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Analysis of the Optical Response of Opaque Urban Envelope Materials: The Case of Madrid †

Gloria Pérez [1,*], Fernando Martín-Consuegra [1], Fernando de Frutos [1], Arturo Martínez [1,2], Ignacio Oteiza [1], Borja Frutos [1] and Carmen Alonso [1]

1 Instituto de Ciencias de la Construccion Eduardo Torroja (IETCC), CSIC, 28033 Madrid, Spain
2 Departamento de Construcción y Tecnología Arquitectónicas, ETSAM, Universidad Politécnica de Madrid, 28040 Madrid, Spain
* Correspondence: gperezaq@ietcc.csic.es

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Abstract: The optical response of opaque materials in an urban envelope plays an important role in a city's energy exchange with the environment as it defines the absorption of radiation and emission of heat. In the present work, the most common surfaces of the finishing materials of pavement and walls in the city of Madrid (Spain) were identified, and their reflectance was measured in situ to determine their solar absorptance and color coordinates. Most of the selected pavement showed a relatively high solar absorptance in the range of 0.87 to 0.60, while in vertical surfaces, the range was 0.85 to 0.29. The variations of the color coordinates obtained for pavement were 27.1, 11.4, and 6.7 for ΔL*, Δa*, and Δb*, respectively. Significantly higher values were obtained in the case of vertical surfaces (47.5, 20.5, and 23.6, respectively). The results were included into a database intended to be the seed for a catalogue of the experimental thermo-optical properties of opaque envelope materials in Madrid. The catalogue will be useful for the analysis of the stimuli generated by the urban environment for citizens and for achieving more reliable results from energy simulation tools in the search for strategies to improve urban comfort and sustainability.

Keywords: optical properties; urban envelope; opaque materials; energy refurbishment; urban heat island

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1. Introduction

In the context of an increasingly urgent energy transition, the management of solar radiation in urban environments is the subject of a growing number of studies [1]. The need for the distributed generation of renewable energy directly at places where high consumption occurs has led to the proliferation of studies aimed at quantifying incident solar radiation in urban landscapes [2–6]. However, the needs of inefficient cities with high consumption cannot be met by renewable energy potential alone. Energy demand must be drastically reduced through retrofitting so that these renewable installations can be reasonably sized [7–9]. In solving this complex equation, less attention is being paid to outdoor comfort and the influence of the microclimate on the energy efficiency of urban fabrics [10]. A complete bioclimatic analysis of a building, aimed at the rational use of natural resources, must take into account not only the characteristics of the environment [11], but also the influence of the buildings on the microclimate [12]. Land surface temperature has already been positively correlated with urban density and floor area ratio [13]. Further, a building's frontal area density has an effect on the physiologically equivalent temperature, thermal comfort, and air quality at the pedestrian level above the sidewalk [14]. Solar obstructions caused by urban morphology are fundamental, but so is the configuration of public spaces, including vegetation and the optical characteristics of the materials that conform to them [15]. The passive cooling of outdoor urban spaces has also been addressed through comparative studies that aimed to investigate the suitability of materials in order to contribute to lower ambient temperatures and fight the urban heat island effect [16].

Improving the quality of the outdoor environment of our cities has been identified as a priority challenge at the European level. High-quality urban spaces—such as well-designed streets, footpaths, squares, and parks—provide the structure that enables cities to come to life and encourages and accommodates diverse activities [17]. The optical response of opaque surface materials has a major impact on this challenge [18]. On the one hand, this response regulates the reflection and absorption of solar radiation, thus conditioning the impact of solar heating on the urban microclimate and on a building's energy efficiency [19,20]. Recent research has shown how substituting high-emission thermal terrestrial materials with low-emission ones plays a key role in modifying the outdoor microclimate [21].

However, research on urban coatings must be assessed to consider the potential relationship between the environmental quality and thermal sensation in outdoor spaces [22]. The optical response in the visible part of the spectrum, related to different textures and colors, generates multiple stimuli in citizens, affecting their well-being. Therefore, some strategies for the mitigation of the urban heat island (UHI) effect can lead to considerable benefits in terms of temperature and energy but could also determine a penalization of the well-being of pedestrians [23]. The bio-meteorological observations of a solar reflective coating to investigate its thermal performance from a pedestrian perspective has shown that the surface temperature of coated asphalt concrete was lower than that of regular asphalt concrete, but this effect could increase the mean radiant temperature [24]. Similar research has already been carried out to evaluate the stimuli created by green spaces, finding relations between the reduction in anxiety and psychological distress [25].

