monitoring of environmental parameters and a protected exposure area to ensure the safety of samples.

The site allows the simultaneous display of multiple types of materials, with periodic monitoring of thermophysical performance. This infrastructure represents an important reference for the development of specific aging protocols for European climatic conditions, characterized by air pollution levels generally higher than US reference sites.

3.3 Accelerated Aging

The ASTM D7897 [26] standard defines an accelerated aging protocol for soiling that condenses the equivalent of 3 years of natural exposure over 3 days of laboratory treatment. The method alternate QUV/spray equipment applying both physical ageing (UV irradiation and thermoclimatic cycles) and chemical ageing (spraying with salts, dust, humic acid and carbon black mimicking natural sites pollutant composition).

The standard cycle, developed for the average of the three US climatic conditions, may however not be completely representative of natural aging in the European environment: comparative studies indicate that doubling the standard accelerated ageing cycle provides results more representative of European climatic conditions, characterized by higher levels of air pollution.

In addition to ASTM D7897, EELab developed an innovative method for accelerated biological ageing, by using controlled cultures of microorganisms in optimized environmental conditions and a liquid substrate composed from microorganisms nutrients and reagents from D7897. The experimental apparatus allows simulating biological growth in a short time, providing a rapid assessment of the susceptibility of materials to biofouling [27, 28].

Accelerated aging methods have the advantage of rapidity but require validation through correlation with natural aging results, moreover some materials can also suffer more pronounced deterioration in accelerated tests than in real conditions, requiring specific corrective factors for the type of material. Cool Roof Rating Council allows accelerated soiling aging to be used only pending the completion of a complete natural aging cycle.

4 Experimental Results

4.1 Comparison Between New and Aged Samples

Experimental analysis regarding the performance of solar reflective materials before and after aging reveals significant degradations that compromise long-term energy efficiency. Experimental data collected at the EELab laboratory on different types of materials show reductions in SR ranging from 10% to 40% after three years of natural exposure.

Bituminous membranes protected by reflective coatings present a reduction in SR up to 35–40% after natural aging. Thermoplastic synthetic sheaths exhibit more stable behaviors, degradations typically usually range from 15–25%. Ceramic and cementitious materials, thanks to their chemical and physical stability show the best durability, with reflectance reductions generally less than 15%.

Surface fouling represents the main factor of degradation in the first two years of exposure, while chemical-physical degradation prevails in the following years. In a highly polluted urban environment, the soiling effect can lead to reductions in reflectance of more than 20% already in the first year of exposure.

Variations over SRI are even more pronounced than in SR alone, as they also incorporate the effects of thermal emissivity degradation. Materials with an initial SRI above 100 can fall below 80 after three years of natural aging, no longer meeting the most stringent regulatory requirements.

The loss of performance after ageing process can be critical for materials with initial SRI just above the regulatory limit values. Products with an initial SRI of 30–35 can fall below the threshold of 29 required by CAMs for paved surfaces, losing regulatory compliance.

Accelerated biological aging studies highlight how biofouling can represent a critical factor in conditions of high humidity too. The growth of microbial biofilms can lead to reductions in reflectance of more than 30% in a relatively short time (6–12 months), particularly for materials with surface properties favorable to moisture and nutrient retention.

4.2 Validation of Accelerated Methods

Validation of the ASTM D7897 method through comparison with natural aging results shows satisfactory correlations for most types of materials. The correlation coefficient R^2 is generally higher than 0.85 for bituminous and polymeric membranes, while it drops to 0.75–0.80 for cement and ceramic materials.

It is important to highlight how some polymeric materials show excessive susceptibility to accelerated treatments, with degradations higher than those observed under natural conditions. This phenomenon requires the application of specific corrective factors by type of material, partially reducing the universality of the method.

The comparison between the results of standard accelerated ageing and that obtained with a doubled cycle demonstrates a better representativeness for European conditions. The extended cycle produces degradations closer to those observed in natural ageing on the Po Valley exposure conditions, characterized by air pollution levels representative of the European urban environment.

