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Durability and performance of opaque high-reflectance envelope systems: A systematic review

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Editor-in-Chief´s
Professor Chen Qiangyan and Professor Xudong Yang,
Journal of Building and Environment,

Dear Editors-in-Chief,

We are pleased to submit the manuscript entitled "Durability and performance of opaque high-reflectance envelope systems: A systematic review" by Andrea Resende Souza, Rita Carvalho Veloso, Joana Maia, Inês Flores-Colen and Nuno Manuel Monteiro Ramos, which we kindly request you to consider for publication in the Journal of Building and Environment.

This paper contributes to the study of the durability of the optical properties of highly reflective materials for building envelopes through a systematic review combined with a meta-analysis of research on highly reflective coatings in buildings over the last decade. The PRISMA method was applied to collect the relevant research papers in the Scopus database, taking into account the assessment of reflectance durability through accelerated and long-term approaches. The report includes a critical discussion of the effects of weathering and soiling of the building envelope and relates reflectance deterioration to various ageing factors. There is also a comprehensive discussion of the loss of building envelope durability, taking into account existing predictive models for different material types. Considering the large gaps in meta-analysis on the durability and weathering effect of building envelopes, an integrated methodology for qualitative and quantitative assessment of reflectance deterioration has also been proposed. Despite considerable efforts over the past decade, our systematic review highlights specific challenges and future research directions. We believe that this manuscript is consistent with the thematic scope of the journal and represents a valuable contribution. The paper is an unpublished original work and we kindly ask you to consider it for publication in the Journal of Building and Environment – Elsevier.

We thank you for your time and consideration. Please feel free to contact us for further information or clarification.

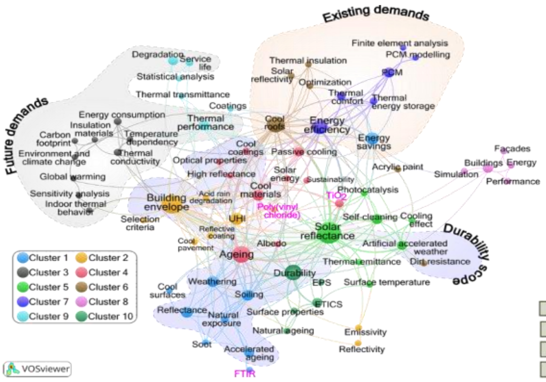
Andrea R. Souza

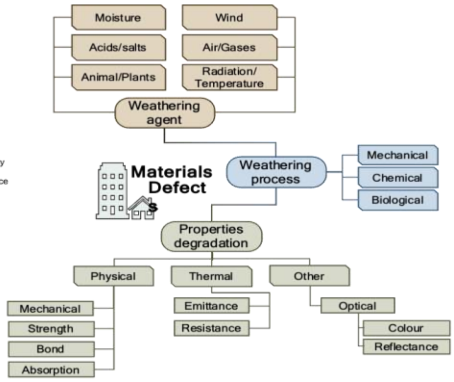
Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

GRAPHICAL ABSTRACT





HIGHLIGHTS

- Highly reflective envelopes are mainly used in dry and hot climates,
- Proposed methodology for evaluating the durability of highly reflective envelopes,
- Weathering and pollution have different ageing effects on envelope material,
- Predicting the durability of envelopes for different ageing approaches.

Durability and performance of opaque high-reflectance envelope systems: a systematic review

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Abstract

The demand for energy-efficient dwellings has led to various design solutions that improve the performance of building envelopes. High surface temperatures affect the durability of insulation systems and energy performance. Highly reflective coatings (cool materials) reduce surface temperatures and improve the durability of thermal insulation systems. Recent research evaluates the impact of these coatings and emphasises their thermal-energy performance and reflectivity, but weathering and soiling can reduce their effectiveness over time. This article summarises the durability assessment of highly reflective coatings for opaque building envelopes through a systematic review combined with a meta-analysis of publications on the ageing reflectance of different building coating systems. The discussion focused on the relationship between weathering phenomena, reflectance loss and degradation behaviour depending on the ageing test used. It was noted that many studies focus on the effect of reflectance on energy demand, but do not address degradation phenomena in detail or specify measures to mitigate the loss of durability. There is also a need for more information on the correlation between the extent of degradation and different approaches, such as accelerated or long-term testing, to evaluate highly reflective building coatings. While most research focuses on highly reflective building envelopes in hot climates, this

review highlights important future research areas. It also proposes a methodology that aims to fill research gaps and enable a comprehensive assessment of highly reflective coatings in building envelopes for sustainable urban development.

KEYWORDS: Buildings coatings; Optical properties; Reflectance loss; Accelerated ageing tests; Long-term weathering; Meta-analysis.

1 Introduction

The new planning paradigms and government legislation aimed at eco-cities share a key feature of sustainable urban development: lower energy consumption, minimal impact on ecological spaces, less use of harmful building materials and more closed-loop systems for waste management [1]. The building envelope materials play an important role in the sustainability of buildings and cities. Those solutions provide the desired aesthetics, but must positively contribute to thermal comfort [1] and reduce operating costs through energy savings during the use phase of the building life [2]. In this scenario, decrease the environmental impact of the building sector is crucial and requires implementing various measures, including improving the thermal properties of building envelopes [3].

Highly reflective (HR) materials have specific optical properties that help keep the surface cooler when exposed to solar radiation and are therefore commonly referred to as “cool materials” [4]. The HR or cool materials have reflectance and emittance values higher than 0.65 and 0.85, respectively [5]. HR coatings are mainly white or light-coloured, as these colours have a high reflectance in the visible spectral range. Nowadays, however, there are also coloured, cool materials that increase the reflectance in the infrared spectrum while maintaining the aesthetic properties of the colour [6]. In this context, highly reflective coatings (HR) offer far-reaching benefits in terms of cooling, as modifying the opaque surface of buildings to increase reflectance requires little technical effort and is cost-effective [7, 8], resulting in lower surface temperatures and reduced cooling loads [9-11].

The use of coloured highly reflective coatings or paints can reduce the surface temperature by almost 10 ºC for dark colours, as shown by Zinzi [12], Bishara, Kramberger-Kaplan and Ptatschek [13] and Dias et al. [14]. In addition, increasing the solar reflectance can lower the surface temperature and thus save energy during average demand peaks [15].

Revel et al. [16] found that installing an HR façade can reduce the operating temperature to 0.8 ºC, compared to 0.3 ºC for HR roofs. Marino [17] found that a building without insulation and with a cool roof reduces the total number of uncomfortable hours in temperate climates from 50% to 31%. Compared to tropical climates, uncomfortable hours can be reduced by almost 90%, as shown by Dornelles et al. [18].

Undoubtedly, the effectiveness of using cool materials depends on the location/climate and the heat transfer coefficient of the insulation system [19]. However, the effects of ageing, combined with climatic weathering, significantly impact the energy-saving potential when the thermal conductivity/reflectivity of the building envelope changes [20].

Saafi and Daouas [21] point out that once the aged reflectance could be reduced by 75-80% of the original value, the calculation of energy consumption should be based at least on the one-year aged solar reflectance. Paolini et al. [22] studied the impact of aged roofs (one-year natural exposure), where a 30% reflectance loss resulted in a 5.6% decrease in heating demand and a 6.5% increase in cooling demand.

While the impact of reflectance loss on building durability has only been reported in recent years, some organisations have attempted to establish guidelines for the minimum reflectance of building envelopes over time.

The Cool Roof Rating Council (CRRC) [23, 24] describes that reflective coatings must have a minimum durability of 3 years, while the Energy Star Programme [25] goes further and defines that the initial solar reflectance for low-slope roofs should be above 0.65 and after 3 years of natural ageing above 0.50, while the values for high slope roofs are 0.25 and 0.15, respectively. On the other hand, ASTM D7897 [26] argues that light-coloured, highly reflective roofs may show a significant loss of reflectivity within one to two years due to surface soiling. However, concerning vertical surfaces, such as façades, the California Commission [27] stated that the 3-year period may not be reliable, as walls are less likely to become soiled than roofs.

According to Paolini et al. [22], Dornelles, Caram and Sichieri [28] and Takebayashi et al. [29], weathering and pollution strongly affect the reflectance of roofs in the first months (4-6 months). In comparison, studies on the reflectance of road surfaces have shown a significant change in albedo before 5 months of natural exposure [30]. Antonaia et al. [31] found a reflectance loss of 2% in cool roof tiles after one month of natural ageing and 3.6% when exposed to a climate chamber. This suggests that building envelope reflectance performance may indeed be affected to varying degrees depending on exposure conditions.

Although recent studies have focused on evaluating the optical performance (reflectivity) of building envelope coatings and the impact on the thermal and energy performance of buildings throughout their lifetime, information on the weathering resistance and ageing mechanism of highly reflective materials is still lacking [32, 33]. This review aims to improve the understanding of the effects of weathering on the degradation of the optical properties of highly reflective materials. The focus is on the potential of cool materials as sustainable coating solutions.

To achieve this goal, a systematic investigation was conducted to improve our understanding of the use and durability of highly reflective coatings. This comprehensive investigation looks at the interplay of different degradation factors and their impact on reflective loss. Also, is provides a comparative analysis of various studies investigating the fraction loss of reflectance in envelope materials. The comparison includes either long-term or accelerated methods and provides valuable insights into the practical application and longevity of highly reflective coatings in opaque building envelopes.

Moreover, considering the results and practises collected in the systematic review, a methodology is proposed for evaluating the durability of the reflection under different conditions, integrating the qualitative and quantitative degradation factors.

2 Methodological framework for systematic review

A systematic review summarises all empirical evidence that meets the predefined eligibility criteria for answering a research question. At the same time, it summarises the relevant information and provides the main results of several studies [34-36]. A statistical analysis, namely the meta-analysis, complements the systematic review by identifying the relevant gaps, supporting new research and defining further studies [37]. Not all systematic reviews include meta-analysis, but combining these two processes results in a reliable and replicable study. Thus, a routine procedure was developed to compile a database of articles that studies the performance of highly reflective opaque envelopes and the effects of weathering on optical properties.

2.1 Research strategy

The research methodology used follows the phased process described in Saretta, Caputo and Frontini [38], which combines the Preferred Reporting Items of Systematic Reviews and Meta-Analyses (PRISMA) flowchart [35] and a bibliometric mapping [39].

In this study, VOSViewer software [40] was used to create a bibliometric map between the topics included in the review to analyse the synergy between different research areas concerning the durability of the reflection of opaque covers. The research method used is distinguished as follows:

- Phase I: Literature search;
- Phase II: Selection and screening of studies;
- Phase III: Meta-analysis of the eligibility process;
- Phase IV: Presentation of the bibliometric results and mapping (Section 3) and discussion of the compiled results about the ageing of the opaque envelope system (Section 4 and Section 5).

A literature review should be based on a solid and reliable source of information. Online databases such as Scopus, Web of Science (WoS) and Google Scholar [35] are often used. The three databases have comparatively stable coverage but differ in the export of bibliographic data [41]. The authors chose Scopus to use in this review once they offer more indexed journals, source titles, fill open access sources [42]. Additionally, it has bibliographical information necessary for the VOSViewer software.

2.2 Boundaries and inclusion criteria

In the first phase (PRISMA Identification), studies on the durability of highly reflective façade coatings were collected from the Scopus database. To achieve this goal, the authors considered the search field "*Article title, Abstract, Keywords*" on Scopus and used *wildcards* and *Boolean operators*. Table 1 shows the proposal for the individual keyword combinations.

Table 1. Researched keywords for the bibliographic database.

Combination	Keywords
K1	solar AND reflect*
K2	high AND reflect*
K3	ag?ing*
K4	durability*
K5	weath*
K6	building AND envelop*
K7	fa?ade* OR roof*

The selection phase (phase II) is based on the conditions of the screening process in the PRISMA declaration [35]. In this phase, defining the research boundaries to refine the identification based on the keywords (Phase I) is essential.

The search in Scopus applied the criteria listed in Table 2: (i) the criteria for the combination of keywords considered the optical property and the long-term impact in different applications; (ii) the subject area included the construction sector; (iii) for the type of document, journal articles and reviews were selected, as it can usually be challenging to obtain a full conference paper; (iv) only English-language documents were selected; (v) a Pareto principle was applied to select the most representative publication period, setting the range between 2012 and 2022.

After implementing the delimitation criteria in Scopus, the documents were screened by reading the abstracts and selected for the next phase. In the inclusion phase, the screened papers were read and searched for research papers that answered the four questions: (i) Does the research focus on solutions for buildings?; (ii) Is a clear ageing methodology presented?; (iii) Is it possible to identify the materials and the nature of the envelope system?; and (iv) Are the reflectance values exhibited before and after the tests?.

Table 2. Delimitation criteria for Scopus database.

Criteria	Value
Keyword combination	
Comb 1	K1 OR K2 AND K3 OR K4 OR K5 AND K6 OR K7
Comb 2	K1 OR K2 OR K3 OR K4 OR K5 AND K6
Subject area	Engineering OR Energy OR Environmental science
Document Type	Article OR Review
Source type	Journal
Language	English
Year	2012 – 2022

These questions have been specifically elaborated to refine the research objective of identifying the environmental influences and mechanisms of reflectance deterioration. In this way, the following possible answers are included:

- Question 1: Application of materials with high reflectance or studies of optical properties on façades, walkways/roads, or roofs;
- Question 2: Description of ageing tests (e.g., accelerated, or long-term) if long-term environmental conditions are present along the exposure; and if accelerated, the equipment and type of degradation are described;
- Question 3: Characterisation of the materials used, such as the technical specification, type of application, type of coating and solar orientation;
- Question 4: Indication of the initial reflectance results after ageing and the exposure time to allow calculation of the performance loss.

It is emphasised that studies presenting only qualitative results as subjective criteria (i.e., good, excellent, or poor) were included in the review as this assessment could help explain the performance.

3 Statistics and bibliometric findings of the systematic review

Fig. 1 illustrates the methodology used for the systematic review, which follows the guidelines of the PRISMA flowchart. The selected keywords and boundaries (Table 1 and Table 2) were used to identify 1066 papers for screening. As part of the screening process, 157 records were considered for full reading after analysing the abstracts, and 59 papers were selected using the competency questions described in Section 2.2.

The selected works represent almost 4% of the identification records (1330). This small number underlines the need to study the effects of weathering on building systems, especially when we consider the impact of future climate changes, e.g. the increase in average temperatures and more frequent heat waves (the frequency of hotter days) [43].

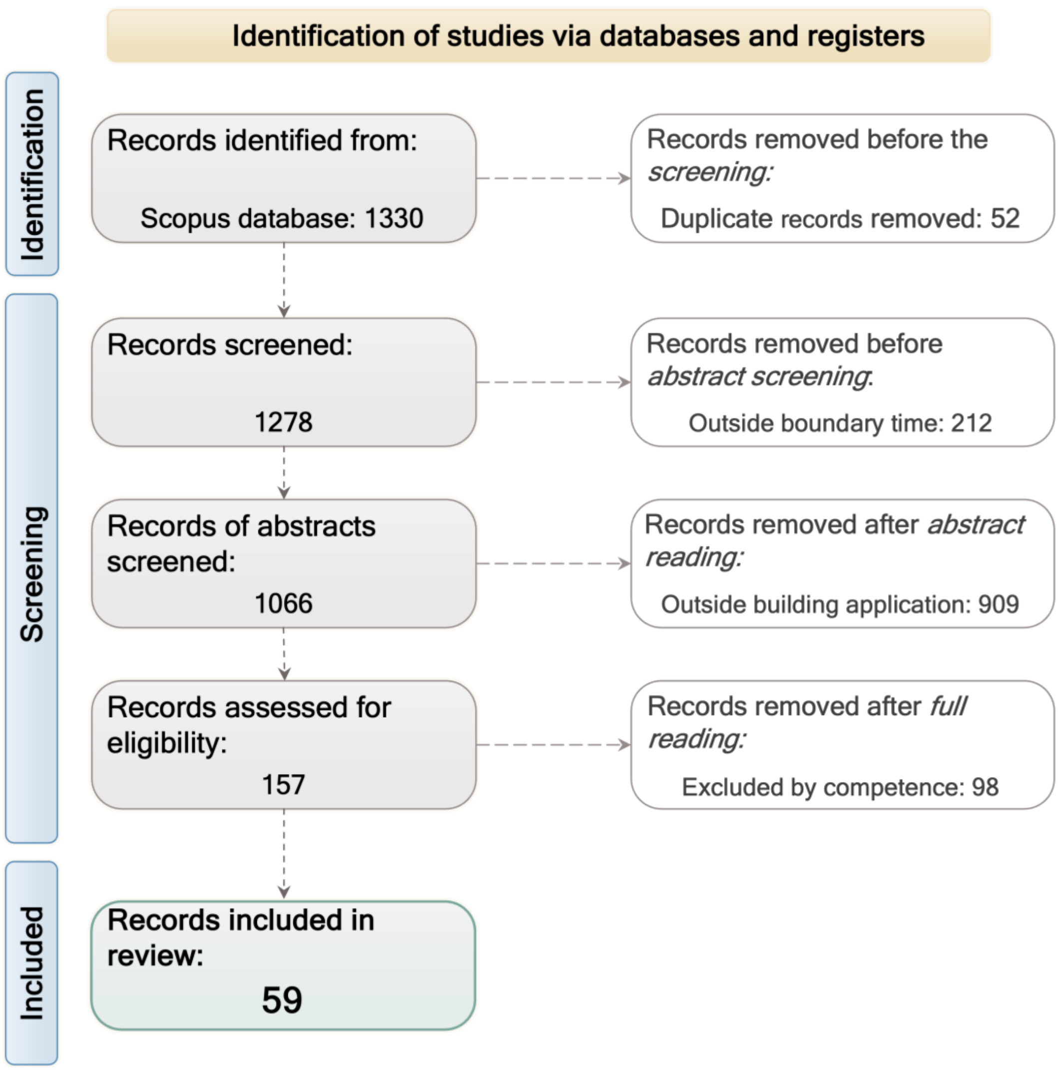

Fig. 1. Result from PRISMA statement flowchart.

