Energy and Buildings 76 (2014) 615–621

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Reflectance properties analysis of mineral based mortars for renders: Research of their energy performance

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ARTICLE INFO

Article history:
Received 30 August 2013
Received in revised form 24 February 2014
Accepted 9 March 2014
Available online 24 March 2014

Keywords:
Façade
Render
Lime
Reflectance
Radiative
Energy

ABSTRACT

Passive performance of buildings is nowadays one of the key points, not only for reducing energy consumption of buildings, but also for decreasing "fuel poverty". Among the constructive systems in buildings, façades are the ones having higher influence on thermal performance in urban spaces. Lime renders are specialized systems which can improve not only the durability of the support but also the thermal properties. According to previous researches, a modification of their radiative properties can reduce thermal fluxes between 24% and 89%.

In this paper, the influences of the aggregate content in lime pastes, as well as the nature of the aggregates, colour and roughness, on the visible near and medium infrared reflectance are analyzed. Ten types of aerial lime mortars were prepared and two methods of reflectance determination were performed. Finally, the effect of the resulted reflectance on the constructive systems of façades was analyzed using pseudotime-dependent software, for which an annulation of the thermal fluxes or significant reduction of them can be observed, when modifying the aggregate nature.

1. Introduction

According to the International Energy Agency, the building sector is responsible for around 36% of the final energy consumption [1], which is mainly due to an energy-inefficient envelope followed by an intensive use of energy for conditioning [2]. In spite of the governmental efforts to improve the conditioning equipment of buildings in Spain (2005), 3.4% and 9.1% of the households cannot afford the electricity and gas–water bills, respectively [3,4]. Nowadays, "fuel poverty" is even more dramatic due to the economic crisis. Under these circumstances, energy efficiency strategies need to be considered; firstly, the constructive system performance and its adaptation to climate in order to achieve thermal comfort with the minimum energy consumption is to be analyzed, and, afterwards, the active systems effectiveness should also be taken into account [2,5].

In urban spaces, external and internal façades (courtyards or dividing walls) are the constructive system with the highest incidence on the energy demand [2]. For this reason, since the energy crisis of the 1970s, different materials and systems have been implemented to improve the thermal resistance of this constructive system, based on the conductive mechanism of thermal transmission. However, radiative properties have scarcely been analyzed, even though thermal fluxes can be reduced between 24% and 89% by modifying the radiative properties of the finishing element [6].

Moreover, 98% of the extraterrestrial solar energy is concentrated within 280 and 3000 nm [7] divided into 46% within 378–760 nm, and 29% and 15% in 762–1300 nm and 1305–2500 nm, respectively [8]. Hence, it is clear that a modification in the 378–760 nm as well as 762–2500 nm can considerably modify the performance of the surfaces. From those wavelengths onward, most of the energy is mainly absorbed by the water vapour and the carbon dioxide, while under 280 nm, the energy is absorbed by the ozone.

Concerning this, renders are commonly used as protection for the supports to guarantee structural stability as well as to adapt the building to the artistic aesthetic styles. Therefore, a thorough analysis of them is interesting from the energy point of view. In spite of the importance of this issue, the only publication related to renders is the one from Kolokotsa et al. [9] who, in 2012, published

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http://dx.doi.org/10.1016/j.enbuild.2014.03.024
0378-7788/

Table 1
Naming of the mixtures.

	Reference marble dust	Non-coloured microsilica 1	Non-coloured microsilica 2	Coloured microsilica 1	Coloured microsilica 2
1:1	R1	A1	B1	C1	D1
1:3	R2	A2	B2	C2	D2

a paper analysing the optical performance of several types of mortars applied over a brick support. In addition, reflectance of the Portland cement concrete was examined by Levinson and Akbari [10] and performed in 2010 with the publication of a prototype of a reflective floor tile [11]. In relation to the previous studies, some researches focused on the performance of the coatings [12,13]. The effect of coatings in social housing in summertime was simulated by Santamouris et al. [14]. However, the majority of materials and constructive systems were used to be placed on the roof and pavement [15–21].