The analysis of local climatic factors highlights how the greater frequency of rainfall events in Europe favors self-cleaning phenomena that attenuate the effect of soiling compared to US conditions. However, the higher concentration of urban pollutants compensates this beneficial effect.

The accelerated biological aging method developed by EELab shows promising results in simulating microbial growth. Preliminary tests highlight a good correlation with field observations for different types of materials, with test times reduced to 2–4 weeks compared to the 6–12 months needed in natural conditions.

4.3 Practical Applications

The application of remote sensing techniques for mapping the SR of urban surfaces has made it possible to quantify the impact of aging on a territorial scale. The analyzes conducted on urban areas of the Po Valley show average reductions in roof reflectance of 15–20% over 5–7 years, with significant variations depending on the orientation, type of material and intensity of local traffic.

Long-term monitoring conducted on sample buildings confirmed the importance of post-ageing assessment. Buildings designed to meet minimum requirements with materials with initial reflectance just above the limit values show increases of 8–15% in air conditioning consumption after 3–5 years, highlighting the loss of energy effectiveness.

5 Discussion

5.1 Importance of Post-Aging Performance

The experimental results unequivocally demonstrate that the performance evaluation of cool materials based solely on initial values significantly underestimates their long-term behavior. The degradation of thermophysical properties over 3–5 years can compromise the energy efficiency expected in the design phase, with consequent economic and environmental impacts.

The cost-benefit analysis of cool roof systems must necessarily consider the performance degradation curve over time. Initial energy savings, often used to justify the additional investment, can be reduced by 20–40% over the first decade of implementation. This consideration significantly changes payback times and the economic convenience of investments.

The need for periodic maintenance or early replacement of materials represents an additional cost often not considered in initial assessments. Materials with superior initial performance but greater stability over time can be more convenient than apparently cheaper but less durable solutions.

The design of air conditioning systems based on thermo-energy performance of the casing that does not consider aging may result in under-sizing of the systems. The loss of effectiveness of solar reflective materials leads to increases in summer heat loads which can compromise internal comfort and increase energy consumption beyond design forecasts.

5.2 Adaptation to European Conditions

European climatic and environmental conditions present significant differences compared to the contexts for which international reference protocols were developed. The greater frequency of precipitation favors self-cleaning phenomena which can attenuate the effect of surface soiling. Higher urban density and higher air pollution levels increase the degradation of urban surfaces.

The variability of European climates requires careful approaches: the Mediterranean conditions (hot and dry summers, mild and rainy winters), determine different degradation mechanisms compared to the continental climates of Northern Europe (harsh winters and significant temperature variations).

Experimental evidence of performance degradation suggests the need to review regulatory criteria currently based on initial values. The introduction of minimum performance-based requirements after standardized aging would ensure greater long-term performance reliability and a more correct assessment of energy efficiency. The definition of accelerated aging protocols specific to the European context would allow a faster and more representative characterization of materials, supporting both the product development phase and performance certification.

5.3 Perspectives

The development of new generation cool materials must focus on performance durability as well as initial values. Some promising research directions are represented by self-cleaning coatings based on photocatalytic effect, super-hydrophobic surfaces (lotus effect). These technologies help reduce pollutant adhesion while anti-microbial formulations contribute to prevent biological growth.

The integration of sensors for the continuous monitoring of thermophysical performance would allow the implementation of predictive maintenance strategies, the optimization of the building stock's management and maintaining the effectiveness of the systems over time.

The development of predictive models that, integrated with studies that can predict UHI by using multispectral satellite image [29], can estimate the performance degradation based on local climate and environmental parameters would allow more accurate design and the design of optimized maintenance strategies. The integration of machine learning techniques and big data analysis could be a good strategy to support the identification of degradation patterns and long-term performance prediction.

The application of high-resolution remote sensing techniques for urban-scale monitoring would make it possible to quantify the effectiveness of cool materials implementation policies and optimize UHI mitigation strategies.