3.1 Selected studies distribution

In the screening process, only studies published between 2012 and 2022 were considered, as the authors applied the Pareto principle to select the period covering more than 20% of the total publications (more information, see Fig. S1.1 in the Supplementary Data). Furthermore, the distribution of the 59 selected papers indicates that there needs to be more information on the durability of highly reflective materials for building envelopes or coatings due to the reduction between the identified and the selected datasets.

Screening by abstracts reduced the total number of 1330 papers selected to 157 documents for a full reading. These studies focused on different applications for optical properties, such as reflectance assessment for remote sensing data of the atmosphere or urban surface characterisation, as in Despini et al. [44]. Instead, they focused on mirrors, glazing envelopes or solar panels (not the material) as in Muralidhar Singh et al. [45] and Mainini et al. [46] (for a better understanding of the screening and inclusion selection, see Fig. S1.2 in the Supplementary Data).

There are two main approaches to evaluating the optical durability of coatings: tests under natural conditions, i.e. a long-term evaluation, or accelerated tests under simulated conditions [47]. Therefore, the 59 selected papers were categorised according to the ageing methods, as shown in Fig. 2. In addition, six studies were catalogued that investigated the performance of the same material under natural and accelerated conditions, referring to Antonaia et al. [31], Takebayashi et al. [29] and Paolini et al. [48].

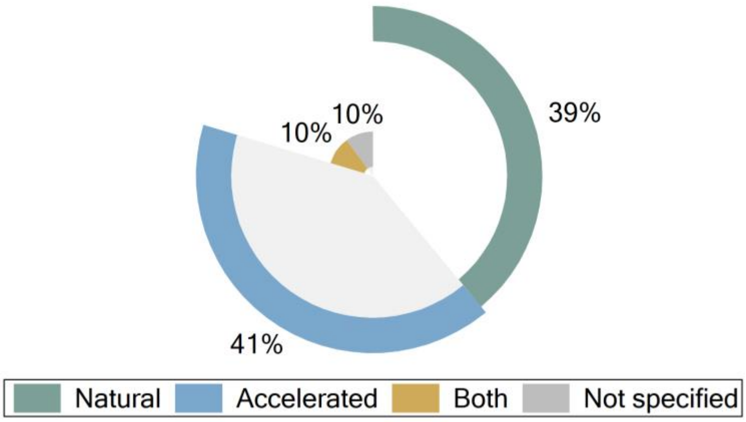

Fig. 2. Categorisation of ageing approaches, according to 59 selected papers.

Considering the adoption of ASTM D7897 [26] as a standardised and accelerated method for evaluating cool roof products and the fact that the Cool Roof Rating Council (CRRC) defines evaluation for three years of natural exposure [49], it was expected that the number of studies on natural approaches would be higher than those on accelerated ones.

The durability of building materials is influenced by climatic factors such as temperature, humidity, solar radiation and rain distribution [50]. Moreover, most studies on applying high-reflectance materials are in mild or hot climates [51]. Consequently, Fig. 3 shows the geographical and Köppen-Geiger classification distribution of the 59 selected papers. Looking at the country distribution (Fig. 3a), 37% of the studies belong to the Mediterranean climate (Italy, Greece, Spain, and Portugal), followed by China, Brazil, and the USA, with arid and warm temperatures.

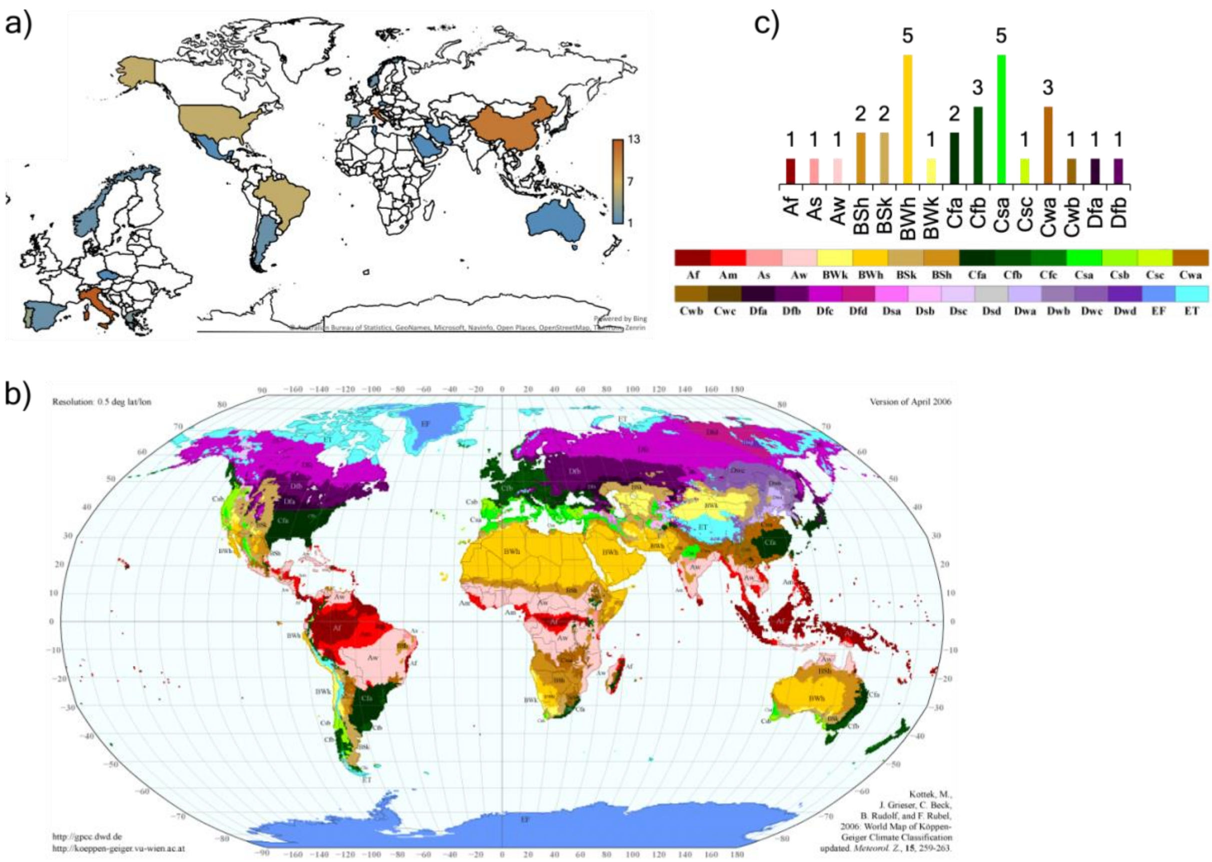

Fig. 3. Geographical distribution of selected papers. a) Number of records by country, b) Köppen-Geiger climate classification [52], and c) Distribution of papers by climate.

With this in mind, it can be verified in Fig. 3c that 24% of the records belong to temperate climates (C), followed by 17% in arid climates (B). It can be concluded that the selected works are, at the same time, representative of the impact of high-reflectance applications in climates with high temperatures and high solar radiation, as well as of the deterioration of coatings considered with the climate effect of solar and rain factors.

3.2 Bibliometric analyses

Bibliometric mapping enables the visualisation of the relationship between specific knowledge using mathematical and statistical tools [53]. A bibliometric map includes a clustering technique that interprets the size relationships, number of nodes and relative position by clustering the similarities between groups of nodes [54, 55].

Thereby, a keyword mapping was created using the metadata of the 157 articles screened, resulting in the network in Fig. 4. The mapping and clustering technique of VOSViewer allows the interpretation of similarity and interaction between topics by analysing the colour and proximity of the nodes [54].

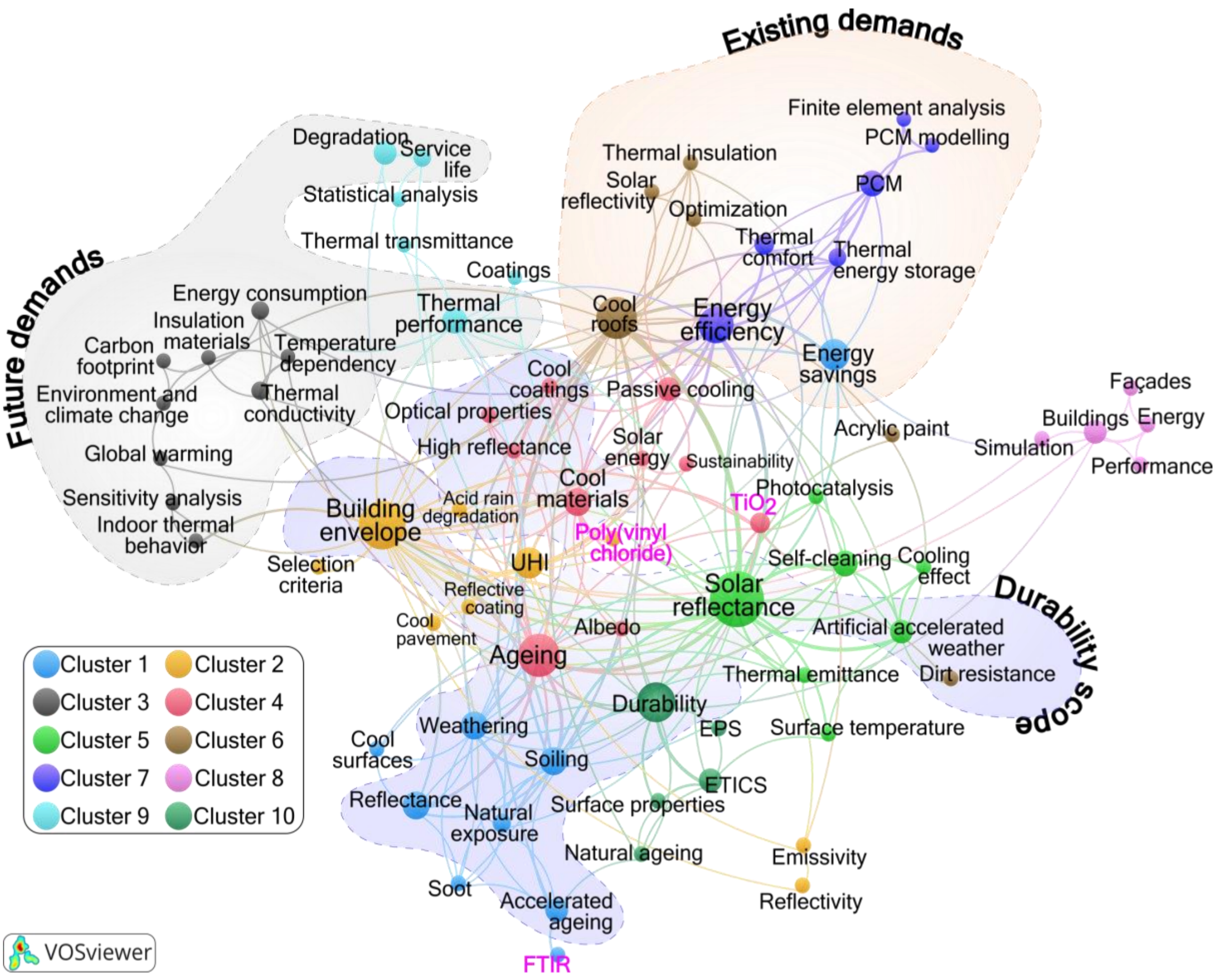

Fig. 4. Keywords co-occurrence mapping cluster under Durability Scope.

To explain the exclusion of results that were not considered in the selection process, keyword mapping also provides information on the interrelationships between the scientific domains. When examining the cluster concepts in Fig. 4, it is possible to identify some keywords that are related to other study objects, e.g. *poly(vinyl chloride)* – cluster 2 – TiO_2 in cluster 4 and *FTIR* – cluster 1 (pink words), which represent topics more related to the development of high reflectance materials than to durability studies, such as Veloso et al. [56].

In addition, it is possible to analyse the most current area of research in the "Existing Requirements" bundle, namely the application of cool roofs to reduce energy consumption and analysis into the development and optimisation of thermal insulation roofs. The "Future demand" bundle illustrates the relationship between the performance of the thermal envelope of buildings by linking the issues of degradation and durability (cluster 9) with the concerns of climate change and energy consumption (cluster 3).

Fig. 4 gives an overview of the issues related to applying highly reflective coatings, such as the systems used, e.g., roofs or walls, the current importance, and the future research roadmap – "Durability of cool coatings".

Finally, the selected keywords (Table 1) guide the needs and problems presented concerning the effects of weathering, ways of evaluating the durability of coatings and the effects of reflection on thermal evaluation. Complementary to this, Fig. 4 shows a holistic state of research that supports the subdivision of the Analysis and Discussions section.

4 Reviewing climatic and soiling effects on highly reflective envelopes

Materials used in building envelopes are designed to act as a protective or sacrificial surface once they form the first barrier between the weather agents and the building [57]. Layers such as renders, paints and varnishes applied to the façade can protect the envelope system from solar radiation, precipitation and thermal stress and ensure the structural integrity of the building [58, 59]. Hence, modifying the performance of the materials used in façades can increase the durability of the envelope systems.

The deterioration of some properties during the lifetime is called the ageing of the material. Ageing also refers to an experimental technique that accelerates natural degradation [60]. Apart from accelerated methods, ageing can also be natural, and in this case, it is necessary to distinguish weathering from the process of pollution.

Weathering is related to natural environmental ageing due to climatic conditions (i.e., air temperature, relative humidity, solar radiation, rain, and wind). In contrast, soiling is related to dry and wet deposition of atmospheric particles (i.e. soot and dust deposition, biological growth and chemical attack) [6, 61]. For an example of weathering and soiling applied to building envelopes, see Table 3.

Table 3. Ageing process against agents and envelope effect.

Process		Agent	Effect	Degradation
Weathering	Physical	Sun (Air temperature and Irradiation)	Increase of the surface temperature resulting in thermal cracks	Physical, Thermal
		Water (Rain/Ice)	Leaching of surface material, shrinkage by ice thaw	Physical, Thermal, Optical
	Chemical	Sun (Irradiation)	Surface degradation by UV ageing	
		Water (Acid rain)	Surface chemical alteration	
Soiling	Physical	Dust and Soot (Black carbon, automobile exhaust dust, artic haze)	Physical surface modification as refractive index	Thermal, Optical
	Chemical	Biological growth (Algae, Fungi)	Surface chemical and physical alteration	

Nonetheless, not all building materials are susceptible to all weathering influences or mechanisms. In the case of envelope systems, the composition of the finishing layer (which is most sensitive to environmental changes) must be evaluated first. For example, polymeric materials used as paint/varnish or in mortar plaster are highly susceptible to radiation, whereas this factor does not affect brick, stone or concrete [58].