In this paper, the influence of the aggregate content in lime pastes as well as the nature of the aggregates, colour and roughness on the visible, near and medium infrared reflectance are researched. Ten types of aerial lime mortars were prepared and two methods of reflectance determination were performed, namely, an experimental one based on the use of a pyranometer and a standard one with a spectrometer. Materials and methods were contrasted and some recommendations on their use have been extracted. Finally, the effect of the resulting reflectance on façades constructive systems has been analyzed using a pseudotime-dependent software.

2. Materials and methods

2.1. Materials

Following the general criteria "grease over lean", the traditional finishing layer of the renders is commonly made of a blend of fine aggregate and aerial lime [22]. A dolomitic marble dust is the most common aggregate used in Spain. Hence, a mortar comprised by this aggregate and an aerial hydrated lime CL90S, in a proportion ratio 1:1, in volume, was used as reference. In addition, the effect of the aggregate content was analyzed by the selection of a high proportion ratio 1:3, in volume – one commonly used as base layer. Table 1 shows the names of the mixtures.

The effect of the aggregate nature was evaluated by the substitution of the reference dolomitic marble dust for two types of coloured microsilica dust, which were selected to avoid the "optical roughness" effect [23]. At the same time, colour influence was evaluated by the selection of other two types of ochre-pinkish coloured microsilica dust. Fig. 1 shows the appearance of the mixtures.

Mixtures were poured into 110 mm × 110 mm moulds of 10 mm thickness to simulate a render or plaster. Then they were compacted according to UNE EN 196-1. After 7 days of curing time, the samples were demoulded and stored under laboratory conditions (60% RH and 20 °C) for 90 days to ensure the stabilization of the mineralogical properties. At this curing time, samples were mechanically smoothed and treated with sandpapers of 40, 60 and 100 grit sizes. This was done to examine the effect of roughness on the measurements. Afterwards, specimens were dried at 40 ± 5 °C during 7 days and introduced into a desiccator in order to achieve the laboratory temperature and later placed into sealed bags, where they were preserved up to the test day.

2.2. Methods

Reflectance measurements were performed by two methods: a standard one based on the use of a spectrophotometer [24], and, alternatively, a portable pyranometer was used to compare the resulted data, because of its higher availability compared to the previous one.

2.2.1. Portable pyranometer

The portable pyranometer used was a LICOR 189. This instrument measures the integrated total irradiation, independently from the incidence angle, within the 300–1100 nm wavelength range. It is equipped with a photovoltaic detector and, although its response does not cover the complete spectral range as thermopile ones do, its price and simplicity are some of the advantages taken into account for using it [25]. The procedure consisted on comparing the irradiance measurements when placed looking at the sky and facing down, with a 3 s difference between them; this implies not paying attention to temporal drift of irradiation. The device was calibrated every ten measures. However, in spite of it, under natural lighting conditions, a total error of ±5% is implied according to the manufacturer specifications, for which the typical absolute error is of 3% in the range of environmental temperatures from 15 °C to 35 °C, as well as the cosine effect [26]. This value is in accordance with similar devices [25,26].

Tests were performed in June 2009 and 2010. Selection of the days and hours was based on the maximum height of the sun with the minimum variation of the type of radiation: direct-diffuse, although variability of the sun and its effect on the measurements was controlled by performing the test in a north room with diffuse radiation towards the sun, following Akbari et al. recommendations

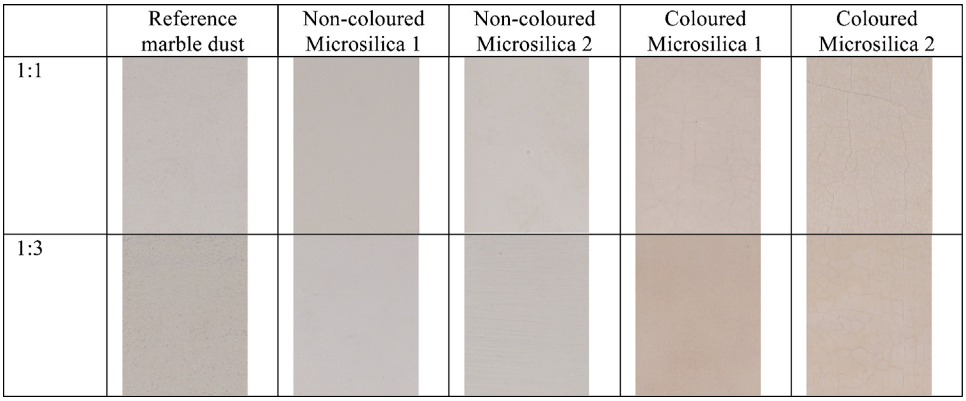


Fig. 1. Photographs of the mixtures.

