

Article

Experimental Evaluation of Advanced Reflective TiO₂-Based Coatings for Passive Cooling of Building Envelope Materials

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Abstract

Space cooling is one of the fastest-growing end uses in the building sector, and reflective (“cool”) coatings have emerged as a low-cost passive strategy to limit solar heat gain through the envelope. This study evaluates the summer thermal behaviour of three building-envelope materials commonly used in flat roofing—self-protected asphalt sheet, steel sheet, and ceramic tile—under outdoor conditions in Valencia, Spain. Sealed cubic prototypes were monitored to compare uncoated reference specimens with specimens coated with a conventional high-performance white acrylic paint produced by SOETAM and with an advanced reflective coating based on a laminar TiO₂ nanostructure produced by Q+TERMIK. External surface temperatures were assessed by infrared thermography and internal air temperatures by autonomous data loggers. External white coatings significantly reduced surface temperatures across all substrates, with the effect most pronounced in low-thermal-inertia materials: the advanced reflective coating achieved peak surface-temperature reductions of 21.0 °C (33.2%) for asphalt and 17.4 °C (28.8%) for steel, outperforming the high-performance coating, with corresponding internal reductions of up to 9.7 °C (22.0%) and 8.1 °C (18.6%). The results indicate that the advanced reflective coating produced greater thermal mitigation than the conventional coating under the tested outdoor conditions, despite both coatings being applied with similar thicknesses. The advanced reflective coating generally produced the greatest thermal mitigation, particularly for low-thermal-inertia substrates, while the ceramic tile exhibited a different internal thermal response, highlighting the influence of substrate properties on coating performance.

Keywords: cool coatings; building envelope; thermal performance; titanium dioxide (TiO₂); urban heat island; passive cooling; energy efficiency



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1. Introduction

Paint has undergone a significant evolution in its use as a coating in construction, in both exterior and interior applications. It has evolved from uses primarily for aesthetic purposes to those aimed at protection, health, and hygiene, and subsequently toward applications focused on both indoor comfort and energy savings, with the ultimate goal

of improving the building envelope in accordance with sustainability criteria. Today, these coatings not only offer aesthetic qualities but also incorporate advanced properties such as biocidal and bactericidal performance, high solar reflectivity, and passive cooling capacity, directly contributing to the energy efficiency of buildings. In the current context of decarbonization in the building sector, this paradigm shift positions coatings as active elements in improving the thermal envelope, mitigating global warming, and reducing the urban heat island effect.

The building sector accounts for approximately 30% of global final energy demand and a comparable share of energy-related emissions, and space cooling is among its fastest-growing end uses, driven by rising temperatures, urbanization, and the wider diffusion of air conditioning [1,2]. In hot climates, much of this cooling demand originates from solar heat gains through the building envelope, which are further aggravated in cities by the urban heat island (UHI) effect. Within the current context of decarbonization, passive strategies that reduce envelope overheating without additional energy consumption have therefore become essential. Among them, reflective surface finishes—commonly termed “cool” coatings—stand out for their low cost, ease of application, and immediate effect on surface temperature [2]. This has redefined the role of architectural coatings: once primarily decorative or protective, they are now active components of the thermal envelope that contribute simultaneously to energy efficiency, indoor comfort, global-warming mitigation, and UHI reduction.

This functional shift is the result of a long historical evolution. The first white façade finishes were lime-based mineral paints, valued for their availability, appearance, and antiseptic properties, before being progressively replaced by synthetic materials [3]. The whiteness of these lime washes reflects solar radiation and, together with their high porosity, water-vapour permeability, and alkaline fungicidal effect, makes them behave as early cool coatings that reduce cooling demand when applied to façades in hot climates [4]. The colour of the finishing layer thus lowers summer thermal loads and cooling energy needs, acting as an effective passive strategy in hot climates while improving thermal comfort, hygiene, and the surrounding microclimate [5].

At the urban scale, light-coloured, highly reflective, and highly emissive surfaces help mitigate the UHI phenomenon [6]. Increasing the solar reflectance of envelope coatings is therefore a recognized sustainable strategy against urban overheating, an issue of particular relevance in Mediterranean cities, where the UHI markedly increases the cooling demand of residential buildings during summer [7]. The high albedo of these coatings may entail a heating penalty in winter; however, the magnitude of this effect is climate-dependent and is generally outweighed by summer benefits in warm zones [8]. Experimental and modelling studies have repeatedly confirmed that cool coatings reduce cooling loads and improve indoor thermal comfort across a range of climates [9,10], and comprehensive reviews now treat them as a mature passive-cooling technology for buildings and cities [11].

The incorporation of titanium dioxide (TiO₂) into commercial white paints during the 20th century was a turning point in the development of these coatings as a radiative-cooling strategy, enabling reductions in cooling demand together with greater formulation flexibility than conventional pigments [12]. Radiative cooling—reflecting solar radiation while emitting heat through the atmospheric window—has since become an active research field [12], and the demonstration of sub-ambient cooling under direct sunlight established its physical potential [13]. Beyond their optical role, TiO₂-based coatings were also found to exhibit photocatalytic, self-cleaning, hydrophobic, and antibacterial behaviour; nevertheless, the same photochemical reactivity that drives these functions can compromise the durability of the binder, which has motivated both industrial stabilization strategies and nanoparticle-based formulations [14].