Berdahl et al. [62] emphasise that even the most robust materials can be subject to weathering and environmental influences over time, with climate and environment playing a crucial role in the ageing of the façade [63]. Throughout the life of a building, weathering, mechanical stress, the accumulation of pollutants, and microbial growth affect the optical and radiation properties of envelope materials, reducing the cooling benefits of highly reflective materials [20, 48].

Highly reflective materials can improve the durability of façade systems due to their thermophysical and optical properties, reducing the cracking caused by thermal stresses and increasing the UV resistance of façade elements [64]. In the case of highly reflective coatings, the weathering and soiling affect the optical properties and solar reflectance of the surface [65]. Studies by Ferrari et al. [66], Morini et al. [67], and Synnefa, Santamouris and Livada [68] show that weathering parameters, especially maximum air temperature and relative humidity, in addition to the absorptivity of the coating, significantly affect the reflective properties of layers under natural weathering, especially about surface colour. Furthermore, certain polymeric and organic materials [59, 62] can be modified to resist UV-induced photochemical degradation by incorporating titanium oxide.

4.1 Pollutants deposition and Atmospheric agents

Changes in solar reflectance result from the deposition of pollutants on the surface of the building envelope. For example, a dark façade may have an increased reflectance due to the accumulation of light-coloured particles such as silica or salts. Conversely, a lighter surface may have a lower reflectance due to soot deposition[69, 70]. The deposition of these atmospheric particles depends on factors such as the location of the building, whether it is in a rural or urban/industrial environment, and the slope of the envelope [66]. Therefore, the material type, texture and colour of coatings affect the interaction with environmental variables, modifying the performance of the albedo over time [71].

Berdahl, Akbari and Rose [61] highlight that in the urban environment, the deposits of iron, chromium, carbon, black and organic carbon could contribute most to the change in solar reflectance. Cheng et al. [69] linked various atmospheric contaminants to the reflectance performance of seven roofing products used between one and 4 years of natural exposure. At the end of the observation period, carbon and iron particles have the most significant eigenvectors on the correlation between soil properties and reflectance loss. A reduction of almost 20% was observed for light surface colours and an increase of 10% for dark colours.

Wu et al. [72] studied the effects of soot deposits in coatings applied to typical roof structures in a controlled environment. The results showed a change in the colour of the samples and the solar reflectance. Regardless of the coating, the solar reflectance decreased by more than 50% after soot deposition, and the brightness coordinate of the colour parameter CIELab decreased by 30%. Similar results were also confirmed by Takebayashi et al. [29], where white paints soiled with soot reduced reflectance by 60%. Conversely, Paolini et al. [48] used an aqueous mixture of dust minerals, soot, humic acid and salts to simulate solvents in accelerated weathering tests of cladding materials. The white roofing membranes had a reflection loss of 30%, while the grey PVC membrane had only 17%. For wall cladding materials, the average loss was 15%, which was not significantly related to the colour degradation of the coating.

A comparison of the studies by Wu et al. [72] and Paolini et al. [48] makes it possible to evaluate the combined effect of the pollution solutions. Wu et al. [72] use 0.5000 g/L of soot, while Paolini et al. [48] use a concentration of 0.0625 g/L in their solution, which explains the difference in reflectance loss, namely 50% versus 17%. However, in the soot deposition, it is necessary to evaluate the dry mass of pollution per unit area, as described by [70]. Wherein more than the pollutant concentration ratio, the high dry mass of soot reduces reflectance.

Moreover, Tang et al. [73] indicates that the presence of nitrogen oxides in the air can be deposited in the surface of roofs reducing the reflectance of white colours and also the photocatalytic performance of special roof coatings.

4.2 Salts deposition

Other soiling elements such as salts (Na, Mg, Cl) or nitrates, sulphates and silicates, when deposited on the surface, can influence the scattering and absorption of light by changing the refractive index [62, 74] once most salts have a crystalline structure with a higher refractive index than the commercial cladding layers. Sleiman et al. [70] pointed out that inorganic salts do not affect spectral reflectance like soot/matter but mainly affect the dark surfaces due to the refractive index. The salts can also affect the fixation of other pollutants due to solubility. In addition, the presence of salts can affect the biological colonisation of the surface [65].

4.3 Biological growth

The biological growth of opaque envelopes is referred to as the growth of living organisms on the external surface and can affect health. The development of biological colonisation is influenced by climatic factors such as the availability of water and organic material. On the other hand it is also related to material composition [48, 75, 76] and even to the properties of the surface layer [62, 77, 78]. However, the effects of solar reflection by organic materials in highly reflective coatings are poorly known [75]. Studies investigating a self-cleaning coating [79] linked some reflection reduction to biological growth. In addition, some authors noted that colonisation tests are more complicated to carry out [48, 80].

Mastrapostoli et al. [81] demonstrated that highly reflective roofs on light colours lost almost 25% of the original reflectance after 3 – 4 years of exposure. The authors relate the ageing of reflectance to the deposition of some pollutants, mainly microbiological growth. Mesophilic bacteria and filamentous fungi were found in the aged coating even after cleaning, while some bacteria were removed with the cleaning process.

Cheng et al. [75] investigated microbial growth in cool roof coatings by comparing laboratory protocols with natural microorganisms from three sites in the United States. The results showed that the bacterial colony is more abundant than the fungal colony. In both cases, follow the first-order kinetic model to estimate the time for the surface properties to change, resulting in a 50% reduction in the original solar reflectance in less than one month. Fungal colonisation tends to make surfaces darker, which explains the high loss rate. Shirakawa et al. [82] also found a 50% reduction in roof samples exposed in a rural environment in Brazil.

Biological growth, just like salts, had a minimal effect on solar reflectance compared to pollutants, but in this case, it is more evident in light colours than dark ones [80]. Parracha et al. [76], in a comprehensive study of the effects of surface roughness and environmental conditions on biological colonisation of white ETICS (with high reflectance), found that the samples became darker with biological growth, indicating a change in reflectance in the visible spectrum; the darker effect was also confirmed by Cheng et al. [75].

4.4 Solar radiation – ultraviolet energy

Shi et al. [83] evaluated high reflectance coatings exposed to an environment of intense UV irradiation, and the chains of the material break down, leading to internal stresses due to chemical structures and surface cracking, a process known as photodegradation [62]. Different types of materials with UV absorption can be used as protective coatings. A parameter used to indicate burning, fouling and degradation by light as photodegradation is the yellowing index defined in [84, 85]. ASTM E313 [86] described that lower yellowness index values indicate less surface chemical degradation by UV exposure [87].

The high reflective coatings doped with mixed oxides such as titanium oxide, black iron oxide, and zinc oxide are characterised by UV protection and better weathering resistance [88, 89]. UV resistance is evaluated by evaluating the spectral reflectance of the samples, with a lower reflectance expected at a wavelength of 400 nm [90].

The effects of photodegradation are correlated with the colour and composition of the coatings. As Zhang et al. [90] and Xu, Xu and Zhang [91] described, white coatings doped with titanium particles alter solar reflectance in accelerated weathering tests but retain spectral reflectance in the ultraviolet region. Tang et al. [73] found that the solar reflectance of roof membranes decreases by 2% to 4% due to natural photodegradation. The authors also show that outdoor UV irradiance is different and less constant than indoor UV irradiance.

Santamouris et al. [92] present results after natural irradiation of roofing materials, demonstrating that acrylic membranes and aluminium sheets show a reduction in reflectance across the spectrum, especially at the shorter wavelengths, indicating photodegradation of the coatings. However, in the same study, the coatings with high reflectance properties retained their original reflectance in the UV and visible spectrum. However, a survey conducted by Diamanti et al. [93] on photoactive mortars showed almost 70% of solar reflectance loss due to natural exposure.

4.5 Summary of the effects of ageing agents on spectral reflectance

The combination of chemical and physical stress with the effect of matter deposition influences the radiation behaviour of hull materials [83]. Annex B of the Europe Organization for Technical Assessment – EOTA [94] contains the degradation factors for assessing building product service life considering three exposure situations (outdoor, indoor and underground). Degradation factors for external envelopes include Solar radiation (UV and thermal effects); depressed temperatures (lower temperature than the normal values of the project); water (liquid, vapour and solid); chemicals (acids, alkalis, de-icing salts, atmospheric composition); compatibility between components, user stress and fatigue, and biological factors (animals, plants, mosses and lichens, fungi, and bacteria).

The most aggressive ageing factors for high-reflectance envelopes are likely to be biological growth, deposition of atmospheric pollutants, e.g. black carbon and soot, and chemical degradation by ultraviolet radiation [22, 68]. Table 4 summarises the scope of the effects of various factors on the reflectance of coatings. However, most of the studies listed focus on the durability of white or light-coloured coatings. More studies are needed on non-white, highly reflective surfaces.

Table 4. Effect of agents on high reflectance envelope coatings.

Ref.	Specimens	Agent	Exposure period	Reflectance loss
Paolini et al. [48]	Extracted roof and wall materials	Soiling mixture	Accel.	-30%
Berdahl, Akbari and Rose [61]	Extracted light-grey roof membranes	Pollutants – soot	18 yrs.	-20%
Wu et al. [72]	Silicate white coatings applied on roof mortars	Pollutants – black carbon	Accel.	-50%
Tang et al. [73]	White roof membrane photocatalytic property	Ultraviolet – photodegradation	22 mos.	-4%
Rosso et al. [95]	Different types of marble used as envelope coating	Acid rain – solution of SO_3 and NO_2	Accel.	-3%
Cheng et al. [75]	Aluminium surfaces coated with white acrylic paint	Microbiological growth – fungal	Accel.	-70%
Mastrapostoli et al. [81]	Extracted white roof membranes	Microbiological growth – bacterial	3 yrs.	-40%
Shirakawa et al. [82]	Corrugated fibre cement tile	Microbiological growth – cyanobacteria + dirt	5 yrs.	-45%
		Microbiological growth – fungal		-20%

The effects of weathering and soiling on the degradation of high reflectance vary, primarily due to the changes in spectral reflectance for different materials, as shown in Fig. 5.

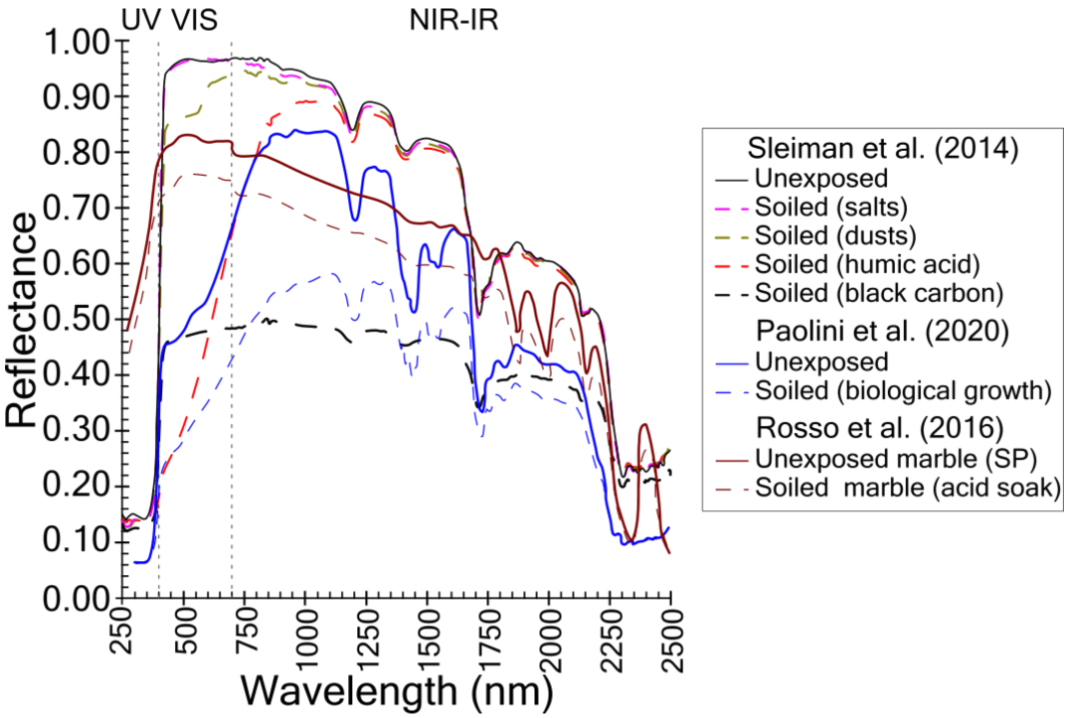

Fig. 5. Effects of soiling agents on the spectral reflectance of roof and façade coatings.

Sleiman et al. [70] investigated the influence of soiling factors, as defined in ASTM D7897 [26], on single-ply white roof membranes. These membranes have a high reflectance in the visible, near infrared and infrared spectra, with most soiling mainly affecting the visible range. On the other hand, Paolini et al. [48] investigated a beige-coloured polyolefin roofing membrane for microbiological growth. In their study, a reduction in reflectance was observed across the spectrum, along with a notable effect on visible reflectance due to colour effects, in contrast to the results of Sleiman et al. [70].

Furthermore, Rosso et al. [95] investigated the durability of Statuario marble cladding for façades under acid exposure. Polished Statuario marble holds a high reflectance, even in the UV range. The degradation behaviour of acid on marble differs significantly from that observed in the roofing membrane studied by Sleiman et al. [70].

The salts do not significantly affect the spectral response, especially for bright surfaces, as the study by Sleiman et al. [70] in Fig. 5. The dust deposition is, in many cases, only a physical weathering affecting the visible range responsible for the colour, with a reduction only between 400 and 700 nm. Furthermore, as shown in Fig. 5, chemical degradation by the wet acid and black carbon shows a change in the entire solar spectrum, especially in the infrared range, in a wavelength interval between 500 nm and 1500 nm [96, 97], and for the acid in the visible-infrared range between 400 nm and 900 nm [70].

The EOTA [94] does not include the change of appearance in the list of reaction once almost all of the degradation agents leads to an aesthetical modification. However, the individual assessment of weathering and pollution factors can lead to varying degrees of deterioration of reflectance of envelopes, as shown in Fig. 5.

Therefore, weathering and soiling can not only affect the appearance but also significantly influence the infrared range in highly reflective coatings, changing the overall reflectance values and, consequently, the durability and thermal behaviour of the envelope.

5 Analysis of the observed degradation of the envelope reflectance

The weathering, mechanical stress, soil depositions and microbiological growth during the service life of buildings will affect the optical and radiative response of the envelope materials and reduce cooling savings. Some authors [69, 97, 98] point out that the differences in solar reflectance behaviour should be better analysed considering the results of accelerated and long-term tests and that a more reliable prediction of reflectance ageing should be proposed considering different materials and tests. In this way, this section provides an overview of aged reflectance and attempts to relate some of the results collected in the systematic review.

Environmental and stress testing attempts to simulate or estimate the effects of meteorological factors on durability by using accelerated methods such as climate chambers [47]. In reliability analysis, predicting failure at different levels of loading is critical. For example, façades show different thermal behaviour at different air temperatures and solar radiation under the same conditions [67, 68].

In situ testing combines two approaches, unlike environmental and stress testing, which is usually conducted in the laboratory under accelerated conditions. The first is the monitoring campaign during the lifetime of the material or building. The second is exposing the material to natural conditions over an extended period to detect failure [99].

The accelerated ageing test considers a limited number of phenomena [31] and can increase a single stress factor [99], such as radiation or temperature. Furthermore, in some cases, it is necessary to supplement accelerated weathering with soiling procedures to bring the simulated conditions closer to the natural stress [66, 70]. On the other hand, natural ageing can guarantee a faithful reproduction of environmental conditions and natural interaction between degradation products. However, the repeatability and reproducibility of natural tests are limited and uncontrolled [80].

Considering the different methods of evaluating the durability and performance of highly reflective materials, it is important to define a benchmark against which the values reported in the literature can be compared. The fractional loss (φ), defined by Eq. 1, was proposed by Sleiman et al. [100] and will be used to compare the performance of the different materials collected in the systematic review.

$$\varphi = \frac{\rho_i - \rho_a}{\rho_i} \tag{1}$$

Eq. 1 considers the initial reflectance (ρ_i) and the aged reflectance (ρ_a). A positive value of fractional loss means a decrease in initial reflectance, and a negative value represents an increase in reflectance. However, more than considering the initial value of the optical properties, it also needs to evaluate the aesthetics of the façade. Namely, the value of fractional loss has different effects on performance considering the colour. If the initial reflectance is lower, as in the case of a dark colour, a negative loss fraction means a drop in optical performance but an improvement in the thermal. In contrast to the light colour, a negative fractional loss represents an improvement in both parameters (optical and thermal).