A recent synthetic review of methods has identified six research gaps in the use of cool pavements for UHI mitigation. These are the lack of research on how permeable pavement affects building energy consumption and greenhouse gas emissions when used for UHI mitigation; the lack of research to quantify the relationship between cool pavements, surface and air temperatures, and human thermal comfort at multiple spatial scales; the lack of research on the durability of cool pavements; the need to fully evaluate numerical simulations against detailed field experiments; the lack of research on the life cycle assessments (LCA) of cool pavements; and the improper use of terminology for pavement-related strategies in research [26].

Previous works have analyzed the effect of the surface finish of buildings on their energy exchange with the environment as a basis for mitigation strategies for the urban heat island effect [27,28] and for improving the energy performance of buildings, with special attention to their renovation [29]. These works have shown that the use of multi-functional and innovative materials in building envelopes can provide radical improvements in the energy efficiency and economic value of new and refurbished buildings, while improving outdoor thermal comfort. In addition, the benefits of the solar resources to the public must be addressed. Due to the dynamic shadowing effects present on building surfaces, quantifying these phenomena is essential for predicting solar radiation availability that can significantly affect the potential for solar energy use [1]. As a continuation of these works, it is necessary to extend this knowledge outside of buildings to study the configuration of the urban space, and to assess the influence that the surroundings have on the buildings and that the buildings have among themselves and on the environment [28,30]. Frameworks for evaluating building energy performance and outdoor thermal comfort are being developed for the holistic assessment of the urban environment [31].

A monitoring campaign of the energy performance and indoor environment quality of dwellings located in inefficient and deprived residential areas in city outskirts is being carried out in Madrid (Spain) [32,33]. The areas are socioeconomically vulnerable, containing a high proportion of dwellings without thermal insulation and having high energy needs. The present work aims to take the focus away from the interior of the buildings to analyze the exterior spaces. This will make it possible to assess the influence of the outdoor environment on the thermal performance of buildings and to reach innovative and integral conclusions for the rehabilitation of neighborhoods that include the improvement of the thermal performance of buildings, harnessing the solar potential, and improving the quality of the outdoor environment [34].

Some studies point to the disparity between the results of predictive microclimate models and in situ measurements obtained by monitoring climatic parameters in urban environments [35]. The precise characterization of the optical properties of urban finishing materials would allow for obtaining more accurate models than those currently used.

2. Objectives

The specific objective of this work is to carry out an inventory that includes the experimental optical properties of the most common opaque surface finishes in the urban areas of the outskirts of the city of Madrid. Both pavements and vertical surfaces are considered in this analysis. This catalogue will be useful for deepening the knowledge of the optical characteristics of these materials and their effects on the energy performance of buildings and on outdoor comfort. In addition, the use of the experimental optical parameters will provide more realistic results from energy simulation studies. This, in turn, will allow for the elaboration of more efficient proposals for the improvement of urban spaces aimed at reducing the urban heat island effect and achieving more sustainable cities.

3. Materials and Methods

The work was carried out in two campaigns that consisted of field visits to selected neighborhoods.

3.1. First Campaign

The first step of the analysis consisted of a visual identification of the opaque materials conforming the horizontal and vertical surfaces of the urban landscape. Visits were made to eight neighborhoods along the city of Madrid: Picazo, Orcasitas, Orcasur, Fuencarral, Villaverde Bajo, Simancas, Tetuan, and Montecarmelo. Before starting the visits, a route was traced in each neighborhood to register the materials in the buildings and the urban spaces representative of the area whose identification allowed a general material characterization.

Through a walking tour, the finishing materials present along the way were photographed, including the vertical and horizontal finishes accessible from the pedestrian level. The aim was to capture the variety of combinations of textures and colors present during the tour.

In addition to the fact that the classification sought to distinguish and locate the materials in the urban environment, an attempt was made to anticipate their potential impacts on urban environment through the assignment of a descriptive reference to each photographed material. In the case of vertical finishes, the reference indicated the vertical placement within the façade or wall. This information is of interest as, although there is a greater variety of coatings in the lower parts of buildings, most of the time, they represent a low percentage of the envelope. The categories were as follows: cladding covering the total or most of the vertical element surface (TVS), cladding covering only the lower part (LVS), or cladding covering only the higher part (HVS). In the case of horizontal finishes, the reference categorizes the materials according to the specific use: sidewalks (SDW), driveways (DRW), or landscaped areas (LND). Correlative numbers were added to the reference to differentiate the materials of the same category.

Each of the photographed materials was geo-located using maps and street views on the Google maps ® system to facilitate future consultation. In the case of restricted areas for street views, general photographs of the surroundings were taken instead.