Current research aims to reconcile the high reflectance of TiO_2 with long-term durability under real environmental conditions. Rutile nanoparticles are widely used as a white pigment owing to their high refractive index, opacity, and whiteness, and are frequently combined with silver nanoparticles to inhibit microbial growth and extend the service life of exterior coatings [15]. The photocatalytic and optical performance of TiO_2 depends strongly on particle size, crystallinity, surface-to-volume ratio, and surface chemistry; optimizing the size of rutile-phase particles improves stability, while nanolayered structures enhance dispersion and reduce agglomeration without significant loss of performance [16]. From an optical standpoint, the light-scattering efficiency of rutile is governed by Mie theory and tends to be maximized when the particle diameter is comparable to the incident wavelength. Consequently, particle sizes ranging from 200 to 300 nm are considered close to the optimum range for the scattering of solar radiation in the visible region of the spectrum, contributing to high reflectance [17]. Controlling particle size and dispersion is therefore decisive for maximizing solar reflectance per unit of pigment and, consequently, the thermal performance of the coating.

At the building scale, the effectiveness of reflective coatings has been demonstrated experimentally using test cells, reduced-scale prototypes, and instrumented roofs monitored by infrared thermography and temperature data loggers. Field studies report external surface-temperature reductions of up to roughly 20 °C and interior reductions in several degrees on glass substrates [18], while rooftop campaigns comparing commercial cool-roof products have measured surface-temperature reductions ranging from approximately 9 °C to more than 30 °C [19]. Comparable temperature-reduction effects have also been documented at the urban scale for cool roofs and cool pavements [20]. A recognized limitation, however, is the progressive loss of solar reflectance caused by soiling and weathering, so that the long-term performance and durability of these coatings under real exposure remain an active research concern [21].

Despite these advances, a central challenge persists: simultaneously achieving high solar reflectance, photochemical stability, long-term durability, and thermal performance under real environmental conditions. Moreover, the relationship between the nanostructure of TiO_2 , its dispersion within the coating matrix, and the overall optical and thermal behaviour of the system has not yet been fully established, and comparative field evidence on advanced laminar TiO_2 formulations applied to common roofing substrates remains scarce.

In this context, the present work evaluates an advanced coating based on a laminar TiO_2 composite additive that incorporates pre-dispersed, optimized 280 nm rutile particles, allowing thinner coating films. The present study evaluates the thermal behaviour of commercially available coating systems and does not aim to characterize their intrinsic microstructure or physicochemical properties. Using sealed cubic prototypes exposed to real summer conditions in Valencia (Spain), the thermal performance of this advanced reflective coating is compared with that of a high-performance white acrylic paint and with uncoated references, across three representative flat-roofing substrates: self-protected asphalt sheet, steel sheet, and ceramic tile. The objective is to quantify, through infrared thermography and internal air-temperature monitoring, the surface- and indoor-temperature reductions achievable with each coating, thereby advancing the development of multi-functional coatings that integrate protection, hygiene, improved thermal performance, and energy efficiency, and contributing to sustainability and to the mitigation of environmental impact in urban environments.

It should be noted that the objective of the present work is to evaluate the thermal response of commercially available reflective coatings under real outdoor exposure rather than to characterize their intrinsic optical properties. Therefore, the analysis focuses on

experimentally measured surface and internal temperatures, which directly reflect the thermal behaviour of the complete coating–substrate system under practical conditions.

2. Materials and Methods

2.1. Experimental Design

This study was designed to evaluate the effect of reflective coating systems on the thermal behaviour of common building envelope construction materials under summer outdoor conditions in Valencia, Spain. While reflective coatings benefit the entire building envelope, this experimental approach specifically focuses on materials predominantly used in flat roofing systems. This focus is justified because horizontal roof surfaces receive the most direct and perpendicular solar radiation, making the thermal mitigation effect of cool coatings most significant in these areas. The experimental approach was based on the construction and monitoring of sealed cubic prototypes, each representing a simplified building-envelope element exposed to solar radiation. The prototypes made it possible to compare the external surface temperature of the exposed material with the temperature reached inside an enclosed air volume, thereby providing an approximation of the thermal response that could occur in an interior space.

The experimental campaign focused on a representative hot summer day, 30 July 2025, selected because of its clear-sky conditions and high ambient temperatures. Two complementary measurement strategies were used: external surface temperature measurements obtained by infrared thermography (detailed in Section 2.5) and internal air temperature measurements recorded by autonomous temperature data loggers placed inside the sealed prototypes (detailed in Section 2.6). The comparison was structured by substrate material and coating treatment.

The objective of the experimental design was to compare the relative thermal behaviour of different coating systems under identical outdoor exposure conditions rather than to establish statistically representative population parameters.