5.1 Accelerated ageing tests

Accelerated ageing tests induce degradation similar to natural ageing in a short time, trying to avoid the synergistic effects between agents that are incompatible with natural degradation [47]. The accelerated tests could simulate, among other things, the chemical [101], optical [98] or thermal [102, 103] stability of coatings for building envelopes.

Most methods of accelerated ageing result in weathering effects (sunlight, rain and replacement damage) of 60 to 250 hours of ultraviolet exposure, equivalent to 3 months or 1 year [29]. For some materials, exposure of more than 2000 hours does not result in additional damage [94]. However, the short-term effects on highly reflective coatings could be negligible [48] and only partially simulate the conditions for durability assessment [94]. To overcome the negligible results, acceleration factors such as the Arrhenius equation, the Coffin-Manson relationship or the Peck model can be calculated to correlate accelerated and natural ageing [104]. Thus, when UV radiation is combined with high humidity and temperature, 624 hours can simulate 20 years of natural exposure defined by the multifactor model of Eq. 2 [67].

$$AF_{UV+t/RH}=\frac{1}{3}(AF_{T1}\times AF_H)+\frac{2}{3}(AF_{T2}\times AF_{UV}) \quad (2)$$

Where, $AF_{UV+t/RH}$ represents the combined factor for UV, temperature, and humidity, AF_{T1} denotes the temperature acceleration factor, AF_H is the acceleration factor for humidity, AF_{UV} is the UV acceleration factor of the total UV energy throughout the test. And AF_{T2} is the temperature acceleration factor, exclusively during the cycles with only application of temperature and UV radiation factors.

Most envelope coatings suffer from photodegradation [90], so the usual accelerated ageing test for building materials is conducted in climate chambers such as the Quick Ultraviolet (QUV) device [48], the Atlas Solar Simulation [59] or the Q-SUN device [105]. In addition, accelerated ageing techniques could include the evaluation of biocolonization [76, 106], acid attack resistance [95] and evaluation of special coatings such as anti-graffiti polyurethanes [107] and UV treatments [88].

Concerning highly reflective roof coatings, ASTM D7897 [26] presents a procedure for evaluating the effects of air pollutants, microbiological growth, and changes in physical or chemical properties in a 24-hour weathering cycle on the solar reflectance of roofing materials.

The systematic review collected accelerated approach studies to investigate the performance of highly reflective building envelopes. The accelerated results were divided by technique, for QUV devices – standardised procedure ASTM D7897 [26] – and other accelerated ageing approaches.

A total of six studies present results on the deterioration of reflectance of envelope materials [29, 48, 49, 66, 70, 108]. Two focus only on the assessment of colour [107, 109], and one presents the evaluation of colour and reflectance [67] after exposure to the QUV weathering chamber (summarised in Table S2.1 in Supplementary Data). The fractional loss of reflectance was calculated using Eq. 1, considering the initial and aged reflectance for the materials in the QUV test.

Fig. 6 shows the results for 63 samples for the QUV process for different envelope coatings. 84% of the materials evaluated with the QUV method were used on roofs. This result was expected after ASTM D7897 [26] focused on QUV instruments to assess the soiling and weathering of roofing materials. Morini et al. [67] and Paolini et al. [48] have applications for walls and paints that could be used on facades. Also, about 30% have negative values for fractional loss, which means that the aged reflectance is higher than the original value.

The influence of the material properties on the ageing resistance can be analysed based on the fractional loss of reflectivity, Fig. 6a. The flexible roofing membranes [48, 49, 70] show the highest loss with an average of 0.30, while retroreflection (RR) [67] and phase change materials (PCM) [108] demonstrate the lowest values with an average of -0.10 and -0.20, respectively. Furthermore, materials with higher initial reflectance could show higher degradation after ageing and weathering tests, as described by the authors [48, 69, 100].

A closer look at the ageing approach, the studies that consider only UV/rain cycles, namely Morini et al. [67] and Pisello et al. [108], lead to an increase in the aged reflectance (negative value of fractional loss). In contrast, combining UV/humidity with the soiling approach leads to higher values of fractional loss.

Fig. 6b shows the effect of exposure time on QUV with the change in reflectance. It is demonstrable that increasing the exposure time for materials under the same process conditions results in a loss of reflectance. However, to better investigate the exposure time, it is necessary to consider the acceleration factors (Eq. 2) and compare the ageing simulation conditions with the natural equivalent.

This review presents the acceleration factor only in one study [67]. The ageing test given in ASTM D7897 [26] corresponds to four cycles of 12 h, 8h UVA at 0.89 Wm^{-2} and 4h water condensation at 50 ºC as described by Paolini et al. [48] and Sleiman et al. [70]. However, Takebayashi et al. [29] used UVB instead of UVA energy and Pisello et al. [108] used an intensity of 0.77 Wm^{-2} from UVA instead of 0.89 Wm^{-2}.

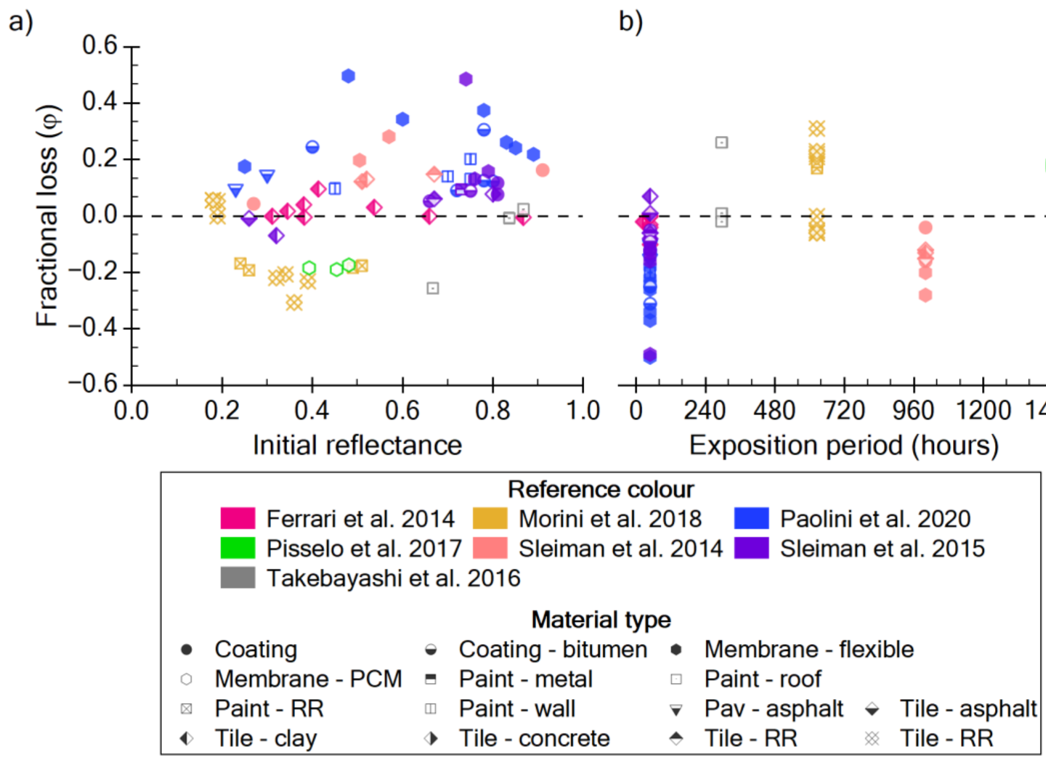

Fig. 6. Evaluation of the aged reflectance with the QUV test. a) Fractional loss compared to the initial reflectance, b) Correlation between reflectance change and exposure time.

According to Morini et al. [67], 26 days of accelerated exposure with an acceleration factor of 280 equals 20 years of natural exposure in Rome. Furthermore, Takebayashi et al. [29] established that 250 hours under QUV with UVB energy is equivalent to one year of natural ageing in Japan. Sleiman et al. [70] estimate that 100 hours under QUV with UVA equals one year of natural exposure in Florida.

The use of Quick-Ultraviolet (QUV) devices for weathering envelope materials can be explained by the effect of ultraviolet radiation on photodegradation, which affects many organic and inorganic coatings in buildings [59, 67]. However, other methods could be used to estimate degrading climatic factors such as pollutants, biological growth, and freezing/thawing.

Considering other weathering methods, such as Atlas and Q-Sun devices, biodegradation, and acid degradation, 18 studies assessing different weathering tests were listed. Three studies use an original method combining humidity, temperature and UV radiation [78, 109, 110], one uses a sunrise test chamber for weathering resistance [31], two use dirt resistance [111, 112], one study investigated microbial [75] and two others acid degradation [95, 113]. The xenon lamp approach is the most commonly used, with six studies using the Q-SUN test chamber [72, 79, 90, 91, 105, 114] and three using the Atlas sun simulator [98, 101, 115].

In contrast to the QUV tests, more studies also assessed colour parameters as a visual-aesthetic criterion for durability loss. Four studies focused only on colour assessment, while five considered colour and reflectance and nine assessed reflectance only. The studies are summarised in Table S2.2 in the Supplementary Data. The fractional loss of reflectance was also calculated considering the other accelerated approaches.

Fig. 7 shows the results for the 78 samples compiled for the 7 different accelerated tests for various envelope coatings. The most tested materials are coatings or paints that can be used as roofs or facades (54%), while application on roofs comes second with 28%. The use of different accelerated methods might be related to the need to evaluate the durability of novel materials such as selective coatings [115] or coatings with special properties such as hydrophobic [105] or self-cleaning coating [79].

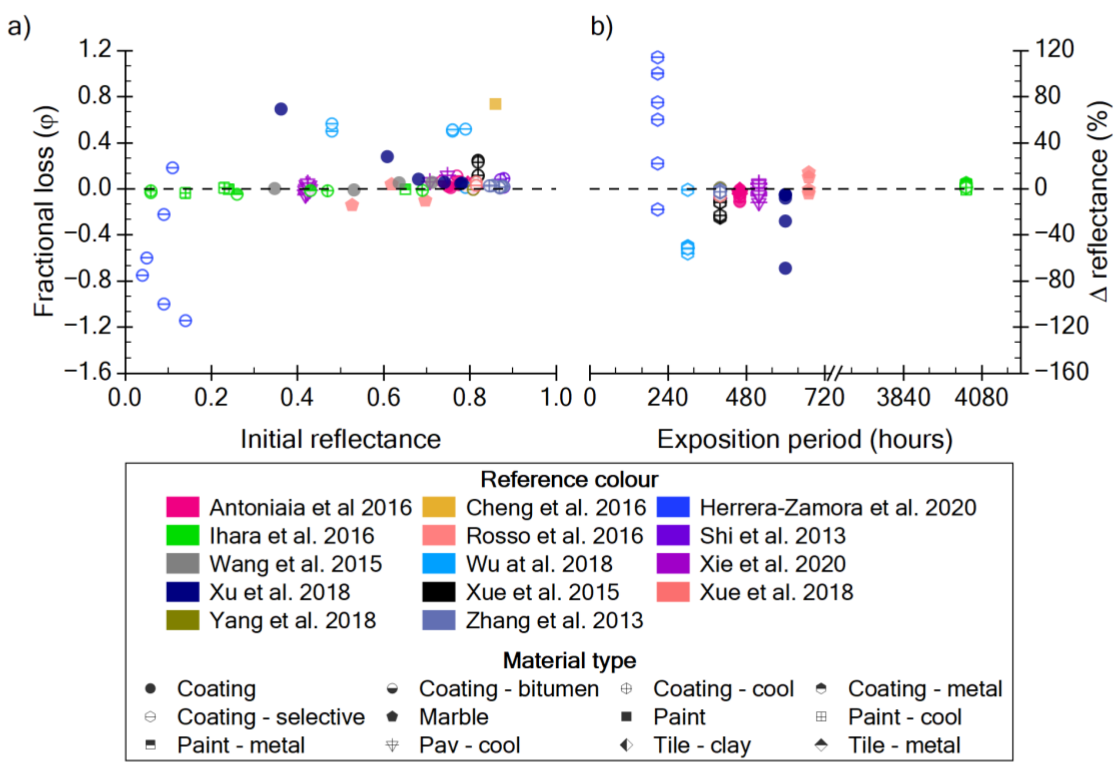

Fig. 7. Evaluation of the aged reflectance with the accelerated tests. a) Fractional loss compared to the initial reflectance, b) Correlation between reflectance change and exposure time.

The ratio between the aged and the original reflectance shows whether there is an increase or decrease in reflectance after the ageing test. Fig. 7a shows the values for the 78 samples, of which about 70% show a lower reflectance after weathering. However, in the same studies as Herrera-Zamora et al. [115] and Rosso et al. [95], black selective coatings increase by an average of 70%, and marble facades show an average increase of 10%. The behaviour of several materials under accelerated tests can be seen in Fig. S2.1 in the Supplementary Data).

In contrast, the study of microbial growth in white coatings for roofs [75] found the most significant decrease in reflectance, with the surface becoming darker and reflectance decreasing by 70% after two months of inoculation.

Analysing Fig. 7b, it is not possible to establish a trend between the exposure time and the fractional loss of reflectance, as the results for the differently accelerated tests (Fig. 7a) are more variable and show higher intensities than the results for the QUV tests (Fig. 6a). Nevertheless, it is possible to check the effect of the different acceleration procedures in Fig. 8.

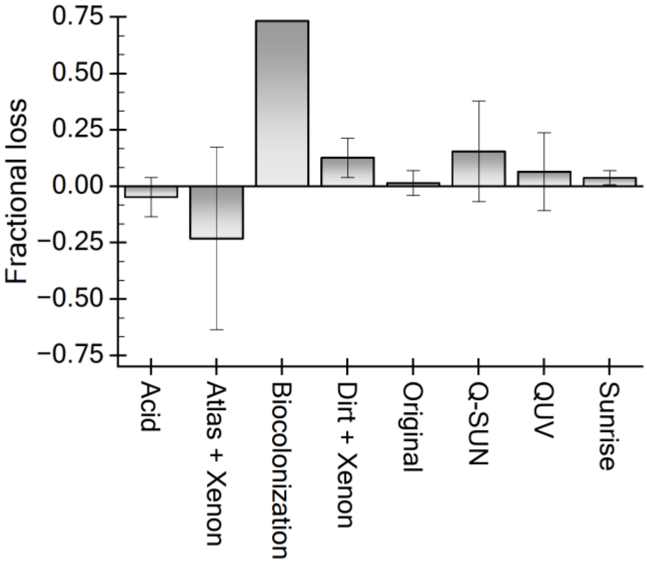

Fig. 8. Assessment of fractional loss in accelerated ageing techniques in the systematic review.

Biocolonization has a more substantial influence on reflection loss due to the physical and chemical decomposition of the surface. In the case studied, the change is on white surfaces with a higher original reflectance [75]. Considering the original methods, Xie et al. [110] evaluate the lower ageing of pavements with titanium oxide; the studied properties could influence the weathering, resulting in a lower reduction of the original reflectance.

Instance Atlas + Xenon has been used for coatings with unique properties, e.g. thermal collectors [115], where an increase in reflectance results in a loss of power, or cool materials with NIR reflectance properties that are less susceptible to variations in the visible/colour range, as in [98].

Consider the results of the accelerated ageing tests collected during the systematic review and listed in Fig. 8. As in the case of the QUV test, few studies give acceleration factors or relate the accelerated exposure time to natural exposure. Fufa et al. [101] state that 1488 hours in the Atlas Solar Simulator corresponds to an exposure time of 9 years. For the method initially proposed by Xie et al. [110], the correlation is 300 hours to 25 years and Wu et al. [72] state that for a Q- SUN with dirty black carbon deposition, the correlation is 300 hours to 80 days.

Performance results from artificial accelerated weathering tests are a valuable additional tool for assessing the durability of materials. However, it should be noted that the test conditions used in these accelerated tests differ from natural exposure conditions [31]. The effect of a pollution mixture in accelerated ageing tests shows more reliable degradation compared to natural exposure, as noted by Sleiman et al. [70] and Paolini et al. [48].

Therefore, the degradation processes observed in accelerated ageing tests may not accurately reflect the failure mechanisms that occur under natural conditions, with no correlation between acceleration factors and natural weathering established in the studies.