The images of the materials were included in information sheets, which in this first phase contained the assigned reference, location (neighborhood/street), estimated frequency of use of the finishing in the studied neighborhood, and perceptible morpho-material characteristics. The latter were determined through an evaluation of the finishes through the eyes of trained personnel and refers to surface material, color, tone, aging level, texture, and size of the unitary element, if applicable. In the case of vertical finishes, the estimated wall height (expressed as building levels) and orientation were also collected.

3.2. Second Campaign

The second campaign consisted of recording the optical properties of the materials identified in the first campaign as the most frequently occurring finishes in the sample, as well as those with the largest surface area. In situ measurement of the reflectance was carried out at representative and accessible urban elements. The reflectance was recorded in the 350 to 1700 nm wavelength range (covering 95% of the total solar energy) with a Stellarnet handheld fiber optic equipment fitted with a reflectance probe. The equipment consists of a tungsten halogen lamp with a color-equalizing filter, a miniature spectrometer covering the wavelength range between 350 and 1080 nm (model BLK-C-SR), and another spectrometer covering an overlapping range from 900 to 1700 nm (model Dwarf Star). These elements were connected through a fiber optic reflectance probe in which seven illumination fibers were installed around a central reading fiber. The measuring system allowed for an adequate signal-to-noise ratio with low measuring times. The probe was placed using a suitable accessory at a fixed distance from the measuring surface and was at a 90° angle. This was the most suitable configuration for the majority of the materials at the urban envelope that showed appreciable surface roughness. The system was calibrated previous to the measurement of each sample by blocking the light from the lamp to define the 0% reflectance signal and by measuring a Spectralon standard to define the 100% reflectance signal.

The solar and visible absorptance values were calculated from the mean spectrum of three measurements in each case. In addition, the three color coordinates defined in the CIELAB 1976 space, corresponding to the CIE 1964 Standard Observer and D65 Illuminant, were calculated for each sample from the mean reflectance spectrum in the visible range (380–780 nm). The L* coordinate indicated lightness, with values of 0 for black and 100 for white. The a* coordinate could have values of between −90 and +90, with negative values for green and positive values for red. Finally, the b* coordinate may also have had values of between −90 and +90, and negative was for blue, and positive was for yellow.

4. Results

4.1. First Campaign: Identification of Materials

Figure 1 shows representative images of the tasks carried out in the first campaign to identify the finishing materials in the selected neighborhoods. In the left, a map is depicted of the route taken to go through the different urban morphologies and open urban spaces encountered within the Picazo neighborhood. In the right image, the information collected at a specific area of the neighborhood is shown. This includes geo-localization and a street view picture of the area and the detailed location and image of three different vertical finishing materials that are properly identified by the assigned reference.

The results from the different neighborhoods of the city were compiled for the selection and classification of the materials more frequently used or used in larger surfaces. Table 1 is representative of the results compiled for the case of vertical finishes in the Picazo neighborhood. The data from the first campaign correspond to the groups named "General data" and "Morpho-material characteristics".

Table 1. Representative information sheet obtained from the experimental campaigns.

Neighborhood	**Picazo**
Date of data collection	18 January 2022
Campaign	1—Identification

Table 1. *Cont.*

Neighborhood	Picazo
VERTICAL FINISHING MATERIALS	
A. GENERAL DATA	
Reference	**TVS-5**
Image	
Location	García Llamas 16
Wall height	3 to 5
Wall orientation	South-east
Frequency of use	>50%
B.1. MORFO-MATERIAL CHARACTERISTICS	
Surface material	Brick
Color	Orange
Tone	Mean
Ageing level	Mean
Texture	Mean
Unit size (cm)	4 × 9
B.2.OPTO-THERMAL PARAMETERS	
Solar absorptance	0.495
Visible absorptance	0.657
Color coordinates (L*/a*/b*)	60.6/20.0/26.8
Infrared emissivity	Pending

Figure 1. Images of the tasks carried out in the first campaign in the Picazo neighborhood. **Left**: definition of the route. **Right**: geolocation and close-ups of the materials. Image created from Google earth Studio and Google Maps.