2.2. Construction of the Experimental Prototypes

The experimental specimens consisted of cubic prototypes with external dimensions of 500 mm × 500 mm × 500 mm. Each prototype was built using a tubular steel frame that defined the cube edges and incorporated four legs, positioning the cube 500 mm above ground level (Figure 1). The five exposed faces were closed using the construction material under evaluation, while the lower face, which was not intended to receive direct solar radiation, was built with a steel sheet and included an access hatch to insert and remove the internal sensors. Once assembled and closed, the prototypes were treated as sealed volumes for internal temperature monitoring.



Figure 1. Aspect of the sample cubes during construction.

Three construction materials commonly used in building envelopes, particularly in flat roofing applications, were selected as substrates (Figure 2). The codes can be seen in Table 1.



Figure 2. Aspect of the sample cubes. From left to right: asphalt, steel, and ceramic.

Table 1. Summary of the materials and codes used to build the cubes.

Code	Substrate Material	Thickness
AS	Self-protected Asphalt Sheet	3 mm
SS	Steel Sheet	2 mm
CT	Ceramic Tile	25 mm

For each substrate, three prototypes were prepared: an uncoated reference prototype, a prototype coated with a high-performance white acrylic coating for exterior applications (SOETAM, hereinafter referred to as high-performance coating and +S when naming samples), and a prototype coated with the advanced reflective coating based on a laminar TiO_2 nanostructure (Q+TERMIK, hereinafter referred to as advanced reflective coating and +Q when naming the samples). The sample nomenclature combines the substrate designation with the coating condition (e.g., AS, AS+S, and AS+Q).

Although the sealed cubic prototypes provide a controlled experimental configuration for comparing coating systems, they do not fully reproduce the thermal behaviour of real buildings, where ventilation, thermal bridges, occupancy and more complex heat-transfer mechanisms also influence indoor temperatures. Consequently, full-scale validation constitutes an important direction for future research.

Likewise, the present work does not include an economic assessment or a long-term durability analysis of the evaluated coating systems, as these aspects were beyond the scope of the experimental campaign.

2.3. Coating Systems and Application Procedure

Two white coating systems were evaluated. The first was a high-performance 100% acrylic coating for exterior applications, supplied by Pinturas Eurosol, S.L.U. (Aguadulce, Sevilla, Spain). The second was a reflective acrylic coating with a laminar structure, supplied by Exclusivas Jucamar QUIMIPLUS, S.L. (Alaquàs, Valencia, Spain).

The advanced reflective coating incorporates a laminar deposition technique for titanium dioxide (TiO_2) nanoparticles. This structural design maintains a thin coating profile, thereby maximizing solar reflectance efficiency while minimizing material consumption. For each coated prototype, two coats were applied to the external surface of the substrate. A layer of PROPRIMER primer, supplied by Exclusivas Jucamar QUIMIPLUS, S.L. (Alaquàs, Valencia, Spain), was applied prior to both the high-performance and the advanced reflective coatings. The coatings were applied to achieve a uniform dry film. With the

stereomicroscope analysis of the final laminar structure thickness (Figure 3), the results show an average coating thickness of 0.3 mm in each substrate.

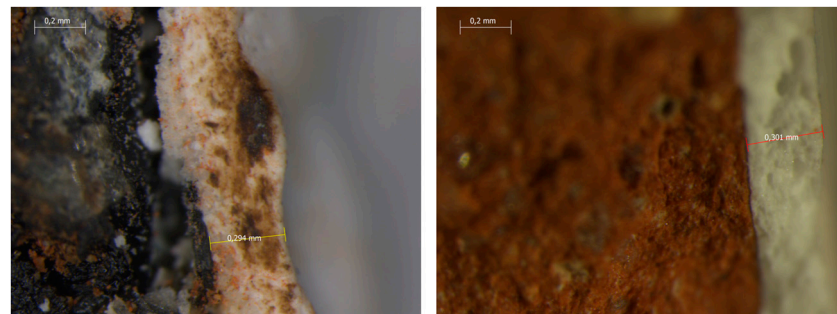


Figure 3. Coating thickness measurement.

The uncoated prototypes were used as reference specimens for each substrate, allowing the thermal effect of applying a white coating to be separated from the intrinsic behaviour of the material. The +S specimens provided a comparison with a high-performance white acrylic coating, while the +Q specimens provided the experimental condition of interest (Figure 4).



Figure 4. Aspect of the prototypes after coating application.

No independent measurements of solar reflectance or thermal emittance were carried out, since the purpose of this work was to evaluate the overall thermal response of the complete coating systems under outdoor exposure rather than to characterize their optical properties.

2.4. Outdoor Exposure Conditions

Temperature values were recorded from 13 March 2025 to 30 September 2025 in València, Spain. All measurements analyzed in this study correspond to one of the hottest days of the series, 30 July. The day was selected as a summer exposure scenario with high solar radiation and clear-sky conditions. An ambient temperature sensor located in the shade in the immediate vicinity of the prototypes was used to characterize the local thermal conditions during the experiment. On 30 July 2025, this sensor recorded a minimum air temperature of 24.5 °C at 06:00 and a maximum of 40.4 °C at 16:00. These locally measured values were used as the ambient-temperature reference in the analysis, since they more accurately represented the conditions experienced by the prototypes than data obtained from an external meteorological source.