5.2 Long-term ageing tests

Long-term tests, also known as natural stress tests, attempt to evaluate materials under real environmental conditions and provide more certainty about degradation factors. However, they are based on a longer exposure time than accelerated tests and depend on the exposition of environmental conditions, such as climate and location (urban or rural environment) [80, 99]. The significance of the information collected increases with the extension of the natural exposure period and the inclusion of a wider range of exposure sites with different environmental conditions [94].

Building environments change with global warming and climate variability [116], affecting the long-term performance of building envelopes. Weather affects façades through radiation, freeze-thaw cycles and humidity, as well as orientation (façade orientation and roof in horizontal direction), reducing the durability of the envelope [117]. The relevant degradation processes in long-term ageing and weathering are solar radiation, temperature, wind, humidity, pollution by pollutants and gases, chemical catalysts such as photodegradation and other mechanical forces [62, 118].

The systematic review collected long-term approaches over reflectance performance under natural exposure. A total of 28 studies were collected, of which three evaluated colour only [76, 87, 109], eight focused on aesthetics of colour and reflectance parameters [6, 82, 93, 96, 119-122], and the other 17 evaluated reflectance [22, 28, 29, 66, 73, 74, 81, 83, 123-126] or reflectance in combination with emittance [31, 48, 69, 127, 128] (Table S2.3 Supplementary Data).

The assessment of natural degradation does not follow a standard procedure, but there is a benchmark that reflects long-term performance. The CRRC and Energy Star® have determined that the threshold is 3 years to evaluate the performance of cool coatings on roofs [83]. After the evaluation period, the fractional loss, according to Eq. 1. is 0.40 for high-slope roofs and 0.23 for low-slope roofs, considering the initial and ageing values of the CRRC [24, 100].

Fig. 9 shows the calculated loss and exposure time for the 487 samples from 25 studies. When considering the applications studied, a higher number of studies were expected to focus on roofs. However, the studies for façade applications correspond to 50%, while roof applications accounted for 48%. Other studies of developing coatings and paving applications sum 5% and 1%, respectively.

Fig. 9a shows the results for the fractional loss of the compiled samples. 95% of the samples show a positive value for the fractional loss of reflectance, indicating a reduction at the end of the exposure period. Compared to the accelerated ageing results, the percentage reflectance loss is higher than accelerated (70% – 147 samples), indicating that some accelerated approaches will not correlate with specific natural ageing conditions for the materials evaluated due to the accelerated factors. For example, the selective coating in the accelerated test by Herrera-Zamora et al. [115] has an average loss of -0.59; in contrast, the natural test by Diamanti et al. [93] has an average loss of 0.72.

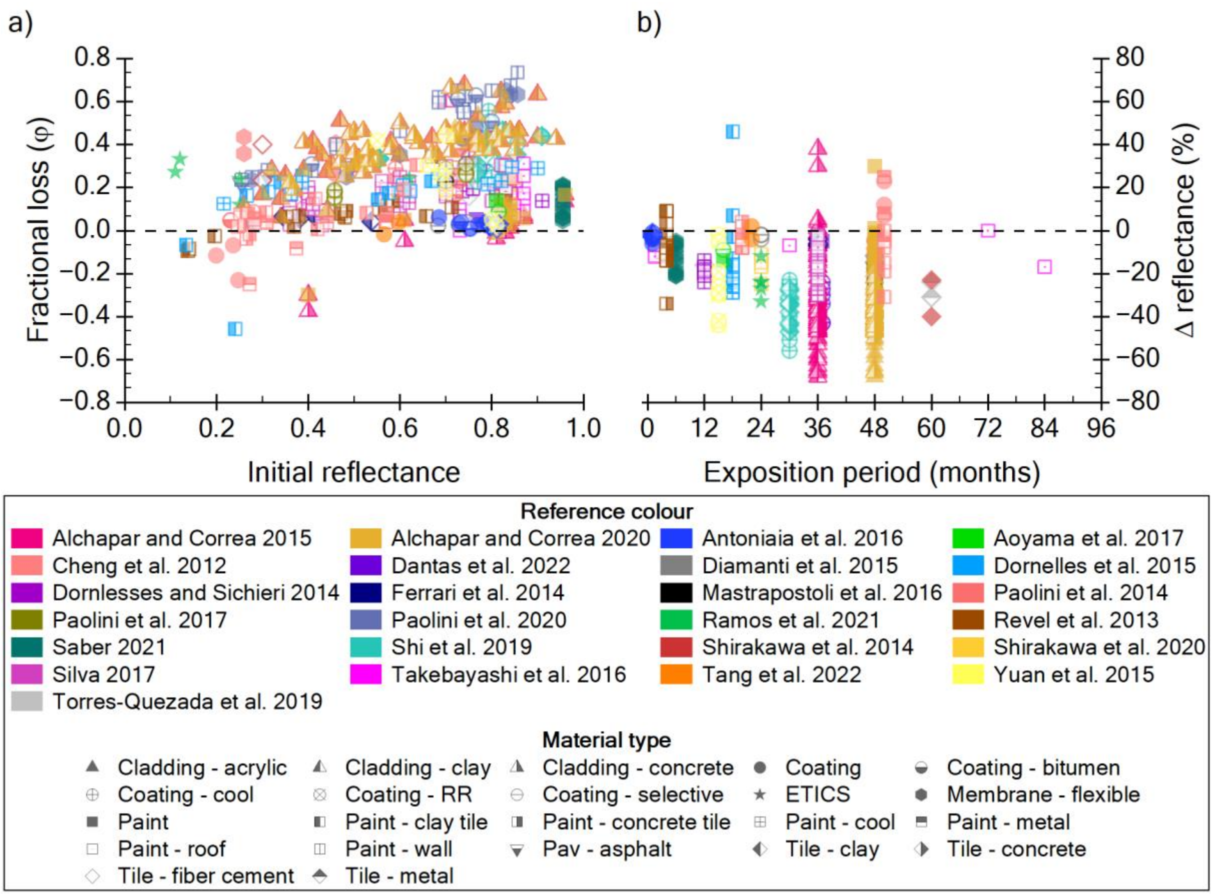

Fig. 9. Evaluation of aged reflectance long-term test. a) Fractional loss compared to initial reflectance, b) Correlation between reflectance loss and exposure time.

Only 25% of the samples in Fig. 9a have a fractional loss above the limit of the CRCC [24], which was calculated as 0.40 (roof with high slope). However, more than 80% of the samples with a loss fraction above 0.40 have an initial reflectance above 0.65 (a value to be considered cool material), confirming the effect of high initial reflectance on the decrease in aged reflectance observed by Sleiman et al. [100].

Considering the exposed environment, some materials with lower initial reflectance could present a higher aged reflectance due to incorporating some pollutants that modify light scattering, such as some salts [62, 74], as observed in the roof coating samples by Cheng et al. [69] for different chemical environmental conditions. Furthermore, the change in reflectance in the NIR range and coatings modification for cool colours could also increase the aged reflectance due to the used oxide [6, 28]. The behaviour of the materials under long-term tests can be seen in Fig. S2.2 in the Supplementary Data.

It is expected that the decrease in albedo during the first months is mainly caused by the pollution of the horizontal surfaces [129], in some cases before reaching the 3 months [71]. Fig. 9b shows that the higher degradation occurs during 36 and 48 hours, ranging from -70% to +40%. Furthermore, the studies for 36 and 48 months of exposure sum up to 60% of all samples. Only 27% of the studies assess reflectance deterioration in less than 36 months and 4% in more than 36 months (CRRC threshold). Nevertheless, a tendency can be identified that the maximum weathering occurs around 50 months after beginning the exposure and achieves rates above 10% after 6 months.

The weathering factors of air temperature, radiation, humidity and dust deposition [50, 80, 126] have different climatic effects on the ageing of reflectivity [59, 62, 94]. Therefore, Fig. 10 shows the reflectance loss from the 25 studies using the Köppen-Geiger climate classification. The most aggressive climate is *Cwa* [83], with a fractional loss of 0.36, while the least aggressive environments are *Csc* [69, 73] and *Dfa* [66], with 0.05. More than 70% of the natural exposure was carried out in the *Cfa* climate, followed by the *Csa* with 12%, while the other climatic zones account for only 15% of the research.

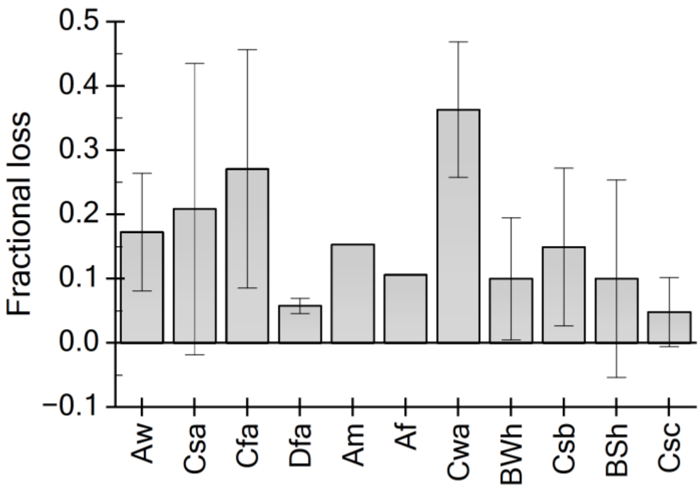

Fig. 10. Distribution of fraction loss considering Köppen-Geiger climate classification of long-term tests.

The *Cwa* have a dry winter with a hot summer, encompassing the 25° and 40° latitudes with high insolation throughout the year, which, combined with the higher air temperature and precipitation in the summer peak, could lead to the most increased reflectance degradation. In addition, the *Cwa* case study of Shi et al. [83] was conducted in two highly populated urban centres, which may generate more pollutants and accelerate the degradation of the used highly reflective roofs.

Although the *Csc* are characterised by a cool, dry summer with cool, wet winters in latitudes between the latitude of 30° and 45°, while the *Dfa* climate is characterised by warm to hot summers, freezing winters, and distributed precipitation over the year, found between 30° and 60° latitudes. Consequently, it exhibits lower radiation and air temperature compared to *Cwa* climates.

This reduced degradation observed in the *Csc* and *Dfa* climate may be attributed to environmental factors and sample characteristics. The unique study on *Dfa*, conducted by Ferrari et al. [66], assessed the weathering performance of coloured tiles with an initial reflectance below 0.50, which is less susceptible to soot-related effects. Therefore, the combination of lower initial reflectance, the cleansing effect of year-round precipitation, and the lower air temperature and radiation could contribute to less degradation in this climate.

In this way, estimating the climate-specific aged reflectance values is essential. The CRRC evaluated various roofing products for *Cfa*, *Dfa* and *BWh* climates, and a partial loss between -15% and +15% has been reported for the same coating type [100]. In the systematic review studies, this effect was lower for the *Dfa* and *BWh* climates.

Moreover, the long-term tests are mainly conducted in temperate climates (C) and reach 90% of the samples considering *Cfa*, *Csa*, *Csb* and *Csc*. This is consistent with the advantages of highly reflective coatings in mild or hot climates [51]. However, in temperate climates, the variations in partial loss between climate subclasses are significant due to the weather factors of air temperature, radiation, and humidity.

The degradation of reflectance in natural tests is predominantly affected by environmental conditions resulting from climate categories, exposure conditions (urban or rural) and exposure duration in combination with the type of coating applied.

5.3 Exploring the degradation trends

Although durability analyses for reflectance are the only measure of aged reflectance performance, they refer to long-term tests and maintain a minimum shelf life of 3 years [130], demonstrating the importance of establishing correlations between accelerated and long-term test results.

The systematic review identified four studies that presented results from both approaches: Ferrari et al. [66], Antonaia et al. [31], Paolini et al. [48] and Takebayashi et al. [29]. Fig. 11 illustrates the correlation between accelerated and natural weathering results.

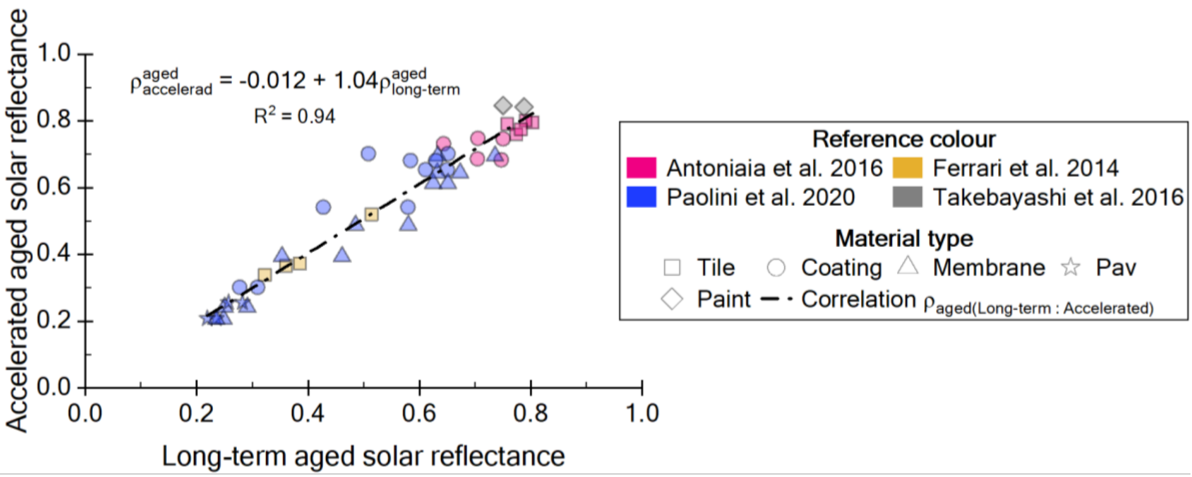

Fig. 11. Correlation of solar reflectance for several materials after natural exposition of an accelerated ageing process.

The excellent correlation in Fig. 11 shows that accelerated tests can effectively simulate long-term effects. For example, Ferrari et al. [66] and Takebayashi et al. [29] used the QUV chamber to compare accelerated results with natural exposure over 48 and 1.5 months, respectively. Meanwhile, Antonaia et al. [31] evaluated using the Sunrise chamber with 1 month of natural degradation. The calculated correlation between aged solar reflectance

($\rho^{aged}_{accelerated}$=1.04±0.047$\rho^{aged}_{long\text{-}term}$-0.01±0.02) is very similar to the results obtained by Paolini et al. [48] and Sleiman et al. [70] for QUV tests.

Moreover, the weathering and ageing factors affect the initial reflectance differently for each used test. In this way, Fig. 12 presents the correlation between the aged and initial reflectance for the accelerated and long-term approach considering systematic review (21 studies for accelerated test – 141 samples – and 25 for long-term evaluation – 487 samples).

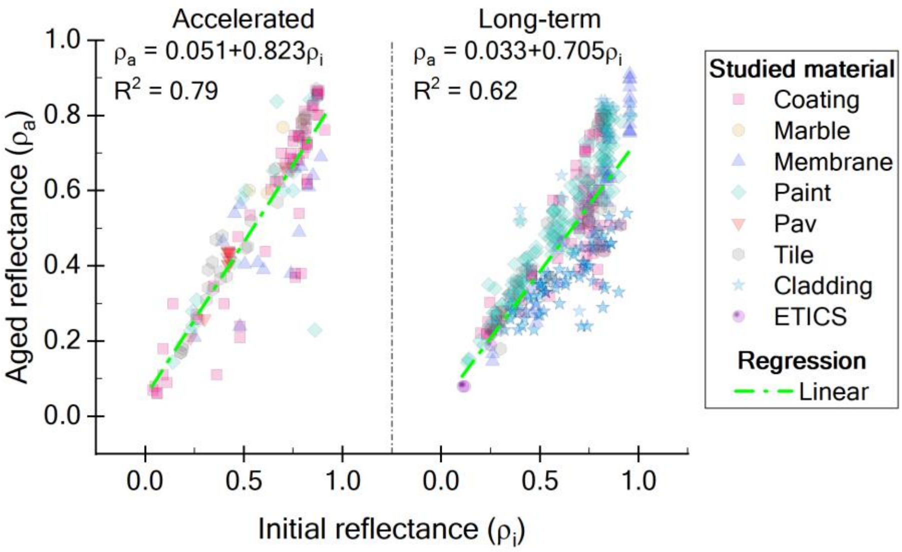

Fig. 12. Regression analysis of aged to initial reflectance in accelerated and long-term tests.