[27]. For each sample, an average of twenty values were registered, with deviations smaller than 1%.

2.2.2. *Spectrophotometer*

A UV/VIS/NIR Spectrophometer, Perkin Elmer Lambda 900, with an integrating sphere of 150 mm in diameter coated with a barium sulfate paint was used. Reflectance was determined within the 250–2500 nm wavelength interval, with a gap of 10 nm. The equipment comprises a photomultiplier detector for the ultraviolet and visible ranges and a lead sulphide one for infrared. Deuterium and tungsten lamps were used for ultraviolet as well as visible and near-infrared range, respectively. The equipment consists of a two beam spectrophotometer, but the samples and the reference standard were measured at the same port of the integrating sphere. A geometry 0°:d was selected, which means that the incident light is normal to the sample, whereas the reflectance is measured in a diffused way. This selection was chosen because normal position of the incident light is the most unfavourable circumstance for which the highest amount of energy can be absorbed. The main drawback is that the perpendicular illumination of the total surface, included valleys and crests, make grooves not to have a huge influence on the results. In fact, since specular component was included in the measurement, the actual incidence angle was 8° instead of 0°.

Three measurements were taken for each sample. The reference standard was a spectralon piece referred as CD-07. A zero reflectance reading was taken using a light trap [28] designed and built at the Instituto de Optica. To evaluate the influence of the roughness, sample measurements were taken at different orientations, rotating the sample. Finally, spectral curves were smoothed with Microcal Origin software.

2.2.3. *Simulation in time-dependent state*

Simulations of the thermal performance of four types of constructive systems of façades, in pseudotime-dependent state, were performed by Antesol V.6 software developed by Dr. Manuel Martín Monroy [29]. This software gave us the pseudotime-dependent performance of the constructive system, since the temperature inside had to be fixed (in our case at 20 °C in winter time and 23 °C in summer time). The analyzed constructive systems are two characteristics types characteristic of Madrid's historical centre: a brick masonry wall 40 cm thick and a timber frame (30% wood and 70% brick) 20 cm thick, both of them with a lime render and gypsum plaster. Meanwhile, the other constructive system was common in 50–60s decades: a perforated brick masonry wall 24 cm thick with gypsum plaster, and a compound wall (24 cm of perforated brick, a wall cavity of 5 cm, a panelling with 4 cm hollow brick and gypsum plaster). Thermal resistance were 0.64, 0.59, 0.72 and 0.70 m^2 K/W, respectively.

For the analysis, south orientation façades with a roughness of 0.40 and an emissivity of 0.90 was stated. Outdoor absorptivity was adjusted to the test results while indoor one was established at 0.3. As the buildings were placed in an urban area, albedo was fixed at 0.2. Furthermore, climatic data was provided by the Agencia Estatal de Meteorología for Madrid-Retiro station [30]. Solar factor was assumed to be 0.8 in sunny days and 0.1 in cloudy ones. Finally, outdoor and indoor wind speed were 3 m/s [31] and 0.2 m/s [32], respectively.