Although the monitoring campaign extended over six months, the present study focuses on the day exhibiting the highest thermal demand. This approach was intentionally adopted to evaluate the comparative performance of the coating systems under representative worst-case summer conditions, where passive cooling strategies are expected to provide their greatest benefit.

It should be noted that solar radiation intensity was not independently recorded during the monitoring campaign. Consequently, the present study evaluates the comparative thermal behaviour of the different coating systems under identical outdoor conditions, but the influence of solar radiation intensity on the observed thermal response could not be assessed directly. This constitutes a limitation of the present study and should be addressed in future research.

2.5. Infrared Thermography

External surface temperatures were measured using an FLIR E95 infrared thermographic camera equipped with an FOL10 lens (FLIR Systems, Inc., Wilsonville, OR, USA) (Figure 5). The thermal sensor resolution was 464×348 pixels, with a thermal sensitivity below 40 mK at +30 °C. The thermographic configuration used in the study included an emissivity setting of 0.98 and a measurement range from −20 °C to 120 °C.



Figure 5. Representative thermographic image measuring external surface temperatures during the experiment.

For all thermographic measurements, a constant emissivity value of 0.98 was used in order to ensure consistent comparative measurements among all prototype configurations. The objective of the infrared thermography was to compare the relative thermal behaviour of the different coating systems under identical experimental conditions rather than to determine the absolute surface temperature of each substrate with laboratory accuracy.

The steel specimens had been exposed to outdoor environmental conditions for several months before the thermographic survey. As a result, their surfaces had lost their original metallic finish and exhibited a matt and partially weathered appearance, increasing their effective emissivity compared with freshly polished steel.

Although the use of substrate-specific emissivity values could improve the absolute accuracy of the temperature measurements, maintaining identical thermographic settings for all specimens ensured a consistent comparative assessment, which was the primary objective of this study.

Thermographic measurements were taken hourly from 08:00 to 21:00. For each substrate and treatment, the analysed thermal value corresponded to the mean temperature

of the frontal face oriented as perpendicular as possible to the incident solar radiation. Thermographic images were acquired from an approximate distance of 1.5 m, with the camera positioned as perpendicular as possible to the measured surface in order to minimise angular effects. This criterion was adopted to maintain consistency among the thermographic comparisons and to evaluate the exposed surface under the most relevant solar loading condition.

Although hourly thermographic data were collected throughout the day, the reporting strategy highlighted three representative measurement times: 09:00, 14:00, and 19:00. These instants corresponded, respectively, to the pre-solar-exposure condition, the peak solar-exposure condition, and the post-exposure cooling period.

2.6. Internal Temperature Monitoring

Internal air temperatures were recorded using TH1165 temperature data loggers (PerfectPrime, London, United Kingdom). The sensors operate autonomously using 3 V AAA batteries and register temperature, dew point, relative humidity, date, time, and probe identification. The measurement range of the data logger with probe is $-40\text{ }^{\circ}\text{C}$ to $125\text{ }^{\circ}\text{C}$, with an accuracy of $\pm 0.3\text{ }^{\circ}\text{C}$.

The sensors were placed inside the sealed prototypes through the lower access hatch and recorded temperature values continuously during the monitoring period. For the analysis presented in this study, the internal temperature reached inside each prototype was reported at hourly intervals. These data were used to compare the thermal effect of each coating not only at the external surface but also within the enclosed air volume.

2.7. Data Processing and Comparative Assessment

The analysis was organised by substrate material and coating conditions. For each material, the uncoated prototype was used as the reference case, while the +S and +Q prototypes were used to quantify the thermal reduction associated with the application of white coatings. The comparison was performed separately for external surface temperature and internal air temperature.

The thermal reduction was expressed as both an absolute temperature difference and a relative percentage difference. The absolute reduction between a reference specimen and a coated specimen was calculated as

$$\Delta T = T_{\text{un}} - T_{\text{co}} \quad (1)$$

where T_{un} is the temperature measured in the uncoated prototype and T_{co} is the temperature measured in the coated prototype at the same time.

The relative reduction was calculated as

$$\Delta T\% = (T_{\text{un}} - T_{\text{co}}) / T_{\text{un}} \times 100 \quad (2)$$

The same approach was applied to compare +Q with +S:

$$\Delta T_{\text{S-Q}} = T_{\text{S}} - T_{\text{Q}} \quad (3)$$

This comparative structure made it possible to distinguish two effects: the effect of applying a high-performance coating relative to the uncoated material, and the additional thermal benefit of the advanced reflective coating relative to a high-performance coating.

3. Results and Discussion

The results are presented in two main groups: external surface temperatures and internal air temperatures, further subdivided by substrate material and coating configuration.

In all internal temperature graphs, a dotted line represents the ambient shaded outdoor temperature for reference.

3.1. External Surface Temperatures

The selected day corresponded to the highest ambient temperature recorded during the monitoring campaign and therefore represented the most severe thermal conditions experienced by the tested prototypes. The maximum external surface temperatures measured for each coating system under these conditions are presented in Table 2.

Table 2. Summary of maximum external surface temperatures and thermal reductions.