The regression analysis for the CRRC and the Energy Star® programme is defined as ρ_a=0.06+0.7ρ_i after the three years of natural weathering [100] in the systematic review collection the calculated the regression parameters of Fig. 12 are: for accelerated weathering a=0.051±0.023 and b=0.824±0.036; for long-term a=0.033±0.016 and b=0.706±0.025.

Investigating the values of the regression parameters, the "b" indicates the magnitude of the weathering effect at the initial solar reflectance, and the intercept parameter "a" predicts the aged reflectance when the initial reflectance is zero. As expected, the results show a higher "b" value for accelerated tests than natural exposure (Fig. 12). This discrepancy results from a combined effect that does not occur under real conditions. Notably, the "b" parameter almost coincides with the CRRC parameter in long-term tests, which underlines the data quality in the systematic review. In contrast, the intercept values for accelerated and long-term testing (Fig. 12) are lower than the

CRRC value. However, the “a” value for the accelerated results is closer to the CRRC, which could be explained by the fact that more samples of roof coatings were collected in this approach once the “a” value varies by product type [100].

Once the aged reflectance depends on the material type, Sleiman et al. [100] suggest estimating the preliminary aged reflectance using Eq. 3, where the aged reflectance (□a) depends on an opaque soil layer parameter (□) and a pollution resistance parameter (□) ranging from 0 to 1, where 0 means no resistance at all and 1 means complete resistance [27] and on the initial reflectance (□i).

$$\rho_a = \alpha + \beta(\rho_i - \alpha) \quad (3)$$

Fig. 13 shows the soil layer (□) and the pollution resistance parameter (□) for the systematic review of the collected studies for the accelerated and long-term approaches (141 samples for accelerated and 487 samples for long-term). The Building Energy Efficiency Standards – Title 24 of the California Energy Commission assume that □□equals 0.20 and □ equals 0.70 [131].

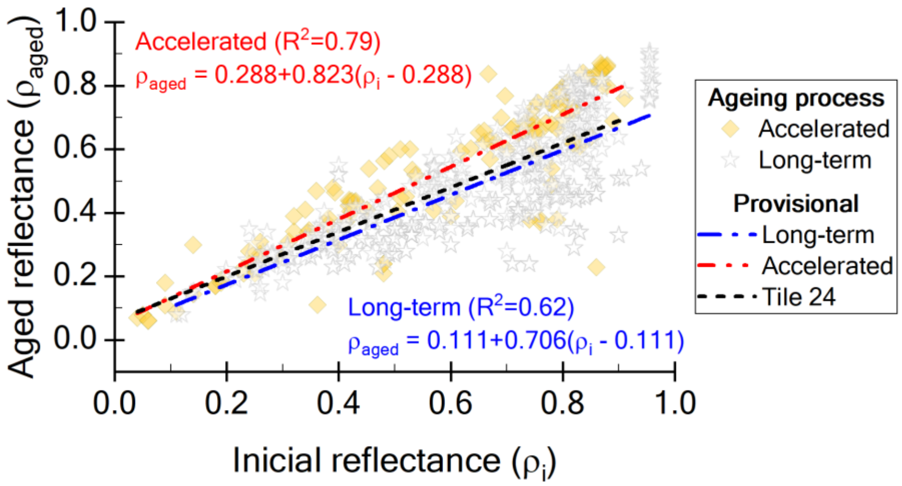

Fig. 13. Prevision aged reflectance for accelerated and long-term gated research and Title 24 equation.

The parameters of Title 24 assume the degradation only by soiling and do not consider properties such as the roughness or the spectral reflectance [100] in the case of the non-white high reflectance materials that have a modification of the reflectance in the near-infrared solar spectrum [132].

The different values of the soil layer (□) over the long-term could be explained by the type of material collected in this approach, e.g., a large number of special coatings with selective cool properties (Fig. S2.2 in the Supplementary Data). Once, the Title 24 parameters only assume degradation due to contamination and do not consider properties such as roughness or spectral reflectance [100] in the case of non-white highly reflective materials that exhibit a change in reflectance in the near-infrared spectrum [132].

In addition, the effect of the pollution resistance parameter (□) is lower in the long-term test than in the accelerated test due to dust exposure, ultraviolet radiation, acid rain, moisture penetration and condensation, and wind and biomass accumulation [81]. Table S2.4 (Supplementary Data) show the soil layer (□□□a and the pollution resistance (□□ parameters calculated for each envelope material and weathering approach, confirming the effects of surface, unique properties and the combined effects of weathering and pollution.

6 Critical interpretations of the systematic review results

Given the observable weathering effects of highly reflective coatings, it is evident that solar reflectance decreases over time due to the influence of weathering and soiling [62] as shown in Table 4. Against this background, the following points deserve critical consideration:

1. The lack of a discernible correlation between the intensity of degradation factors and surface characteristics, especially roughness and texture, warrants further investigation.
2. To better understand the weathering processes, it is imperative to establish a clear link between natural weathering phenomena and the prevailing climatic conditions.
3. Identifying the factors contributing to accelerated degradation in the context of accelerated tests (as explained in equation 2) is an essential area of investigation for correlating different tests.
4. The presentation of results describing changes in appearance compared to spectral reflectance is central to elucidating the underlying ageing mechanisms.

However, ageing tests commonly used to evaluate the durability of different coatings [99] have specific gaps when applied to building envelopes, especially in highly reflective materials [48, 96]. The results of this systematic review highlight several pressing issues that need to be investigated in future research:

1. Formulating an accelerated testing protocol applicable to the full range of accelerated tests remains critical.
2. Establishing a robust correlation between long-term outcomes and accelerated outcomes, an area to which only a limited number of studies – four to be exact – have contributed, requires careful investigation.
3. Developing predictive models for degradation, regardless of the specific type of ageing, is proving to be a critical undertaking.
4. Establishing a defined threshold for aged reflectance, with particular attention to its impact on thermal performance assessment, deserves our special attention.

Therefore, a methodology for characterising highly reflective coatings for envelopes was developed to fill many of the gaps found in the research. Fig. 14 shows the proposed methodology flowchart, considering the found gaps and some references from [EOTA [94] and [133].

The first phase, referred to as "Preparation", involves the preliminary identification of materials to be investigated and an assessment of previous research efforts in terms of their durability and performance characteristics. This phase is preceded by an initial investigation of the building envelope and its external properties, aiming to acquire the existing knowledge of ageing results and define the parameters and scope of the ageing methods to be applied.

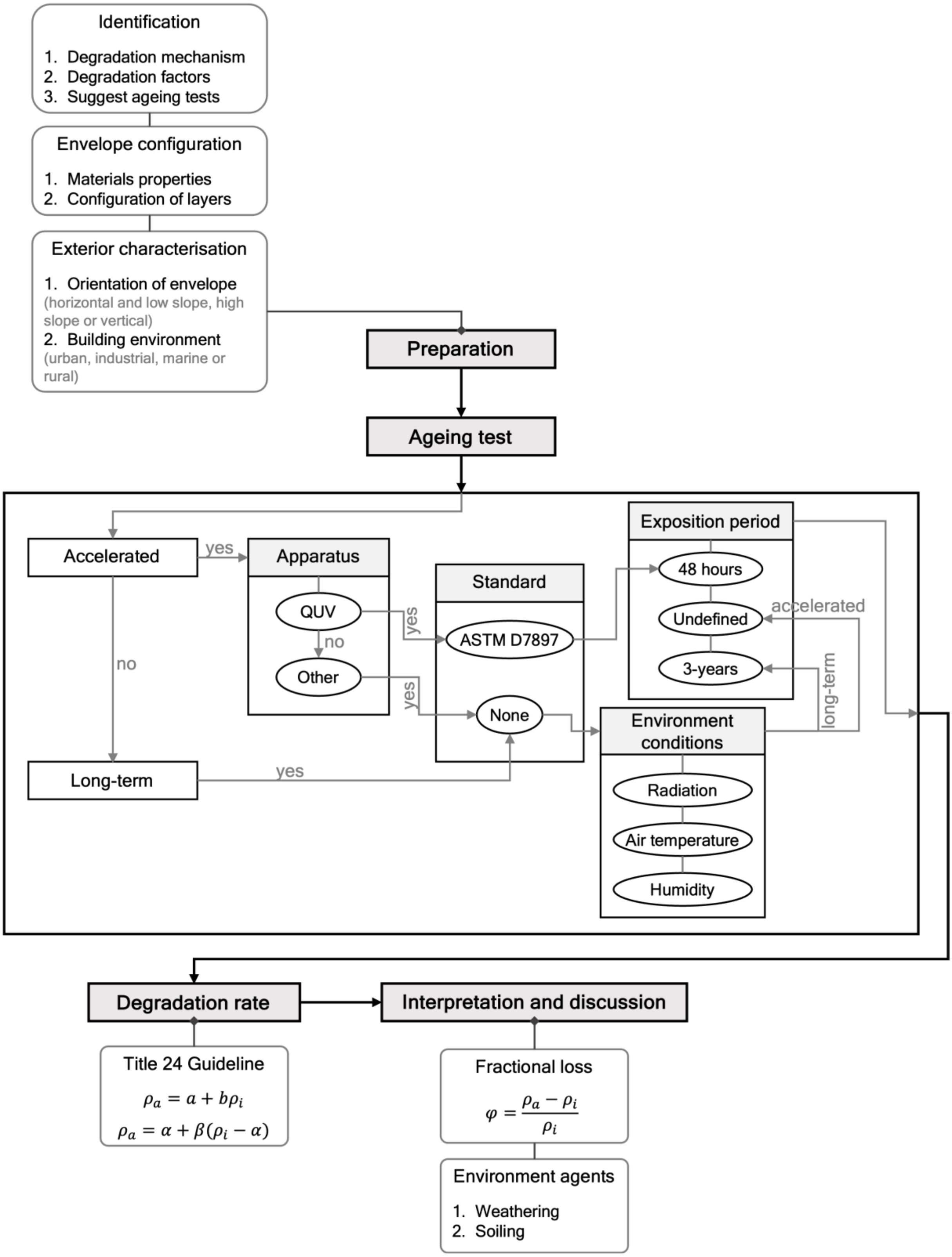

Fig. 14. Proposed flowchart for the combined qualitative and quantitative assessment of the reflectance behaviour of highly reflective envelopes, considering the gaps found.

The second phase comprises the actual "Ageing tests", with options including both accelerated and long-term (natural) exposure protocols. In this phase, an internal flowchart is created to guide the selection of appropriate equipment, standards and procedures based on the findings from the research reviewed. In particular, it must be emphasised that there is currently no standardised weathering procedure for natural weathering. The only guideline is the 3-year limit set by the Cool Roof Rating Council (CRRC) [23, 24]. In addition, the exterior characterisation performed during the preparation phase serves as a crucial reference point for understanding the results, as the orientation of weathering can significantly affect the extent of reflective deterioration, as highlighted in existing studies [48, 83, 93].

Subsequently, in both the long-term and accelerated testing phases (except QUV-based testing), it is essential to document the prevailing environmental conditions and the specific factors introduced during testing. This information is critical as variations in the applied stress levels can lead to different results, even for materials of the same type.

In the third step of this methodology, the "Degradation rate" is calculated by the degradation model (Eq. 3) for each test and material, with particular attention to parameters such as soil layer (α) and pollution resistance (β). This step serves the dual purpose of facilitating a correlation between natural and accelerated results and providing a comprehensive assessment of fractional loss at the end of the exposure period. Then, in the last step, "Interpretation and discussion" can be correlated with the existing literature and provide information on the influences of weathering and soiling on the materials studied.

In this way, an integrated (qualitative and quantitative) assessment of the ageing behaviour of the highly reflective envelope can provide information for building maintenance planning and life cycle analysis databases, helping to evaluate the benefits of the highly reflective envelope in different scenarios, considering the climatic change.

7 Conclusions

The current need for adaptable buildings for resilient cities and climate change is met by adapting thermal envelopes to reduce energy consumption and thus carbon footprint in the use phase of buildings and increase durability. Despite the considerable efforts made over the last decade to improve our understanding of the behaviour and development of highly reflective coatings, a comprehensive systematic literature review has underscored specific challenges and defined targets for future research efforts related to the effectiveness of highly reflective materials in building envelopes. Consequently, this meta-analysis has provided a basis for describing research perspectives in several dimensions, including considerations of sustainability, evaluation of weathering and ageing factors, and prediction of reflectance degradation.

This study contributes to the development of a database for the durability and maintenance of highly reflective materials used in opaque envelope systems to provide decision support for the selection of envelope materials that address the need for resilient buildings and focus on strategies to mitigate climate change and reduce the environmental impact of buildings.

Thus far, despite the guidelines and approaches of various organisations, there is no standardised procedure to define the durability of highly reflective envelope systems. No standardised values have been found that represent the end-of-life of HR coatings. According to the review, the effects of weathering have a different weight on deterioration due to the ageing protocol used (accelerated or natural weathering) and the actual results of climatic conditions.

Nevertheless, the prediction model used by the California Energy Commission could be applied to the studies examined here, regardless of the ageing protocol, but with different deterioration coefficients.

The reviewing process shows that weather conditions strongly influence the materials used in highly reflective envelopes. In this way, the indication of the degradation mechanisms and loss of reflectance can help in the future formulation of maintenance programmes. Therefore, the deposition of pollutants can affect the reflectance in several stages, reducing the contribution of the high-reflectance materials on the energy efficiency of buildings.

The proposed methodology provides a holistic and systematic approach to assessing the reflective resistance of highly reflective building envelopes. By filling the gaps identified in the systematic review and drawing on relevant references, this methodology provides a structured framework for researchers and practitioners to conduct comprehensive assessments, bridging the gap between natural and accelerated test methods while providing valuable insights into the ageing behaviour of highly reflective coatings in real building envelope applications.

Highly reflective materials have received recognition for their potential to mitigate the urban heat island effect, improving energy efficiency and increasing thermal comfort in buildings. However, based on the results of our systematic review, it is noteworthy that most research studies have focused on white-painted roofs in arid and hot climates. Hence, we propose the following avenues for future research, as delineated in the cluster of Fig. 4:

1. Expand the applicability and assess the durability of highly reflective coatings under different climatic conditions, focusing on temperate regions characterised by cold summers, considering the influences of ongoing climate change.
2. Research the impact of employing coatings with darker colours in terms of effectiveness in mitigating greenhouse gas emissions during the building life.
3. Explore the impact of global warming on the longevity of highly reflective materials and identify the effect of reflectance degradation on energy consumption and thermal comfort in buildings.
4. Investigate the possibility of using highly reflective coatings as retrofits in sustainable urban development, focusing on addressing the urban heat island phenomenon.
5. Carry out a comprehensive investigation of the impact of deterioration of highly reflective coatings in the context of life cycle analysis.

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Supplementary Data

Bibliometric results

The authors applied the Pareto principle to select the period covering more than 20% of the total publications, as seen in the area in Fig. S1.1a. Furthermore, Fig. S1.1b shows the distribution of the 59 selected papers.

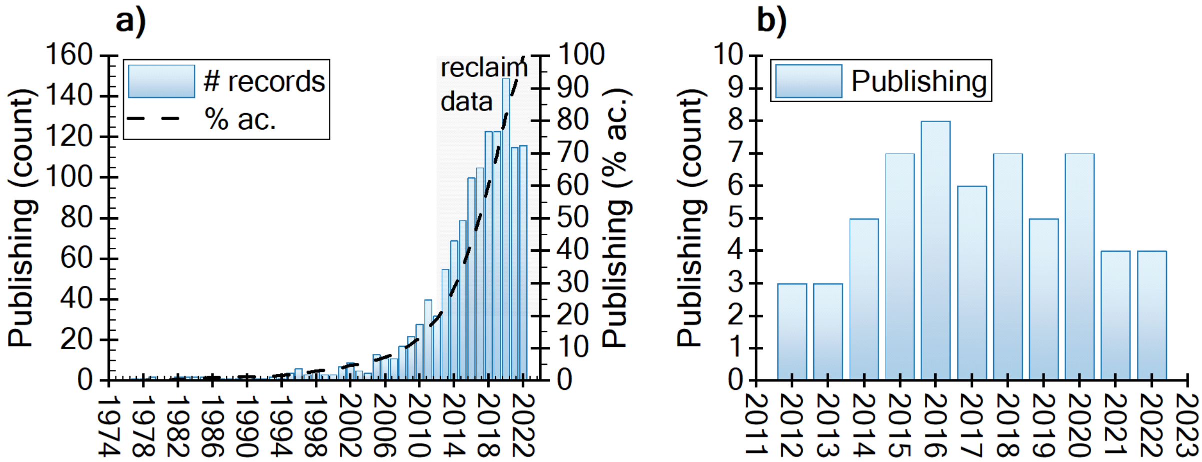

Fig. S1.1. Chronological distribution of the durability studies. a) Identification of the data sets according to the Pareto principle, b) Distribution of the included works.