3. Results and discussion

3.1. *Portable pyranometer*

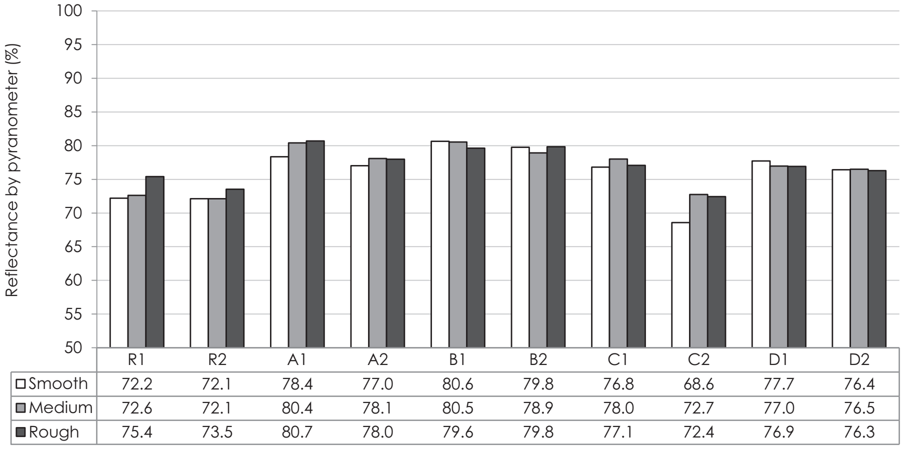
Reflectances varied between 70% and 80% (Graphic 1). Samples A1 and B1 with proportion ratio 1:1 showed the highest values, and on the opposite side, samples with R2 and C2 could be found. Hence, in general, the use of micro-silica sand improved the reflectance of the mortars between 5% and 9%, with the exception of the C2 mixture which could be due to its dark ochre-pinkish colour.

Given that the equipment registered the reflectance in a spectrum (300–1100 nm) in which visible range (380–760 nm) has significant influence, white materials showed the highest reflectance. And, for the same reason, white microsilica mortars showed a slightly higher reflectance (0.2–1.3%) than the coloured ones.

3.2. *Spectrophotometer*

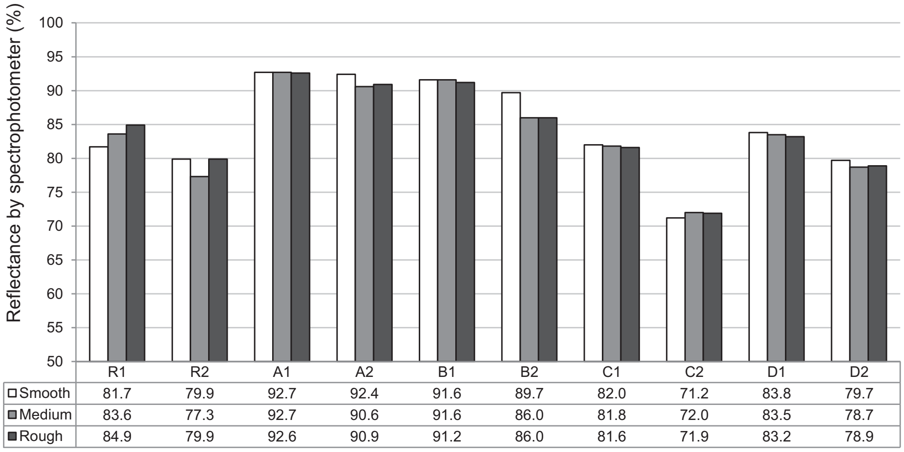
With the spectrophotometer (Graphic 2), average reflectances were within 72% and 93%, which means that they are slightly higher than those measured with the pyranometer. This implies that samples reflect higher amount of energy when it is directional rather than in a diffused way. It is important to notice that since in summertime most of the energy comes in a direct way, consequently, a rejection of solar gains increases.

Regarding roughness, differences were lower than 2% in all cases except for the R1 and B2. In these cases, reflectance increased for rough samples while the opposite took place in the micro-silica ones due to the differences in the particle size. According to Howell and Siegel, optical roughness depends on the relation between the "root-mean-square" and the wavelength [23]. It implies that, in both cases, roughness has a significant influence on the directional reflectance (their values were over the unit, namely, 12–37



	R1	R2	A1	A2	B1	B2	C1	C2	D1	D2
□ Smooth	72.2	72.1	78.4	77.0	80.6	79.8	76.8	68.6	77.7	76.4
▨ Medium	72.6	72.1	80.4	78.1	80.5	78.9	78.0	72.7	77.0	76.5
■ Rough	75.4	73.5	80.7	78.0	79.6	79.8	77.1	72.4	76.9	76.3

Graphic 1. Pyranometer reflectance as finishing function, in percentage.