Substrate	Uncoated Max	+S Max	+Q Max	+Q Reduction vs. Uncoated (°C/%)	+Q Difference vs. +S (°C/%)
Asphalt Sheet	63.2 °C	43.4 °C	42.2 °C	21.0 °C (33.2%)	−1.2 °C (2.84%)
Steel Sheet	60.4 °C	44.3 °C	43.0 °C	17.4 °C (28.8%)	−1.3 °C (3.02%)
Ceramic Tile	49.7 °C	42.0 °C	41.7 °C	8.0 °C (16.1%)	−0.3 °C (0.71%)

Although the experimental prototypes represent a simplified building-envelope model, they provide a controlled methodology for isolating the influence of the coating system on thermal behaviour, which would be considerably more difficult to achieve under occupied full-scale building conditions.

3.1.1. Self-Protected Asphalt Sheet Prototypes

The asphalt sheet prototypes showed the largest differences between the uncoated and coated conditions (Figure 6). At 09:00, before the strongest period of solar exposure, the external surface temperature of the uncoated asphalt prototype was 30.6 °C, while both coated prototypes recorded 26.3 °C. At 14:00, the uncoated prototype reached 59.6 °C, compared with 41.7 °C for +S and 41.0 °C for +Q. At 19:00, after the main period of solar exposure, the uncoated prototype remained at 53.9 °C, while the +S and +Q specimens recorded 38.8 °C and 37.1 °C, respectively.

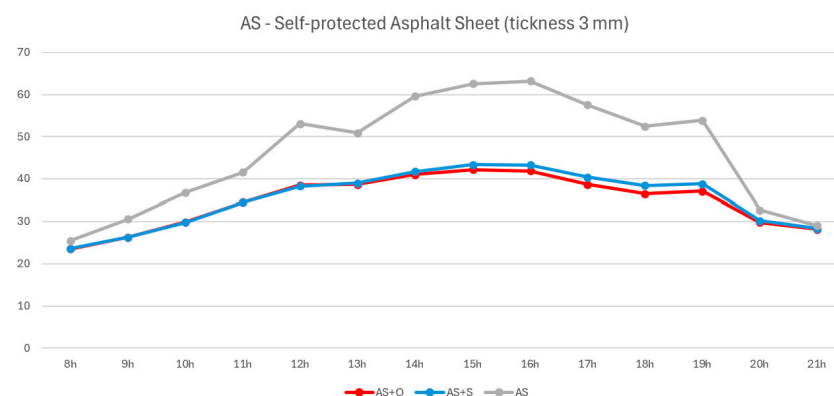


Figure 6. Self-protected asphalt external surface temperature evolution.

The maximum external surface temperature reported for the uncoated asphalt sheet was 63.2 °C at 16:00. At the same peak condition, the +S-coated asphalt prototype reached 43.4 °C, while the +Q-coated prototype reached 42.2 °C. Therefore, relative to the uncoated asphalt surface, the reduction at peak temperature was 19.8 °C (31.3%) for +S and 21.0 °C (33.2%) for +Q. The difference between the two white coatings at the maximum condition was 1.2 °C, with the +Q-coated surface recording the lower temperature.

3.1.2. Steel Sheet Prototypes

The steel sheet prototypes also exhibited significantly lower external surface temperatures when coated (Figure 7). At 09:00, the uncoated steel prototype recorded 31.2 °C, compared with 27.2 °C for +S and 26.7 °C for +Q. At 14:00, the uncoated prototype reached 50.1 °C, while the +S and +Q specimens recorded 42.1 °C and 40.7 °C, respectively. At 19:00, the corresponding temperatures were 43.3 °C for the uncoated prototype, 33.7 °C for +S, and 31.9 °C for +Q.

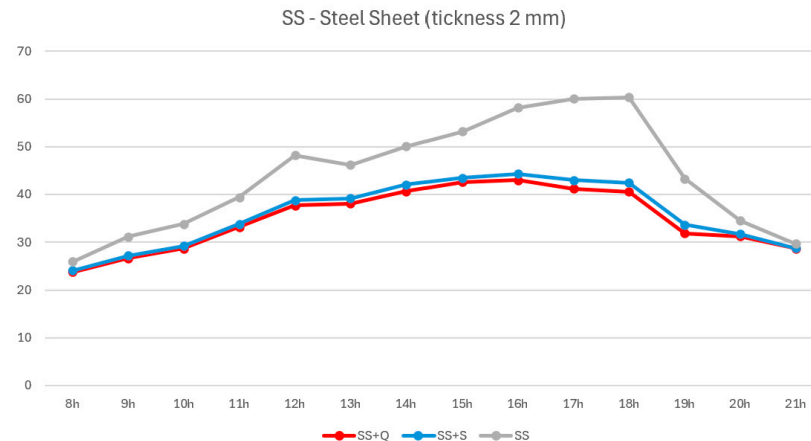


Figure 7. Steel sheet external surface temperature evolution.

The maximum external surface temperature reported for the uncoated steel sheet was 60.4 °C at 18:00. Under the same condition, the +S-coated prototype recorded 44.3 °C and the +Q-coated prototype recorded 43.0 °C. The reduction relative to the uncoated steel surface was therefore 16.1 °C (26.7%) for +S and 17.4 °C (28.8%) for +Q. The difference between +Q and +S at the maximum condition was 1.3 °C.