6 Conclusions

The present research demonstrates that characterization of cool materials based solely on initial performance represents an issue, providing an inadequate assessment of their long-term effectiveness. The standard methodologies for measuring SR and thermal emissivity, although technically consolidated, must be integrated with aging protocols representative of real operating conditions. The experimental results highlight significant degradations of thermophysical performance with a decrease of 10–40% in SR after three-year natural aging. These values are sufficient to compromise compliance with regulatory requirements and the energy efficiency expected in the design phase. Validation of accelerated ageing methods shows satisfactory correlations with natural ageing for most types of materials, with the need for specific adaptations for European climatic conditions. The doubling of the standard ASTM D7897 cycle is more representative of the European urban environment, characterized by higher levels of air pollution than US reference sites.

Some suggestions should be addressed both to manufacturers, designers and policy makers. Manufacturers of cool materials should focus research and development efforts on performance durability as well as initial values. Implementing accelerated aging protocols in the product development phase would optimize formulations for long-term stability. Product labeling should systematically include performance values after standardized aging, helping designers with more reliable information for energy and economic assessments. The development of performance guarantees based on post-ageing values would be a significant competitive differentiator. Designers should consider performance degradation when planning energy assessments, the application of appropriate safety factors or directly using post-aging values for plant sizing should be encouraged. The implementation of periodic maintenance strategies must be planned right from the design phase, with the definition of both timetables and budgets. The selection of materials should favor solutions with proven stability of performance over time, even if characterized by higher initial costs. Economic life cycle analysis must necessarily incorporate the maintenance and replacement costs associated with performance degradation. The introduction of minimum performance-based requirements after standardized ageing would ensure greater reliability of energy performance in the long term. The definition of specific aging protocols for the European climate context would allow a more representative characterization of materials. The updating of the Minimum Environmental Criteria and the decrees on minimum requirements should consider the introduction of post-aging performance thresholds, differentiated by type of material and exposure conditions. Establishing performance durability categories could support material selection and help the development of more durable solutions.

Future research should focus on the development of accelerated aging protocols that can represent different European climate zones (regional variations in temperature, humidity, solar radiation and air pollution). The integration of artificial intelligence techniques for the processing of large climate datasets could support the definition of optimized and predictive protocols. The development of continuous performance monitoring methodologies implemented by using integrated sensors and remote sensing techniques represents an interesting frontier for the optimal management of building stock and the validation of predictive models. Materials research should focus on developing durable solutions, characterized by self-cleaning and anti-microbial properties. The use of nanotechnology, photocatalytic coatings and surfaces characterized by micro/nano structure offers significant opportunities for durability improvement. The integration of solar reflective materials with smart technologies for performance monitoring and predictive maintenance represents a development direction that can transform building energy efficiency management from reactive to proactive. The implementation of urban-scale monitoring campaigns using advanced remote sensing technologies would make it possible to quantify the real effectiveness of cool materials promotion policies and optimize UHI mitigation strategies. Integrating urban climate models with material performance data would support spatial planning and environmental policies at the metropolitan level.

Author Contributions

Conceptualization, C.F. and A.M.; methodology, C.F. and A.M.; software, C.F., M.P., N.M., S.P., G.A., M.A.C., P.T., and A.M.; validation, C.F., M.P., N.M., S.P., G.A., M.A.C., P.T., and A.M.; formal analysis, C.F.; investigation, C.F., M.P., N.M., S.P., G.A., M.A.C., P.T., and A.M.; resources, A.M.; data curation, C.F., M.P., N.M., S.P., G.A., M.A.C., P.T., and A.M..; writing—original draft preparation, C.F.; writing—review and editing, C.F.; visualization, C.F., M.P., N.M., S.P., G.A., M.A.C., P.T., and A.M.; supervision, A.M.; project administration, A.M.; funding acquisition, A.M., G.A., S.P. All authors have read and agreed to the published version of the manuscript.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

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Conflicts of Interest

The author declares no conflict of interest.

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