4.2. Second Campaign: Optical Characterization of Materials

The second campaign, dedicated to the in situ measurement of the finishes identified as most representative, gave rise to the results detailed as follows. Figure 2 collects the images of the twenty materials selected for the horizontal finishes. H1 to H15 correspond to finishes at the sidewalks. H1 to H3 are the most frequently used grey concrete tiles at different degradation stages and H4 and H7 are brand new pavers, in grey and pink colors, used in urban refurbishment actions in the neighborhoods. H5, H6, and H8–H11 are reddish pavement elements with different material compositions, surface patterns, and degradation stages, respectively. Specifically, H8 corresponds to a pink paver in a degraded stage at an area which was intended to be repaired with H7 pavers. H12 and H13 correspond to similar elements within the same urban area in a slightly used black-colored stage and in a degraded grey-colored stage, respectively. H14 corresponds to the prefabricated curb most present in the sample and H15 to tiles of exposed aggregate concrete. H16 to H20 correspond to the following frequent materials used in driveways: asphalt in two different degradation stages, concrete paving sets, and white paint to identify crosswalks and granite slabs, respectively.

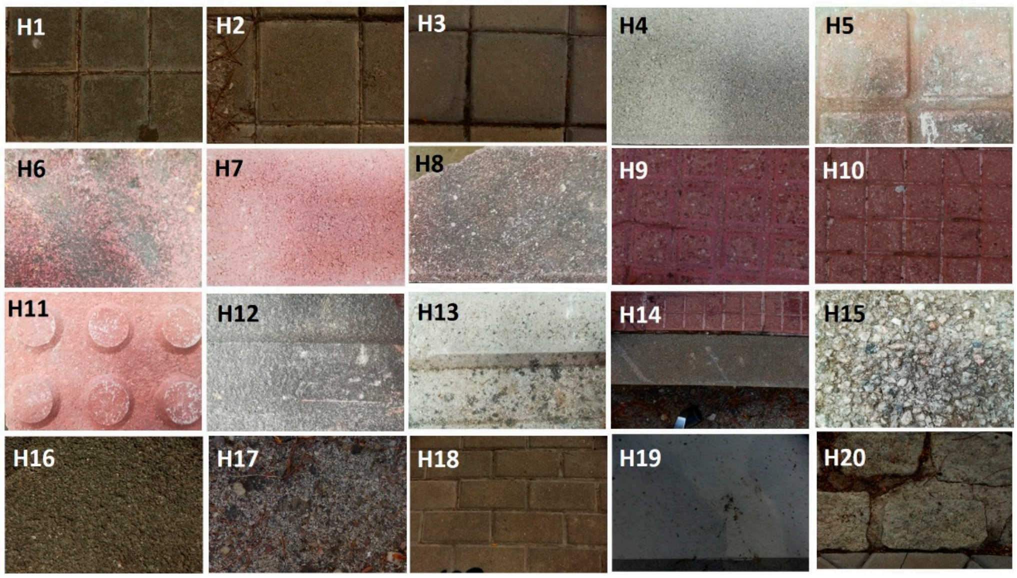


Figure 2. Horizontal surface finishes.

Twenty finishing materials were selected from the surfaces of vertical urban-facing elements (see Figure 3). V1 corresponds to calcareous stone cladding with a smooth surface, V2 to ceramic tiles with a semi-rough surface and common terracotta color, V3 and V4 to concrete blocks painted with two different light colors, V5 to white paint on rough plastering, and V6 and V7 to different continuous cement mortar wall coatings. One of the most common finishing materials in the facades found in the sample from Madrid was the facing brick. V8 to V14 are the cases selected from the wide range of colors and textures found in this type of building facade surface in the neighborhoods analyzed in this work. V15 is an exposed aggregate concrete cladding and V16 to V18 are representative of the wide variety of mortar claddings found in the facades, most of them in light or reddish colors. Finally, V19 is a pre-cast concrete white element and V20 is a granite slab.

The experimental optical response of each of the surface finishes collected in Figures 2 and 3 were measured in situ in the representative and accessible urban elements and the resulting opto-thermal parameters were added to the information sheet (see Table 1). Figure 4 shows the collected the solar absorptance values of the 40 materials under analysis, calculated from the experimental solar reflectance. The lowest value of this parameter in the case of pavements was equal to 0.270 and corresponded to sample H19, the white-painted areas identifying crosswalks in driveways (see Figure 2). Apart from this sample, all the horizontal finish materials showed a solar absorptance of between 0.87 and 0.60. In general, the results indicated that the most usual pavements of Madrid give rise to a high absorption of solar energy.

Figure 3. Vertical surface finishes.