3.1.3. Ceramic Tile Prototypes

The ceramic tile prototypes showed smaller differences among coating conditions than the asphalt and steel prototypes, attributable to the higher thermal mass of the material (Figure 8). At 09:00, the uncoated ceramic prototype recorded 26.6 °C, while +S and +Q recorded 25.2 °C and 25.1 °C, respectively. At 14:00, the uncoated prototype reached 45.1 °C, while both externally coated specimens recorded 40.0 °C. At 19:00, the uncoated ceramic prototype recorded 42.6 °C, compared with 35.8 °C for +S and 35.9 °C for +Q.

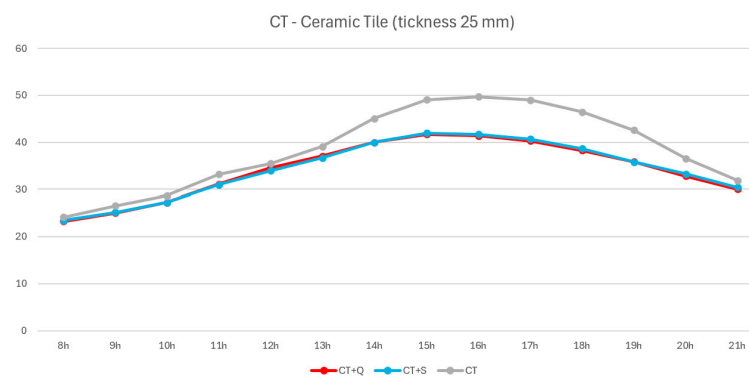


Figure 8. Ceramic tile external surface temperature evolution.

The maximum external surface temperature reported for the uncoated ceramic tile was 49.7 °C at 16:00. The corresponding maximum temperatures were 42.0 °C for +S and 41.7 °C for +Q. Thus, the reductions relative to the uncoated ceramic surface were 7.7 °C

(15.5%) for +S and 8.0 °C (16.1%) for +Q. For ceramic tile, the external surface temperatures obtained with both coatings were very similar, indicating comparable thermal behaviour under the tested conditions.

3.2. Internal Air Temperatures

Internal air temperature measurements confirmed that the external coating configuration also affected the thermal conditions inside the sealed prototypes. The source study reports the internal temperature evolution hourly, while the most relevant comparative results are summarized below as maximum observed differences between coating conditions.

It should be noted that the maximum temperature reductions reported in this section correspond to the greatest differences recorded during the monitoring period, irrespective of the time at which they occurred. These values therefore do not necessarily coincide with those presented in Table 3, which summarizes the temperature differences at the specific time when the uncoated specimen reached its maximum temperature.

Table 3. Summary of maximum internal air temperatures and thermal reductions.

Substrate	Uncoated Max	+S Max	+Q Max	+Q Reduction vs. Uncoated (°C/%)	+Q Difference vs. +S (°C/%)
Asphalt Sheet	53.2 °C	44.1 °C	43.5 °C	9.7 °C (18.2%)	0.6 °C (1.36%)
Steel Sheet	53.1 °C	46.1 °C	45.7 °C	7.4 °C (13.9%)	0.4 °C (0.87%)
Ceramic Tile	46.0 °C	40.2 °C	43.3 °C	2.7 °C (5.9%)	−3.1 °C (−7.16%)

Since each coating configuration was represented by one monitored prototype, statistical dispersion indicators such as standard deviations could not be calculated. Future studies including replicate specimens would allow statistical analyses of the observed differences.

3.2.1. Self-Protected Asphalt Sheet Prototypes

For the asphalt sheet prototypes, the uncoated cube recorded higher internal temperatures than the coated cubes after sunrise and throughout the daytime heating period (Figure 9). The maximum internal temperature difference between the uncoated asphalt prototype and the +Q-coated asphalt prototype was 9.7 °C at 15:00, corresponding to a relative difference of 22.0%. When +Q was compared with +S, the maximum internal difference was 1.8 °C at 18:00, equivalent to 5.0%, with +Q recording the lower internal temperature.

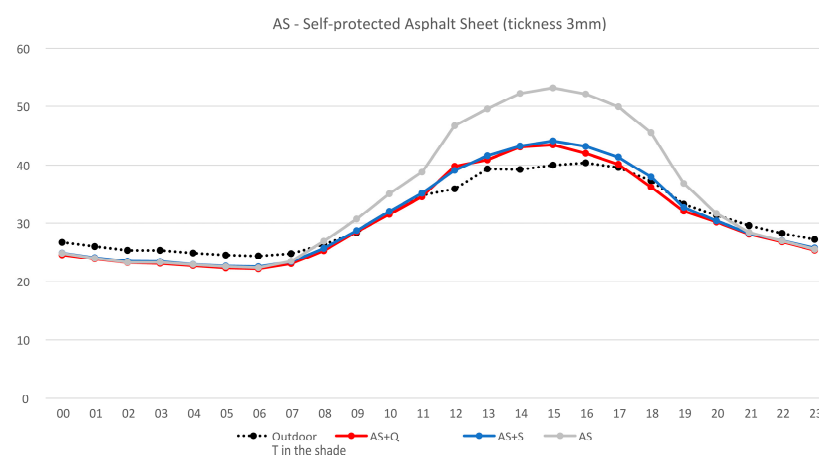


Figure 9. Self-protected asphalt sheet internal air temperature evolution.