Approximately 90% of the records were excluded at the screening stage (Fig. S1.2a) and about 60% at the full reading stage (Fig. S1.2b).

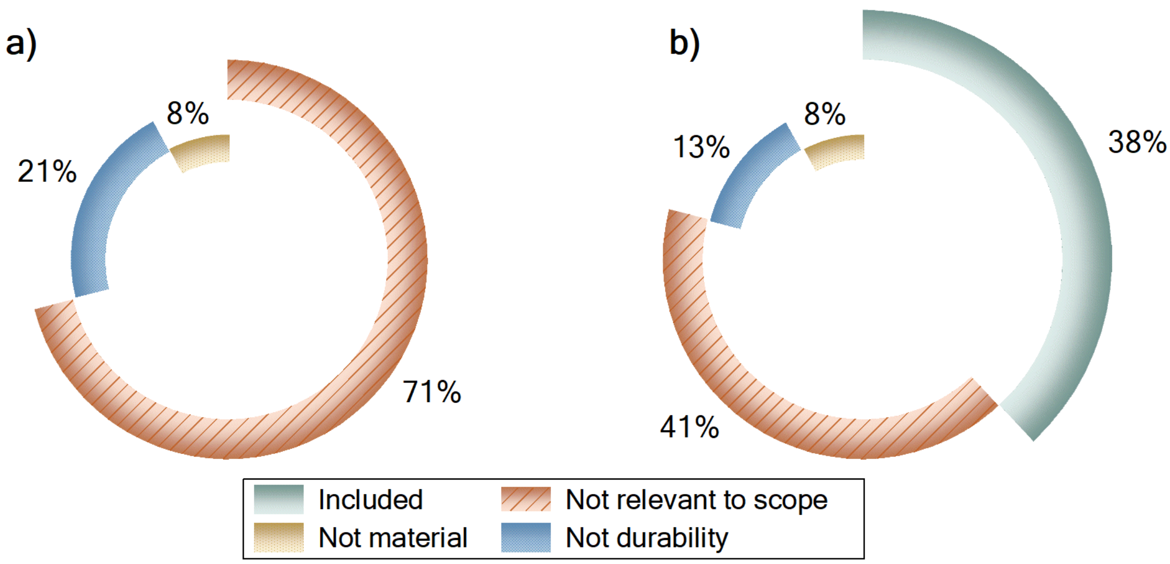

Fig. S1.2. Exclusion reasons. a) Screening by abstract, b) Inclusion by full reading.

Reflectance loss

Tables of quantitative studies are listed in Section 4.

Table S2.1. Accelerated ageing studies for QUV procedure.

Reference	Cases	Accelerated test		Optical evaluation	Main findings
		QUV Procedure	Time (h)		
Rabea, Mirabedini and Mohseni [111]	PU coatings with anti-graffiti property	UV/humidity cycles	864	Colour by colorimeter scan (CIELab)	A reduction of 35% in the lightness resulted in a total colour difference higher than 25. A reduction of the colour difference in samples with anti-graffiti coatings
Sáez-Pérez, Rodríguez-Gordillo and Durán-Suárez [113]	Use of titanium oxide and zinc oxide as paint coating for heritage and architectonic interventions	UV cycles	500	Colour by spectrophotometer (CIELab)	The incorporation of Zinc leads to a lower absolute variation in the lightness of the sample (-1.2) in comparison to the Titanium (-3.1)
Morini et al. [71]	Retro-reflective coatings, light paints, and coloured tiles for cool roof application	UV/rain cycles	624	Colour by spectrophotometer (CIELab) Reflectance by ASTM E903	Reflectance increments on light colour of 18% and reduction of 5% on dark titles. Most samples became darker, and the total colour variation average 4
Pisello et al. [112]	White membranes with PCM property	UV/rain cycles	1440	Colour by spectrophotometer (CIELab) Reflectance by ASTM E903	An increase of 15% in the reflectance for the NIR region
Takebayashi et al. [29]	High reflectance white roof paints	UV/humidity cycles and black carbon deposition	296	Reflectance by JIS K 5602	The results with QUV do not affect the reflectance, but the dirt deposition reduces the reflectance and promotes chalking.
Paolini et al. [48]	Several envelope coatings, such as roof membranes and wall paints	UV/humidity and soiling mixture through spray	48	Infrared emittance ASTM C1371 Reflectance by ASTM E903	Reduction of 21% after accelerated tests. A good fit between reflectance loos for 3 years and the accelerated findings
Ferrari et al. [70]	Clay roof tiles in several colours (organic and inorganic)	UV/humidity and soiling mixture through spray	48	Spectral reflectance by ASTM E903	An average loss of 2%, a higher reduction in inorganic coatings after the accelerated ageing
Sleiman et al. [74]	Coloured coatings for roof	UV/humidity and soiling mixture through spray	1000	Reflectance by ASTM C1549 Spectral reflectance by ASTM E903	Average loss of 15%. Good correlation between the reflectance loss for 3 years and the accelerated
Sleiman et al. [49]	Several envelope coatings	UV/humidity and soiling mixture through spray	48	Reflectance by ASTM C1549	The mean reflectance loss was 11%. All coatings with initial reflectance lower than 0.4 show an increment in the reflectance after the weathering

Table S2.2. Accelerated ageing studies for several experimental procedures.

Reference	Cases	Accelerated test		Optical evaluation	Main findings
		Procedure	Time (h)		
Parracha et al. [82]	ETICS systems	Original method combining heating/UV radiation/pollutants	720	Colour by spectrophotometer (CIELab)	All samples became lighter after the ageing test, an average of 6%. The total colour difference was higher than 3
Sáez-Pérez, Rodríguez-Gordillo and Durán-Suárez [113]	Use of titanium oxide and zinc oxide as paint coating for heritage and architectonic interventions	Original method for infrared heating and water ageing	50	Colour by spectrophotometer (CIELab)	The incorporation of Zinc leads to a lower absolute variation in the lightness of the sample (-4.5) compared to the Titanium (-5.6). And the infrared method is more aggressive than the QUV UV test
Rosso et al. [117]	Cool marble samples for envelope	Accelerated degradation by acid	168	Lightness quantification based on greyscale image grey	Average loss of 20% in the lightness. The degradation rate depends on the acid type and the surface property of the marble (i.e., polish or not polish)
Fufa et al. [105]	Paint for photodegradation treatment	Atlas solar simulator MHG lamp and water spraying	1488	Colour by colourimeter (CIELab)	The samples became darker, with a total colour difference higher than 15
Xie et al. [114]	Cool pavement coatings with anti-ageing additives (TiO_2 particles)	Original method combining weathering factors of humidity, temperature, and UV radiation	518.7	Colour by spectrophotometer (CIELab) Reflectance by ASTM E903	Loss of reflectance is higher on white coatings (7%) than on the cool coloured (< 1%)
Wu et al. [76]	Building envelope mortars with photocatalytic coatings	Q-SUN xenon weathering chamber and deposition of black carbon on the surface	300	Colour by spectrophotometer (CIELab) Reflectance by ASTM C1549	Reflectance loss of 34% in the accelerated chamber and 53% with the black carbon deposition
Xue et al. [109]	Superhydrophobic self-cleaning cool coloured paint coating	Q-SUN xenon weathering test and roughening treatment	400	Reflectance by ASTM E903	An average variation of 4%, mainly in the UV region. The roughening treatment reduces the weathering effect of samples
Wang et al. [118]	Cool coatings doped with TiO_2	Q-SUN xenon weathering test	400	Reflectance by ASTM E903	The light coatings have a mean loss of 3% in the total reflectance. The use of a mixed phase of TiO2 helps to keep the reflectance during ageing, mainly in the UV region
Yang et al. [83]	Self-cleaning cool coloured paint coating	Q-SUN xenon weathering test	400	Reflectance by ASTM E903	A minimum positive change in the reflectance due to the effect in the UV region

Table S2.2 (continued).

Reference	Cases	Accelerated test		Optical evaluation	Main findings
		Procedure	Time (h)		
Xu, Xu and Zhang [95]	Use of TiO_2 to modify the PVC coatings	Q-SUN xenon weathering test	600	Colour by spectrophotometer (CIELab) Reflectance by ASTM E903	The incorporation of titanium reduces the effect of UV degradation from 60% to 10%
Zhang et al. [94]	Development of cool white coating	Q-SUN xenon weathering test	400	Reflectance by ASTM E903	The reduction in reflectance was around 0.03 in absolute values, corresponding to an average loss of 2%
Herrera-Zamora et al. [119]	Selective coatings based on black cobalt	Atlas solar simulator with Xenon lamps and water spraying	208	Reflectance by ASTM E903	Increase of 60% on black coatings after weathering
Ihara et al. [102]	Façades treated aluminium alloy	Atlas solar simulator with water exposure in an original method	4032	Reflectance by ASTM E903 Colour by colourimeter (CIELab) Emittance by spectrophotometer	Lower degradation degree in light colour (<2%), all samples became darker
Cheng et al. [79]	White acrylic coating for roofs	Application of microbial mixture	1440	Reflectance by ASTM C1549	After two months of inoculation, the sample became much darker, losing 70% of the reflectance value
Rosso et al. [99]	Cool marble samples for envelope	Accelerated degradation by acid	672	Colour by spectrophotometer (CIELab) Reflectance by ASTM E903	The reflectance increases for non-polish surfaces (12%) while it decreases for polished ones (2%). All samples became dark with the degradation
Shi et al. [115]	White cool coatings for envelopes based on acrylic emulsion	Dirt resistance with weathering by Xenon Lamp	400	Reflectance by ASTM E903	The reflectance of white coatings reduced by 8% after the exposure to the dirt ageing test, where the weathering corresponds to 1% in the reflectance loss
Xue et al. [116]	Cool white waterproof treatments for roofs	Dirt resistance and accelerated weathering by Xenon lamps	400	Reflectance by ASTM E903	Reduction of 11% in the reflectance after weathering and 24% after dirt test
Antonaia et al. [31]	White automotive paints for cool roofs over several substrates	Sunrise - weather resistance test chamber	460	Emittance by spectrophotometer Reflectance by ASTM E903	Average reduction of 2% in the reflectance. Not a significative variation in the emittance. The used substrate affects the durability. The higher reduction was in the bitumen membranes and the lowest in the aluminium sheet

Table S2.3. Long-term (natural) ageing studies.

Reference	Cases	Long-term conditions				Optical evaluation	Main findings
		Period (months)	Sample orientation/Location	Köppen-Geiger climate	Ambient parameters		
Ramos et al. [91]	NIR high reflectance-coloured coatings for ETICS	24	Horizontal exposition facing South orientation at Porto (Portugal)	Csb	Air temperature, Global horizontal solar radiation, Precipitation, Relative humidity	Colour by spectrophotometer (CIELab)	The average loss was 6% in the lightness. NIR coatings reduce the weathering effect over the lightness of dark colours.
Parracha et al. [80]	ETICS system	48	High slope (45º) facing South in Lisbon (Portugal)	Csa	Air temperature, Precipitation Solar radiation.	Lightness and gloss by ASTM D524 and ASTM D2244	The samples became darker (5%) with the rise of biocolonization. The effects are dependent on the type of insulation and finishing coat
Sáez-Pérez, Rodríguez-Gordillo and Durán-Suárez [113]	Use of titanium oxide and zinc oxide as paint coating for heritage and architectonic interventions	12	Controlled conditions	-	Air temperature (18 ± 2 ºC), Illuminance (50 lux) Relative humidity (50 ± 5%),	Colour by spectrophotometer (CIELab)	The incorporation of Zinc leads to a lower absolute variation in the lightness of the sample (0.1) in comparison to the Titanium (-1.9). The natural exposition is the least harmful procedure
Antonaia et al. [31]	White automotive paints for cool roofs over several substrates	1	Horizontal exposition at Napoli (Italy)	Csa	Air temperature, Global, horizontal, and south vertical solar radiation, Precipitation, Wind speed and direction, Relative humid	Emittance by spectrophotometer Reflectance by ASTM E903	Average reduction of 3% in the reflectance. The used substrate affected the durability. The higher reduction was in the PVC membranes (4%)
Dantas, Vittorino and Loh [78]	Evaluation of white mortars with TiO_2 incorporation	37	Slow slope (33°) facing Northwest at São Paulo (Brazil)	Cfa	Air temperature, Horizontal solar irradiance	Reflectance by ASTM E1918	Average reduction of 30% in reflectance. The paint samples have a higher loss in comparison to the mortar incorporated TiO_2
Revel et al. [6]	Cool paint for roof tiles with NIR reflectance	4	Slow slope (5º) at Ancona (Italy)	Cfa	Air Temperature, Global solar radiation, Relative Humidity	Colour by spectrophotometer Reflectance by ASTM E903	Reduction of 7% of samples. The soiling effect depends on the initial solar reflectance value and the soiling/weathering conditions
Saber [130]	Reflective coating material (RCM) for cool roofs	6	Horizontal exposition at Jubail (Saudi Arabia)	BWh	-	Reflectance by ASTM E903	Average loss of 13%. The Cleaning process can restore the reflectance

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Table S2.3 (continued).

Reference	Cases	Long-term conditions				Optical evaluation	Main findings
		Period (months)	Sample orientation/Location	Köppen-Geiger climate	Ambient parameters		
Dornelles and Sichieri [129]	High reflective white paints for roofs	12	Slow slope (8º) facing North at São Carlos (Brazil)	Cfa	-	Reflectance by ASTM E903	Reduction of 19% in the reflectance. With modification in the VIS and NIR region, due to the roughness and dust deposition
Yuan, Farnham and Emura [128]	Retroreflective coatings for envelope	15	Slow slope (7º) facing South at Osaka (Japan)	Cfa	Air temperature, Global, diffuse, and direct irradiance, Relative humidity, Wind velocity	Reflectance by spectrophotometer	Average reduction of 25%. The hight reflective coatings (35%) have a higher degradation than the retro reflective (11%)
Aoyama et al. [127]	High reflectance white coating with self-cleaning property	16	Slow slope facing North at Kobe (Japan)	Cfa	Air temperature, Precipitation, Relative humidity, Solar radiation	Reflectance by ASTM E1918	Average reduction of 12%. Loos of 8% self-cleaning against 14% of standard roof. Good indication of self-cleaning property. Indication of energy savings depends on the climatic conditions
Dornelles, Caram and Sichieri [28]	Cool paints for clay tile	18	Slow slope (8º) at São Carlos (Brazil)	Cfa	Air temperature, Global solar radiation, Precipitation, Relative humidity	Reflectance by ASTM E903	Average reduction of 15%. Higher reduction on cool paints. The soiling is more significant for coatings with light colours. Reductions in the VIS and NIR region
Tang et al. [77]	White roof coatings with photocatalytic and self-cleaning properties	22	High slope (45º) facing South at San Francisco (USA)	Csc	Air temperature, Precipitation, Global Irradiance,	Reflectance by ASTM C1549	Insignificant reflectance modification (1%). Good indication of self-cleaning 0 Property
Diamanti et al. [97]	High reflective reinforced mortar to the roof with photoactive property	24	Vertical, horizontal, high slope (45º) facing North and South at Milano (Italy)	Cfa	-	Colour by spectrophotometer (CIELab) Reflectance by ISO 9050	Average loss of 3%. Higher reduction in horizontal position than the vertical

.2

Table S2.3 (continued).