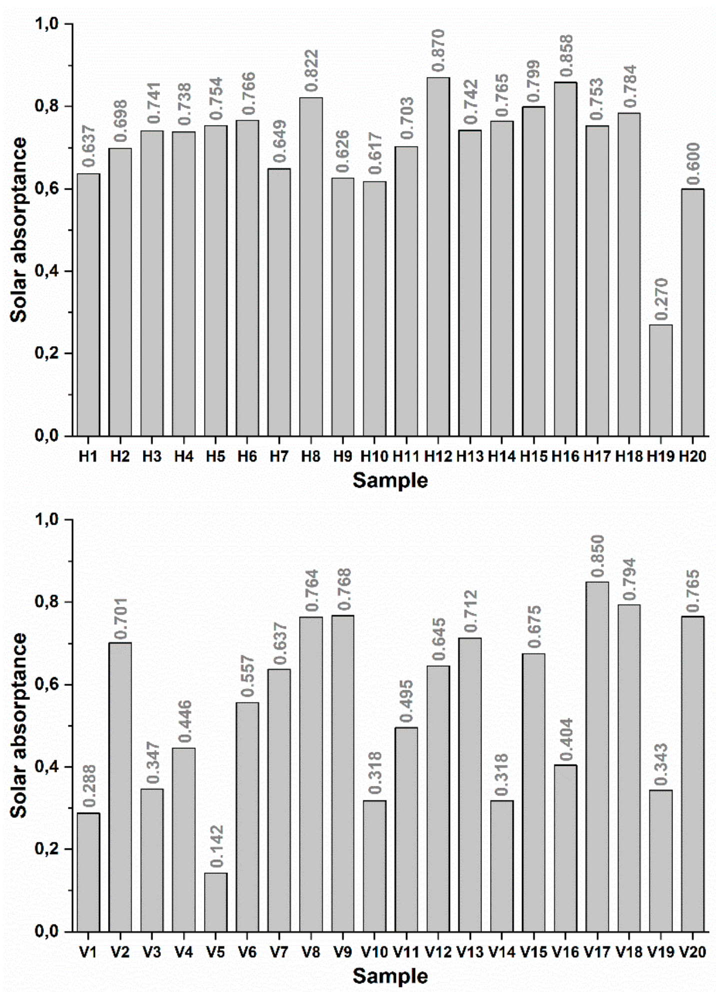


Figure 4. Solar absorptance of the materials analyzed in situ. **Top**: horizontal surface finishes. **Bottom**: vertical surface finishes.

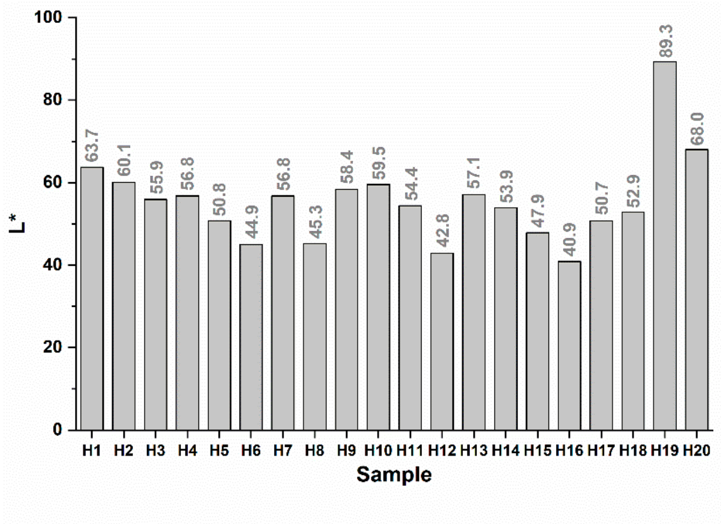
In more detail, the grey-colored cementitious pavements included in Figure 2 (samples H1 to H4, H14, and H18) showed solar absorptance values ranging from 0.64 to 0.78. There is a wide variety for the optical properties of cement and concrete samples in the literature, depending on the use of grey or white Portland cement and on the type of aggregates included in the concrete formulation [36–39]. For matrices based on grey cement, Levinson and Akbari [36] reported solar absorptance values in the range of 0.48–0.81. More recently, Sanjuan et al. [39] studied commercial pavements and obtained solar absorptance values ranging between 0.69 and 0.72 for paving materials made with dark grey Portland cement and fine siliceous aggregates. These values are in good agreement with the experimental results of the present work, taking into account that an increase in absorptance is expected by the weathering effect and the accumulation of dirt in the in-use materials analyzed [36]. Accordingly, within the reddish horizontal finishes (from H5 to H11), higher values of α_s are measured for the samples showing higher aging (H5, H6, and H8). On the contrary, a decrease in solar absorptance is observed between the new black element H12 (0.87) and the corresponding aged sample H13 (0.74). The effect of aging on the optical response of the horizontal finishes will be further described below.