	R1	R2	A1	A2	B1	B2	C1	C2	D1	D2
□ Smooth	81.7	79.9	92.7	92.4	91.6	89.7	82.0	71.2	83.8	79.7
▨ Medium	83.6	77.3	92.7	90.6	91.6	86.0	81.8	72.0	83.5	78.7
■ Rough	84.9	79.9	92.6	90.9	91.2	86.0	81.6	71.9	83.2	78.9

Graphic 2. Reflectance at 300–1100 nm, by spectrophotometer.

in microsilica samples and 90–263 in dolomitic ones). However, it is clear that incident radiation is not trapped in the irregularities of the dolomitic mortars, whereas the opposite took place in the microsilica ones.

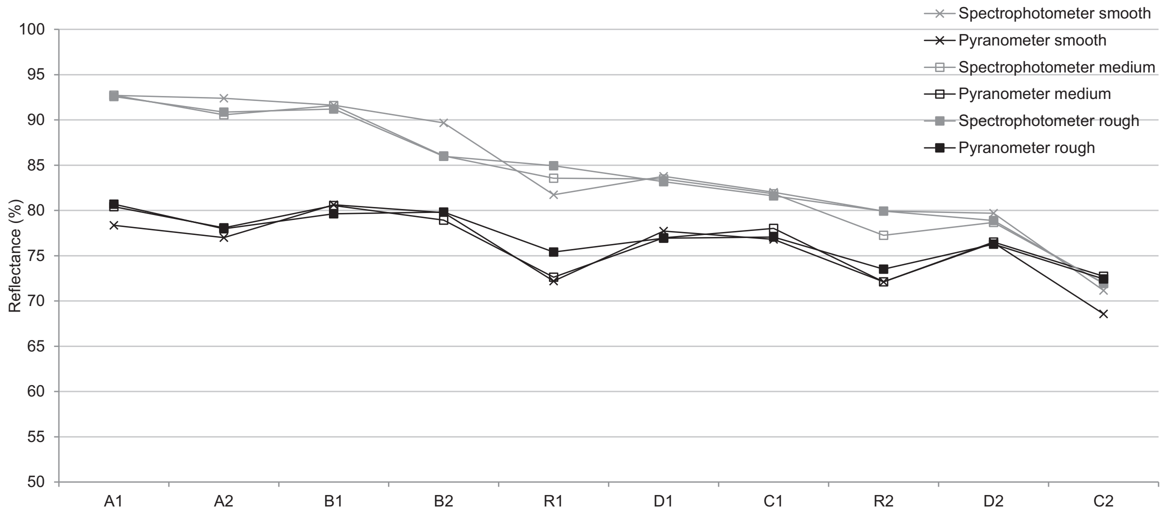
On the other hand, once again, at 300–1100 nm, the highest reflectance values were achieved by the white samples compared to the coloured ones, as was expected in the visible spectrum. This is also the reason why differences between both methods were less marked in the coloured samples (Graphic 3).

At the same time, it should be taken into account that, while pyranometer gives weighed values for the spectral distribution of daylight, the same weight is given for all the wavelengths in the case of the spectrometer by integral values. This is important since, in the cases in which samples reflectance on the near infrared would be higher than in the visible range, reflectance with the pyranometer would be lower. The reason for that is that daylight has a lower content of power in the near infrared than in the visible. This explains the low reflectance showed by the C2 samples because, as can be observed in Graphic 4, their reflectance in the visible range (380–760 nm) is low compared to the rest of the spectrum. Furthermore, in this Graphic 2, it is also clear that, in general, micro-silica samples reflect a higher amount of energy in the infrared spectrum than the dolomitic ones.