3.2.2. Steel Sheet Prototypes

For the steel sheet prototypes, the internal temperature curves began to diverge after sunrise (Figure 10). The maximum internal temperature difference between the uncoated steel prototype and the +Q-coated steel prototype was 8.1 °C at 17:00, corresponding to 18.6%. The maximum difference between +Q and +S was 1.1 °C at 13:00, equivalent to 2.6%, again with the +Q prototype recording the lower internal temperature.

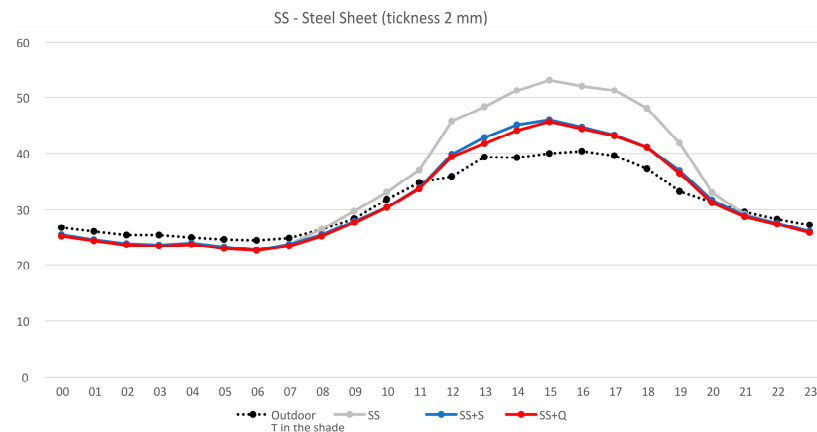


Figure 10. Steel sheet internal air temperature evolution.

3.2.3. Ceramic Tile Prototypes

For the ceramic tile prototypes, the internal temperature differences became more evident from approximately 13:00 (Figure 11). The maximum difference between the uncoated ceramic prototype and the externally +Q-coated ceramic prototype was 3.8 °C at 17:00, corresponding to 10.8%. Unpainted ceramic has inherent breathable properties and higher thermal inertia, so in this case, the improvements are less pronounced than in low-inertia materials. The difference observed between coating with +Q versus +S on the ceramic tile was maximum at 13:00, when +Q was 1.1 °C higher than +S.

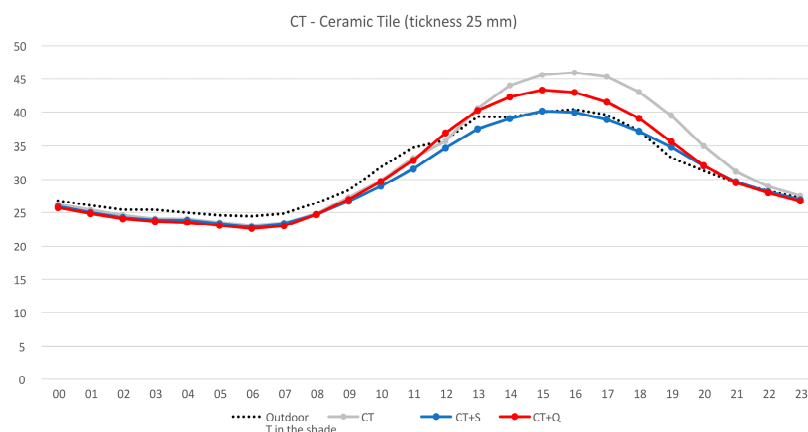


Figure 11. Ceramic Tile internal air temperature evolution.

3.3. Comparative Summary Across Substrates

Across the three substrates, the highest external surface temperatures were observed in the uncoated reference prototypes (Table 2). The largest peak reduction associated with external +Q application occurred in the asphalt sheet prototype, where the maximum surface temperature decreased from 63.2 °C to 42.2 °C. The steel prototype showed a peak reduction from 60.4 °C to 43.0 °C, while the ceramic prototype showed a reduction from 49.7 °C to 41.7 °C.

The results indicate that external white coatings reduced the surface temperature of all evaluated substrates under summer exposure. +Q recorded lower peak surface temperatures than +S in the three tested materials, although the magnitude of the difference depended on the substrate. The greatest absolute difference between +Q and +S occurred in the steel sheet prototype, followed by the asphalt sheet prototype and the ceramic tile prototype.

The white coatings also reduced the internal temperature of all evaluated substrates under summer exposure, although to a lesser extent than observed at the external surface (Table 3). The largest absolute reduction of +Q relative to the uncoated substrate occurred in the asphalt sheet prototype, with a decrease of 9.7 °C (18.2%), followed by the steel sheet prototype, with 7.4 °C (13.9%), and the ceramic tile prototype, which showed the smallest reduction, of 2.7 °C (5.9%).