Regarding the asphalt finishes, the solar absorptance obtained for sample H16 (0.86) is in good agreement with the values between 0.8 and 0.9 reported in [40] for in-use asphalt. The lower value of 0.75 obtained in the present work for the more-degraded asphalt represented by sample H17 is also coherent with the values reported for roads subject to long aging, in which the binder has almost disappeared and the surface is mainly composed of aggregates.

On the other hand, the lowest solar absorptance value for vertical finish materials was 0.142, measured in the white paint on rough plastering (V5 in Figure 3). However, a wide range of solar absorptance values was obtained for the rest of the samples, ranging from 0.850 to 0.288. This variation indicates that typical facades may be found in Madrid favoring the absorption or the reflection of the solar radiation incident on the buildings. A similar variety was reported in reference [41] for the optical response of 80 vertical claddings available in the market, including the most-used materials, as well as the new tendencies found in the city of Mendoza (Argentina). These results suggest that the choice of façade materials is not, in general, defined by the thermal effect expected by their solar response at the specific climatic conditions of the city.

The CIELab color coordinates calculated from the reflectance spectra of the finish materials are shown in Figures 5 and 6. The coordinate L* shows a variation, ΔL*, of 27.1 for the horizontal surfaces, with the same exception of H19 as before. This value is significantly lower than the ΔL* of 47.5 shown by the vertical surfaces. Regarding the a* and b* coordinates, a clearly higher dispersion was also observed in the façade finishes as compared to the pavements in Figure 6. The difference is more significant, taking into account the different scales used in the two graphs. Quantitatively, the variation of a*/b* is 11.4/6.7 in horizontal finishes and 20.5/23.6 in vertical ones.

The quantitative results of the colorimetric characterization were coherent with the appearance of the samples. Horizontal finish surfaces may be divided in two groups, as indicated in Figure 6 (left): one group corresponds to the white-, black-, and grey-colored pavements (H1–H4 and H12–H20 in Figure 2) that show lower a* values, from 0.1 (H19) to 2.4 (H14). The other group collects the reddish-colored pavements (H5–H11 in Figure 2) with higher a* values of between 6.7 for H5 and 17.1 for H7. The color contrast between the groups is used to capture the attention of the citizens, indicating proposed pathways or a proximity to risk elements, such as a driveway. The same intention of capturing attention is assumed for the black (H12) pavement with a significantly lower b* value than the rest of pavements in the low-a* group and for the white paint (H19) with the highest L* value.



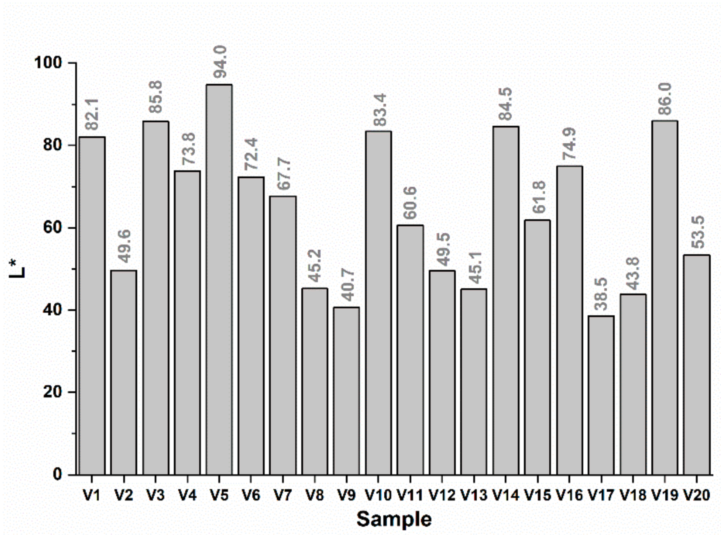


Figure 5. Color coordinate L* of the materials analyzed in situ. **Top**: horizontal surface finishes. **Bottom**: vertical surface finishes.