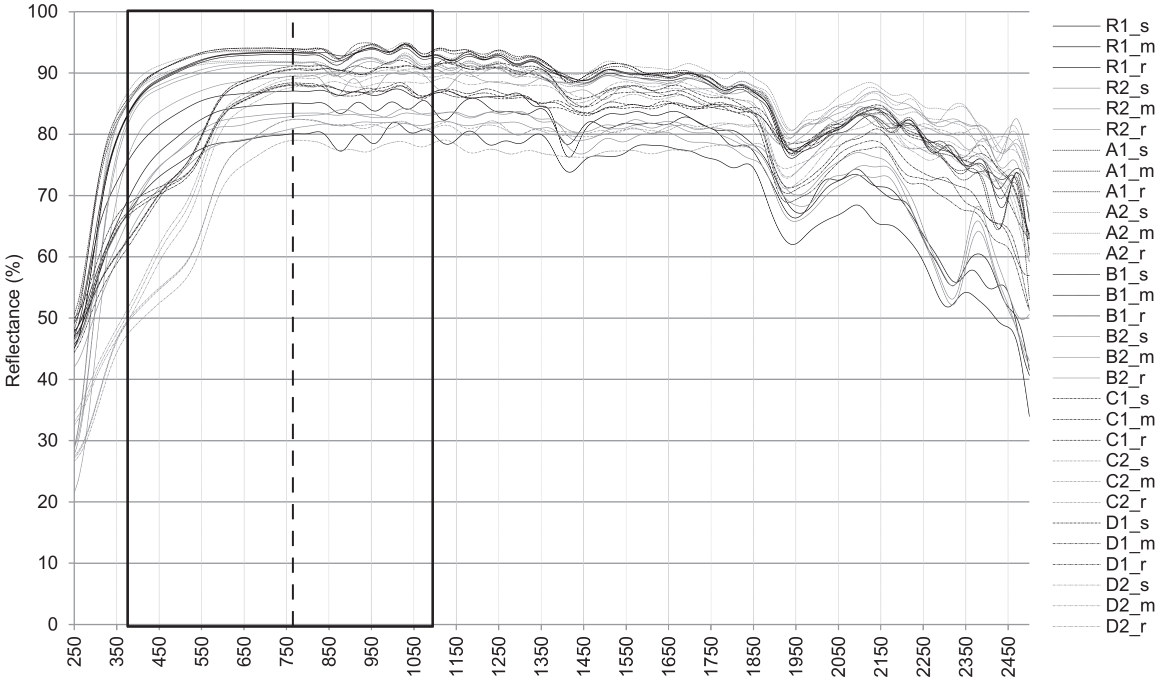
However, taking into account that 44% of the solar power is received ranging from 770 nm to 2500 nm, compared to the 46% of the visible range (380–760 nm), the former acquires a huge importance from an energy point of view since, the dazzle effect is avoided. Hence, if we compare the reflectance in the pyranometer wavelengths (300–1100 nm) and the total (300–3000 nm) as well as the medium infrared (770–2500 nm) intervals (Graphic 5), both have a notable effect, especially in coloured samples. In these ones, the highest reflectance corresponds to the medium infrared interval followed by the total reflectance or the visible one. The amount of coloured aggregate determines its influence on the reflectance. When they increase (proportion ratio 1:3), the total reflectance is higher than the visible reflectance, whereas the opposite takes place in the mixing ratios with higher amount of binder (namely, 1:1) due to the influence of the latter.

Since the higher the chromaticity of colours, the higher the differences between reflectances in different intervals, the use of the pyranometer as technique for relative reflectance measurements can be considered, in these type of materials, only in the case of samples with similar colour and lightness. Furthermore, reflectance would be lower for white colours and almost similar for coloured ones (Graphic 3) when compared to the standard method.

Taking into account the total spectrum (300–2500 nm), A1 and B1 (white micro-silica samples) increased the reflectance in 21% compared to R1, while A2 and B2 increased 15% compared to R2. Moreover, the use of coloured micro-silica aggregate also improves the reflectance compared to the reference samples, in 14% and 2% in the mixing ratios 1:1 and 1:3, respectively. The darker colour of the latter (1:3) is the reason for this reduction in the reflectance.



Graphic 3. Reflectance at 300–1100 nm, by spectrophotometer (grey) and pyranometer (black).