Unlike what was observed at the external surface, the comparison between +Q and +S at the internal level did not show a consistent pattern across substrates. While in the asphalt sheet and steel sheet prototypes +Q recorded slightly lower internal temperatures than +S (differences of 0.6 °C and 0.4 °C, respectively), the opposite occurred in the ceramic tile prototype: +Q showed a higher internal temperature than +S, with a difference of −3.1 °C (−7.16%). This suggests that, for this particular substrate, the internal thermal behaviour of +Q does not replicate the advantage observed at the external surface.

Table 3 shows internal temperatures recorded at the time when the uncoated specimen reached its maximum surface temperature. The temperature reductions shown in this table therefore correspond to this specific instant and may differ from the maximum reductions reported in Section 3.2.

4. Conclusions

This study evaluated the thermal behaviour of three common envelope construction materials under summer outdoor conditions in Valencia, Spain, using sealed cubic prototypes exposed to solar radiation. The experimental comparison considered uncoated specimens, specimens coated with a high-performance white acrylic coating, and specimens coated with an advanced reflective coating based on a laminar TiO₂ nanostructure. Surface temperatures were assessed by infrared thermography, while internal air temperatures were monitored using autonomous temperature data loggers.

The results show that applying a white coating to the external face of the tested materials reduced the surface temperature of all substrates under summer exposure. This effect was most pronounced in the self-protected asphalt sheet and steel sheet prototypes, where the uncoated materials reached the highest surface temperatures. The ceramic tile prototype also showed a reduction in surface temperature after external coating, although the magnitude of the improvement was lower than that observed for asphalt and steel.

The advanced reflective coating generally recorded lower external surface temperatures than the conventional high-performance coating. However, this trend was not fully reproduced in the ceramic tile prototype, where the conventional coating resulted in lower internal air temperatures. This behaviour suggests that the overall thermal response of reflective coating systems depends not only on the coating itself but also on the characteristics of the substrate. The difference between the two white coatings was moderate, with reductions of 1.2 °C for the asphalt sheet and 1.3 °C for the steel sheet at the reported maximum surface-temperature conditions. For ceramic tile, both coatings exhibited very similar external thermal behaviour. These results indicate that the additional thermal benefit of advanced reflective coating over a high-performance white coating depends on the substrate and is more evident in materials with higher thermal response under solar exposure.

The internal air temperature measurements confirmed that the external surface treatment also affected the thermal conditions inside the sealed prototypes. Compared with the uncoated specimens, the +Q-coated prototypes achieved maximum internal temperature reductions of 9.7 °C in the asphalt sheet prototype, 8.1 °C in the steel sheet prototype, and 3.8 °C in the ceramic tile prototype. When compared with the +S-coated specimens, +Q produced lower internal temperatures in the asphalt and steel prototypes, with maximum differences of 1.8 °C and 1.1 °C, respectively.

Overall, the findings support the use of external white reflective coatings as a passive strategy to reduce surface and internal temperatures in roof-envelope materials under hot summer conditions. The results are especially relevant for dark or highly heat-absorbing substrates, such as asphalt-based roofing materials, where the reduction in solar heat gain is more pronounced. For lighter or more thermally massive materials, such as ceramic tiles, the benefit remains measurable but comparatively smaller.

The lower temperatures recorded for the advanced reflective coating indicate a more favourable thermal response under the tested outdoor conditions. Since the optical properties of the coatings were not independently characterized, the specific mechanisms responsible for this behaviour cannot be established from the present study and should be investigated in future research. The effect of the coating was most significant in materials with low thermal inertia, such as the steel sheet and the self-protected asphalt sheet. In materials with higher thermal inertia, such as ceramic tile, the improvements were more moderate but still relevant from the point of view of thermal control, with the high-performance coating performing better than the advanced reflective coating. One possible explanation for this behaviour is that the advanced reflective coating may partially modify the vapour exchange characteristics of the ceramic tile. However, this interpretation remains a hypothesis and should be verified through dedicated water vapour permeability or diffusion resistance tests in future studies.

Taken together, the results suggest that the use of advanced reflective coatings constitutes an effective passive strategy for improving the thermal behaviour of the building envelope, limiting the overheating of construction materials and lowering the internal temperatures reached, and thereby contributing to the reduction in cooling demand and improving indoor thermal comfort in hot climates. This has a direct impact on the energy efficiency and indoor comfort of buildings and contributes to the mitigation of the urban heat island effect, supporting the wider adoption of these coatings as a sustainable solution for the building envelope in hot climates.

The present study focused on the initial thermal performance of the evaluated coatings under representative summer conditions. Future research should investigate their long-term durability under real outdoor exposure, including the effects of weathering, pollution and ageing on solar reflectance and thermal performance.

Future work should also evaluate the annual thermal behaviour of these coatings, including possible winter heating penalties, to provide a complete assessment of their seasonal energy performance under different climatic conditions.

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Abbreviations

The following abbreviations are used in this manuscript:

AS	Asphalt sheet
+Q	Q+TERMIK
+S	SOETAM
CT	Ceramic tile
SS	Steel sheet
UHI	Urban heat island

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