Reference	Cases	Long-term conditions: Period (months)	Sample orientation/Location	Köppen-Geiger climate	Ambient parameters	Optical evaluation	Main findings
Shirakawa et al. [100]	Cool paints for roofs	24	Horizontal exposition facing North at São Paulo (Brazil), Pirassununga (Brazil), Belém (Brazil) and São Sebastiao (Brazil)	Cfa/Aw/Am/Af	Air temperature, Global solar radiation, Precipitation, Relative humidity	Colour by spectrophotometer (CIELab) Infrared emittance ASTM C1371 Reflectance by ASTM C1549 Spectral reflectance by ASTM E903	An average reduction of 17% in the reflectance. Reduction of lightness. Modification of the surface roughness and development of biocolonization
Ramos et al. [123]	NIR high reflectance-coloured coatings for ETICS	24	Horizontal exposition facing South orientation at Porto (Portugal)	Csb	Air temperature, Global horizontal solar radiation, Precipitation, Relative humidity	Colour by spectrophotometer (CIELab) Reflectance by ASTM E1918 Spectral reflectance by ASTM E903	Reduction of 24% in the reflectance. The NIR reflectance coating led to a lower reduction (18%) against 30% of the regular coating. The dark samples became lighter with weathering
Shi et al. [87]	High reflectance and light coatings for roof	30	Slow slope (2º) and high slope (20º) facing South at Xiamen (China) and Chengdu (China)	Cfa/Cwa	Air quality, Air temperature, Precipitation, Relative humidity, Wind velocity	Infrared emittance ASTM C1371 Reflectance by ASTM C1549 Spectral reflectance by ASTM E903	An average loss of 36% on the reflectance. A stabilisation of the degradation after 2 years, the effect of the weather conditions
Alchapar and Correa [132]	Several envelope coatings material (claddings and paints)	36	Horizontal exposition at Mendoza (Argentina)	Cfa	Air temperature, Relative humidity, Solar radiation, Wind speed	Emittance by ASTM E1933 Reflectance by ASTM E1918 Solar reflectance index (SRI) by ASTM E1980	An average reduction of 30% in the reflectance. SRI is influenced by material composition and surface finish. The behaviour of the colours depends on the texture and finish
Ferrari et al. [70]	Clay roof tiles in several colours (organic and inorganic)	36	Horizontal exposition in Arizona (USA)	Dfa	-	Reflectance by ASTM C1549 Spectral reflectance by ASTM E903	Reduction of 6% due to natural ageing. Need for evaluation of the morphology of the samples. Good correlation with the accelerated test and cleaning process

Table S2.3 (continued).

Reference	Cases	Long-term conditions: Period (months)	Sample orientation/Location	Köppen-Geiger climate	Ambient parameters	Optical evaluation	Main findings
Silva [124]	Cool paints for tiles	36	High slope (45º) facing North at São Paulo (Brazil), Pirassununga (Brazil) and Ubatuba (Brazil)	Cfa/Aw/Cfa	Air temperature, Global solar irradiation, Relative humidity, Wind velocity	Colour (CIELab) by ASTM D2244 Reflectance by ASTM C1549 Solar reflectance index (SRI) by ASTM E1980	An average loss of 16% in the reflectance. The reflectance loss for the cool paints is similar to the standard.
Paolini et al. [22]	Several types of roof membranes	48	Slow slope facing South at Roma (Italy) and Milano (Italy)	Csa/Cfa	Air temperature, Atmospheric pressure, Global solar radiation, Precipitation Relative humidity, Wind speed and direction	Reflectance by ASTM E903	Average reduction of 23%. Influence of the inclination and surface composition. Modification in the VIS and NIR region due to pollution
Paolini et al. [48]	Several envelope coatings, such as roof membranes and wall paints	48	High slope (30%) facing North and South, slow slope (1.5%) facing South and Vertical platform at Rome (Italy) and Milano (Italy)	Csa/Cfa	-	Infrared emittance ASTM C1371 Reflectance by ASTM E903	Average reduction of 15% for walls and 23% for roof coatings. Effect of the weather anomalies on the results. Good correlation between accelerated and natural ageing
Paolini et al. [125]	Two façade coatings with and without self-cleaning	48	Vertical platform (south and north) with and without shelter in Milan	Cfa	Air temperature, Wind speed, Rainfall	Colour by spectrophotometer (CIELab) Infrared emittance ASTM C1371 Reflectance by ASTM E903	Decrease almost 25% of white coating No change in the emittance Samples became darker, mainly the white colour
Mastrapostoli et al. [85]	High reflectance white roof coatings	48	Horizontal real case at Athens (Greece)	Csa	-	Reflectance by ASTM C1549	Reduction around 25%. The outdoor pollutants reduce the reflectance of roofs. The ageing impacts the cooling and heating loads

Table S2.3 (continued).

Reference	Cases	Long-term conditions				Optical evaluation	Main findings
		Period (months)	Sample orientation/Location	Köppen-Geiger climate	Ambient parameters		
Alchapar and Correa [126]	Several coatings materials for the façade (claddings and paints)	48	Horizontal exposition at Mendoza (Argentina)	Cfa	Air temperature, Relative humidity, Solar radiation, Wind speed	Colour (RGB colour) Infrared emittance ASTM E1933 Reflectance by albedometer Solar reflectance index (SRI) by ASTM E1980	Reduction of around 30% in the reflectance. Decrease of 4% on paint and 40% on cladding samples. The weathering effect depends on the coating morphology
Cheng et al. [73]	Painted roof products (metal, clay, and concrete tiles)	20 - 50	Slow and high slope (9.5º, 18.4º and 33.7º) facing North at El Centro (USA), Corona (USA), Colton (SA), Shafter (USA), Richmond (USA), Sacramento (USA) and McArthur (USA)	BWh/Csa/Csa BSh/Csc/ Csa/Csb	-	Infrared emittance ASTM C1371 Reflectance by ASTM E903	Reduce average of 2%. The reflectance loss depends on the climate and location. Also, the loss is cyclic due to the rainfall seasons. The slope affects the light colours, and the clay tiles (14%) are more affected by the weathering
Torres-Quezada, Coch and Isalgue [131]	Evaluation of light metal roof (coloured, cool, and white)	60	Horizontal real case at Santa Rosa (Ecuador)	Aw	Air temperature, Cloud cover, Global solar radiation, Relative humidity, Sky temperature, Wind velocity	Emittance and reflectance by infrared imaging ASTM E1933	The metal roof lost around 25% of the initial value of the reflectance over 5 years
Shirakawa et al. [86]	Use of fibber cement as roof tiles	60	Slow slope at Pirassununga (Brazil)	Aw	Air temperature, Precipitation, Relative humidity	Colour by spectrophotometer (CIELab) Infrared emittance ASTM C1371 Reflectance by ASTM C1549	Almost 30% of loss in the reflectance is due to biological growth. Alteration of the colour. The weather parameter affects reflectance and controls the rise of biocolonization
Takebayashi et al. [29]	High reflectance white roof paints	1.5 – 84	Horizontal real case and slow slope (7º) facing South at Kobe (Japan), Kawasaki (Japan) and Kumamoto (Japan)	Cfa	-	Reflectance by JIS K 5602	Average reduction of 13%. Most of the reduction is due to the black carbon deposition

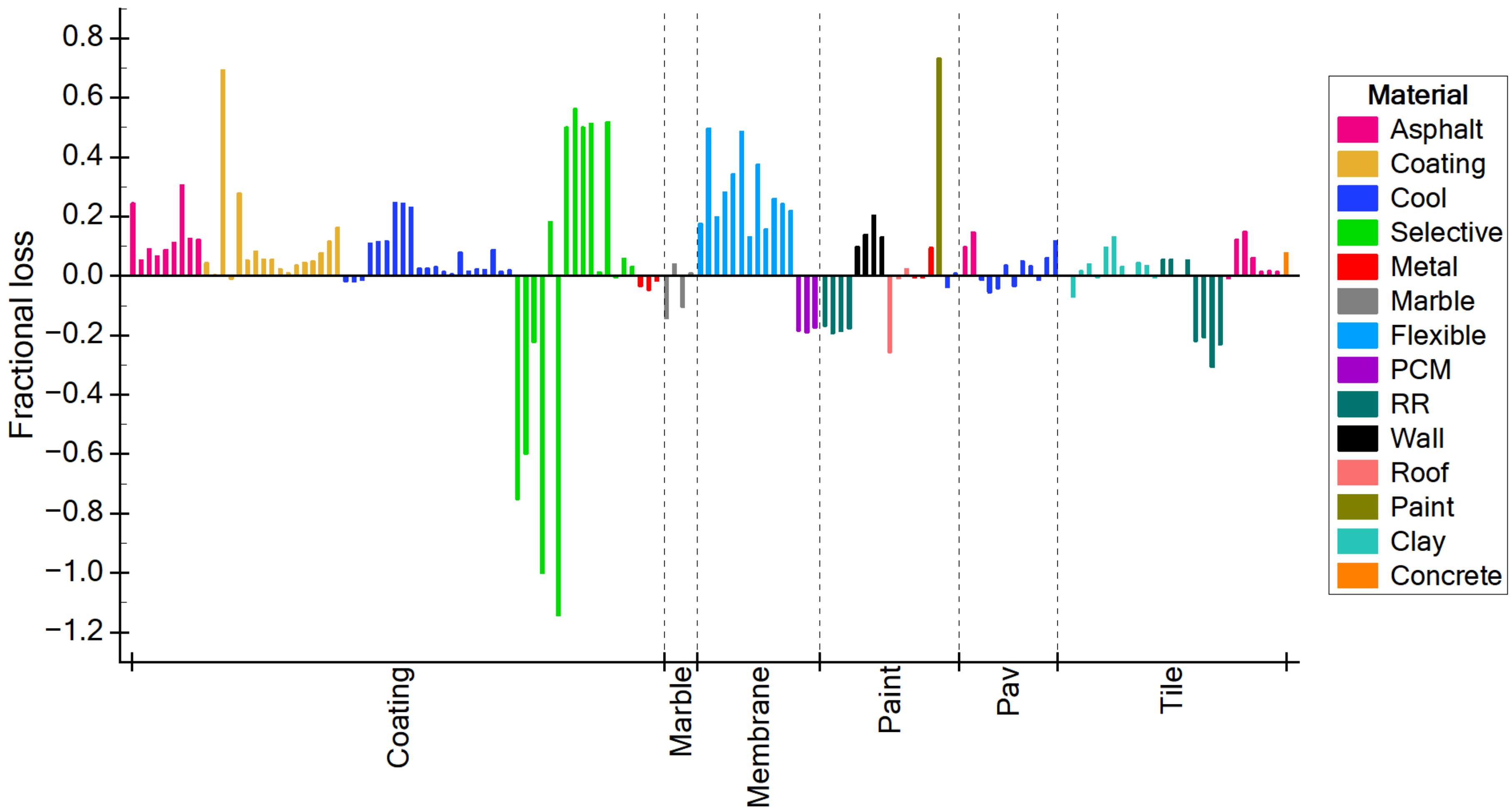

Fig. S2.1. Distribution of fractional loss of multiple materials for compilated accelerated tests.

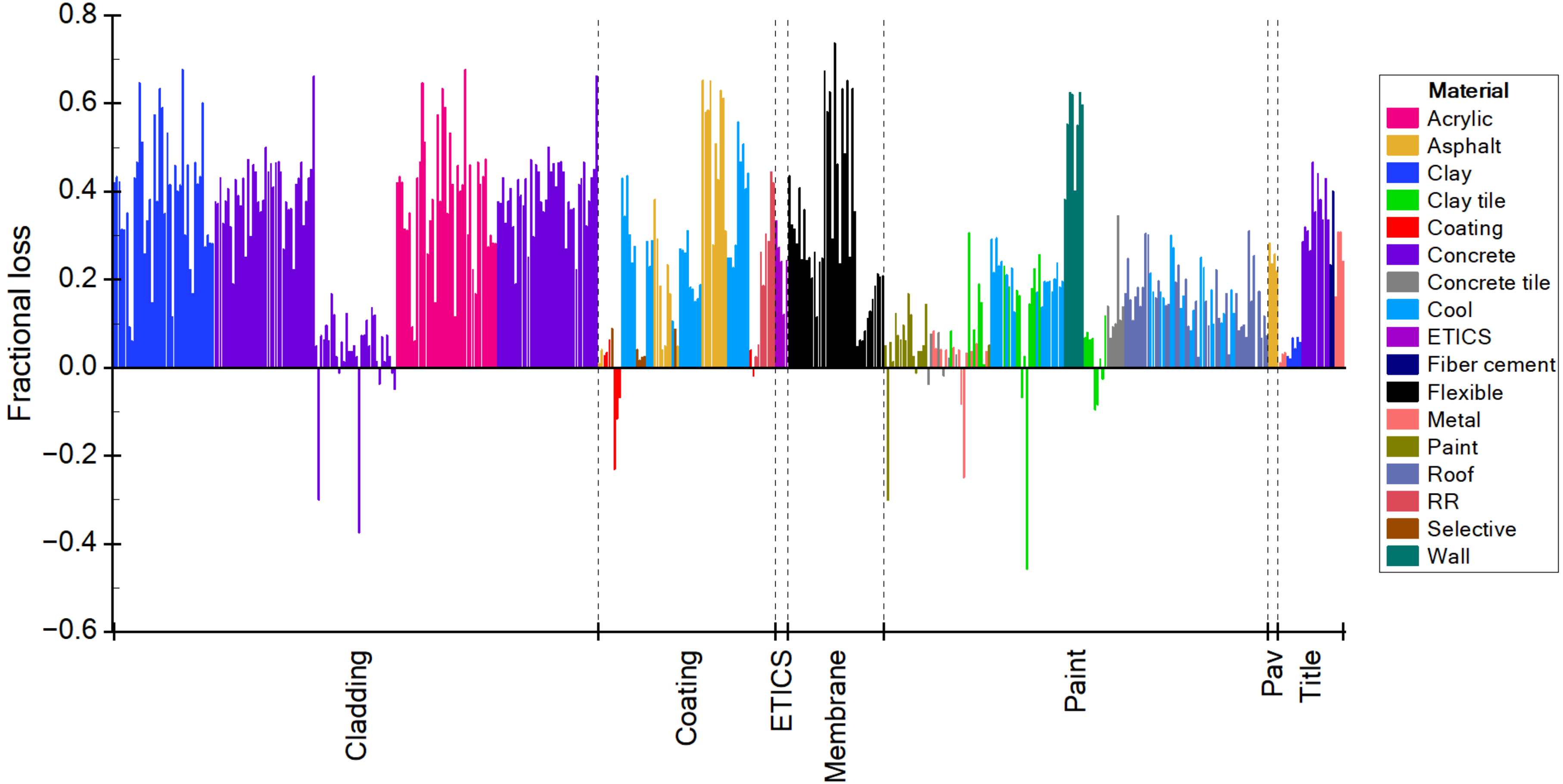

Fig. S2.2. Distribution of fractional loss of multiple materials for compilated long-term tests.

Table S2.4. Soiling parameter (□) and coefficients for aged reflectance.

Ageing process	Sample material	Initial reflectance (□i)	Parameter (□)	Parameter (□)	Statistical
Long-term	Cladding	0.646 ± 0.181	0.058 ± 0.084	0.631 ± 0.050	n= 192 p-value < 10^{-3}
	Coating	0.651 ± 0.182	0.260 ± 0.076	0.630 ± 0.066	n = 70 p-value < 10^{-3}
	ETICS	0.270 ± 0.207	0.004 ± 0.061	0.767 ± 0.044	n = 5 p-value < 10^{-3}
	Membrane	0.747 ± 0.225	-2.253 ± 2.719	0.947 ± 0.048	n = 38 p-value < 10^{-3}
	Paint	0.591 ± 0.216	0.209 ± 0.043	0.790 ± 0.002	n = 152 p-value < 10^{-3}
	Pavement	0.283 ± 0.032	0.139 ± 0.161	0.759 ± 0.265	n = 4 p-value = 0.10
	Tile	0.681 ± 0.188	0.179 ± 0.176	0.680 ± 0.108	n = 27 p-value < 10^{-3}
Accelerated	Coating	0.646 ± 0.264	0.08 ± 0.248	0.878 ± 0.048	n = 65 p-value < 10^{-3}
	Marble	0.659 ± 0.114	0.813 ± 0.287	0.813 ± 0.294	n = 4 p-value = 0.10
	Membrane	0.625 ± 0.194	0.321 ± 0.122	0.559 ± 0.151	n = 15 p-value = 0.003
	Paint	0.551 ± 0.25	0.418 ± 0.153	0.709 ± 0.161	n = 17 p-value < 10^{-3}
	Pavement	0.447 ± 0.231	0.327 ± 0.087	0.879 ± 0.057	n = 12 p-value < 10^{-3}
	Tile	0.493 ± 0.231	0.416 ± 0.111	0.111 ± 0.036	n = 28 p-value < 10^{-3}