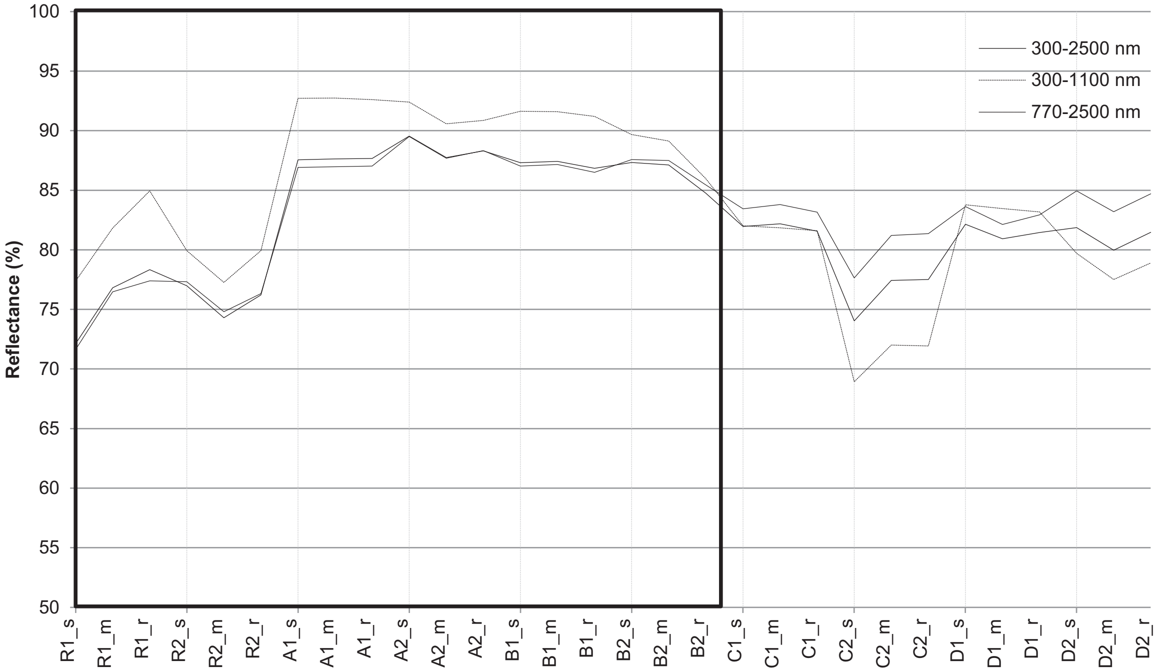
Graphic 4. Spectral reflectance of the samples versus roughness (_s: smooth, _m: medium; _r: rough). The box highlights the pyranometer interval (300–1100 nm), while the dashed line marks the limit of the visible range and the infrared one.

For the aforementioned, it is foreseeable that, in summertime, substitution of the dolomitic dust by the microsilica notably enlarges the reflectance, which implies a reduction on the thermal fluxes in the building as well as an improvement of its energy efficiency.