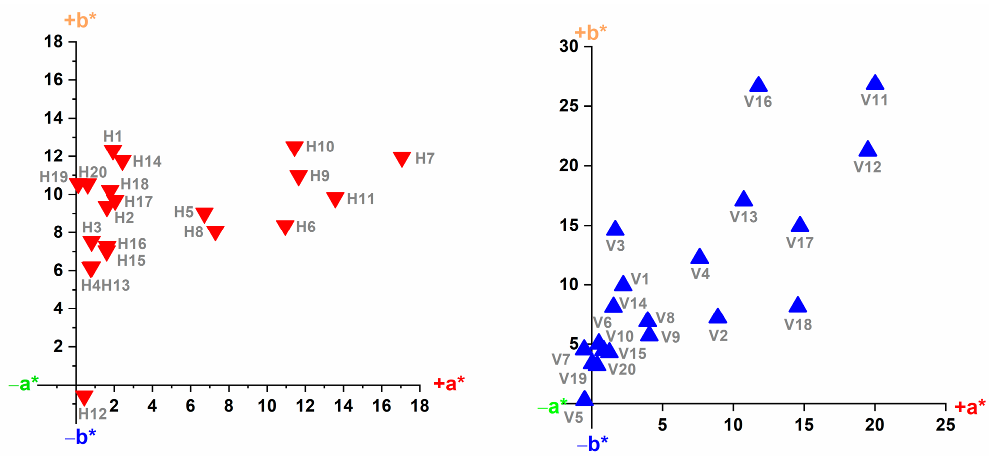


Figure 6. Color coordinates a* and b* of the materials analyzed in situ. **Left**: horizontal surface finishes. **Right**: vertical surface finishes.

A similar differentiation is applicable for the vertical finishes, although with a significantly higher dispersion within each group, as observed in Figure 6 (right). The wide variety of colorimetric responses of facade materials is probably determined by aesthetic aspects and gives rise, to a large extent, to the wide variety of solar absorptance values noted in Figure 4.

As previously noted, an interesting result from the characterization of the surface urban materials refers to the aging effect on their optical response. Figure 7 shows the mean reflectance spectra of four of the measured pavements representing different aging stages. In the case of the pink pavement named as H7 in its brand-new stage, a clear decrease in the reflectance is observed upon aging (sample H8) in the whole solar wavelength range, which gives rise to the significant increase in solar absorptance from 0.65 to 0.82 (Figure 4). This variation will increase the heating of the pavement surface by solar radiation and is coherent with previous works on the effect of weathering, soiling, and abrasion on the solar response of cement-based materials [36]. Regarding the visible range (wavelengths from 380 to 780 nm), the decrease in reflectance with aging accounts for the decrease in the L* coordinate from 56.8 for H7 to 45.3 for H8. A change in the shape of the reflectance spectrum is also observed for wavelengths higher than 616 nm. This change gives rise to the variation of the b* and, especially, the a* coordinates that takes a significantly higher value in the new H7 sample related to the reflectance maximum at 750 nm, which is not present in the aged stage (H8). The results are coherent with the appearance of the surfaces shown in Figure 2.

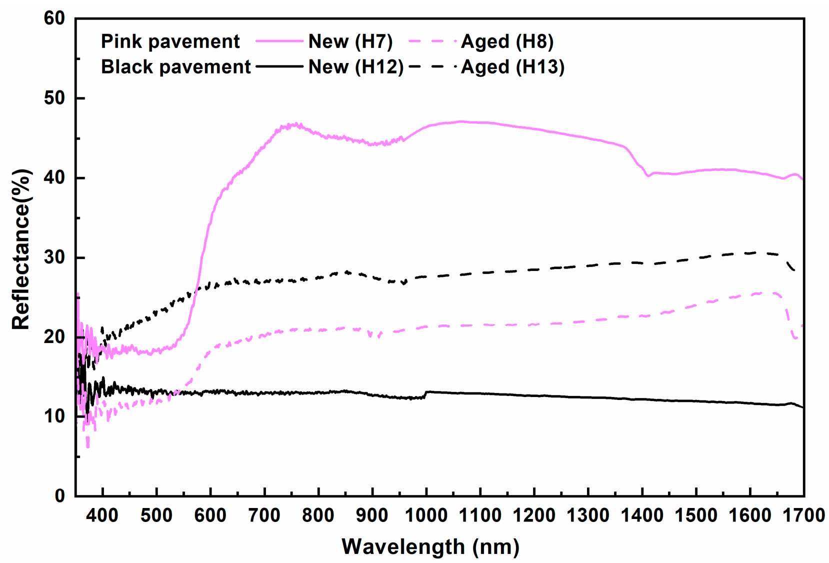


Figure 7. Mean reflectance spectra of the different horizontal surface finishes shown in Figure 2.

A different behavior of the black pavement upon aging is derived from the optical characterization of the H12 (new) and H13 (aged) samples. The new pavement shows a low and nearly constant reflectance along the solar spectral range that accounts for the high solar absorptance (0.87), the low L* value (42.8), and the a* and b* values close to zero, indicating that no color predominates in the black surface. Upon aging, the reflectance of the surface clearly increases at all the wavelengths, giving rise to the decrease in the solar absorptance down to 0.74, the increase in the L* value up to 57.1, and the coherently lighter appearance of the surface (Figure 2). The spectral curve is still flat, except for a smooth decrease in reflectance for decreasing wavelengths in the visible range, below 590 nm, that accounts for the slight increase in the b* coordinate. The change in α_s observed in this case is similar to that previously reported for the aging effect in asphalt pavements [40].

Further analysis is necessary to separate the contribution to the changes observed in the optical response of the urban materials which is due to aging from the possible contributions of other effects, such as the composition of the samples.

5. Discussion

Papers characterizing the optical properties of urban materials are mainly devoted to the analysis of innovative materials to support the interest of their development and application [42–44]. However, urban surface finishes in the outskirts of big cities usually implement conventional materials whose optical properties are scarcely studied. In addition, in most of the works considering these conventional materials [36–39,41], the optical characterization is performed at a laboratory level on new samples or those weathered under controlled conditions, which gives rise to a lower degradation as compared to the in-use samples analyzed in the present work. An exception is, for instance, the work by Sen and Roesler [40], which studied the optical properties of asphalt samples from real roads in different degradation stages and concluded an increase in the effect with aging time.

This type of controlled experiment is necessary to properly define the materials available in the market or in development within energy simulation tools and to predict the effect of their aging in studies of comfort and energy efficiency, both at the building or urban scale. However, in order to obtain a reliable proposal for the refurbishment of urban areas, it is also necessary to perform an in situ characterization of the in-use materials, such as the ones presented in this work. The results will be necessary for the challenging quantitative analysis of the solar energy balance obtained for in-use materials and different retrofitting options. In Qin's review on the development of cool pavements to mitigate the urban heat island effect, held in 2015, it was concluded that the influence of cool pavements on the air temperature in the urban canopy layer is unknown, and that the impact of cool pavements on the thermal conditions of adjacent buildings and pedestrians remains unknown [45]. In fact, works approaching this research gap are very scarce. In [46], a modeling approach was proposed for a detailed analysis of the impact of different pavements and meteorological conditions (wind, sun, and rain) on the absorption and storage of heat and moisture in urban environments, concluding that albedo influences pavement surface temperature in both dry and wet conditions. Remote sensing was used in [47] to assess the cooling effects of city-scale efforts to reduce the urban heat island effect, concluding that Chicago's new reflective surfaces since 1995 produced a noticeable impact on the citywide albedo, raising it by approximately 0.016, while the citywide normalized difference vegetation index (NDVI) increase was approximately 0.007. This finding, along with counts of pixels with increased albedo and NDVI, suggest that the reflective strategies influenced a larger area of the city than the vegetative methods.

In this context, the use of experimental optical properties of surface finishes in the assessment of the initial state of the urban area to be refurbished will allow for better estimating the potential improvement in urban comfort or energy demand from retrofitting actions. Moreover, those parameters related to the interaction of materials with the visible parts of the solar spectrum (visible reflectance, color coordinates, and roughness) will be useful for the analysis of the stimuli generated by the urban environment on citizens. The adequate analysis and management of these stimuli has proven to be necessary to improve the well-being of citizens. Finally, the results will also be of interest for the calibration of aircraft and spacecraft spectroscopic data used for the classification of materials at the urban scale [48].

6. Conclusions

This work presents the optical characterization of opaque surface finish materials in use in Madrid, representing a large European city. The parameters related to the interaction of solar radiation with those materials that affect the city's sustainability are defined and collected in a format useful for future consultation. The experimental results obtained from the in situ measurements in the city of Madrid indicate that most of the materials used in pavements favor glare reduction, as well as solar heating. A wide variety of responses are obtained in the case of facade materials, likely determined by aesthetic aspects that are related to the visual perception of citizens more so than to the thermal implications.

Different lines of action are planned to complete the experimental analysis of the optical response of opaque surface finishes in the city of Madrid. On the one hand, the characterization of the urban materials presented in this work should be completed by the in situ measurement of their emissivity in order to complete the knowledge of their thermo-optical response. On the other hand, the inventory of urban materials in use in the city of Madrid should be completed with the selection and characterization of the most usual materials in roofs. In this case, the in situ characterization may require other approaches, such as the use of drones.

In future research, a quantitative analysis of the solar energy balance obtained for the in-use materials and different retrofitting options will be addressed, including the possible aging effects. The analysis will be based on combining urban outdoor and building indoor energy modeling, and outdoor environmental quality monitoring of the stressed areas of the city under analysis. Finally, the effects of vehicles typically parked and driving along the roads will be considered in future projects, as the solar absorption at their metal surfaces and their shading in parking areas may also affect the solar energy balance.

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