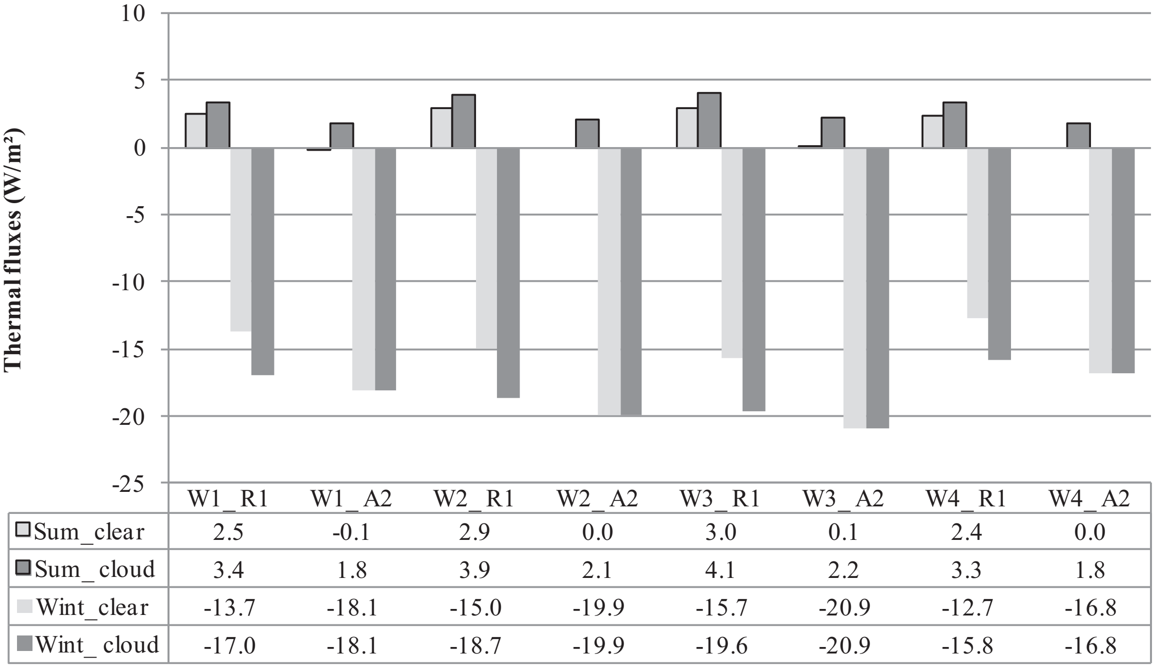
3.3. Simulation in time-dependent state

As expected, strategies are controversial depending on the season (Graphic 6). In wintertime conditions, thermal fluxes increase with the reduction of the absorptivity, because of the decrease of solar gain compensating thermal losses. Differences achieve 32–33% in clear days and 6–7% in the cloudy ones with the lower values in the reference samples. However, as the inclination of the solar beams is smaller in wintertime, solar radiation in façades placed in urban centres is limited or even null in winter [2]. Under this circumstance, differences in thermal fluxes are limited at 0.2 W/m^2 in all cases. Hence, absorptivity has almost no influence on the results.

In summertime, the reduction of solar gain by a low absorptivity of the surface implies that fluxes become null in clear days or reduce



Graphic 5. Reflectance in different wavelength intervals for different finishing (_s: smooth; _m: medium; _r: rough). The box highlights the non-coloured samples.



	W1_R1	W1_A2	W2_R1	W2_A2	W3_R1	W3_A2	W4_R1	W4_A2
□ Sum_clear	2.5	-0.1	2.9	0.0	3.0	0.1	2.4	0.0
■ Sum_cloud	3.4	1.8	3.9	2.1	4.1	2.2	3.3	1.8
▫ Wint_clear	-13.7	-18.1	-15.0	-19.9	-15.7	-20.9	-12.7	-16.8
▪ Wint_cloud	-17.0	-18.1	-18.7	-19.9	-19.6	-20.9	-15.8	-16.8

Graphic 6. Pseudotime-dependent state. Thermal fluxes in summertime (Sum) and wintertime (Wint) conditions for different types of walls (W1: solid brick masonry; W2: Wooden lattice; W3: perforated brick; W4: compounded wall).

Table 2
Pseudotime-dependent state. Clear/cloudy days (W1: solid brick masonry; W2: Wooden lattice; W3: perforated brick; W4: compounded wall).

		Summer (W/m^2)	Winter (W/m^2)
W1	$\alpha_{sw} = 0.90$	11.2/9.0	0.8/−13.3
W2	$\alpha_{sw} = 0.90$	12.7/10.2	1.1/−14.5
W3	$\alpha_{sw} = 0.90$	13.4/10.7	1.3/−15.2
W4	$\alpha_{sw} = 0.90$	10.6/8.5	0.7/−12.3

1.9 times in cloudy days which implies the best performance of the mortar A2 in comparison to the reference one.

Compared to the previous researches (6) in which thermal fluxes were reduced between 24% and 89% for samples of high absorptivity ($\alpha_{sw} = 0.90$) and even null ones ($\alpha_{sw} = 0.05$), in this case a modest reduction is achieved since absorptivity is 0.28 and 0.11 in R1 and A2, respectively. In any case, according to Table 2, comparing results with a render of high absorptivity in short wavelength ($\alpha_{sw} = 0.90$), the same controversial results can be observed and thermal fluxes are reduced between 2.5 and more than 100 times in summertime conditions. Under this circumstance, the reflectance strategy is confirmed to be suitable in the case a summer approach prevails.

On the other hand, absorptivity of the reference samples are similar to the one found in the bibliography for clear coatings [9,33,34] while microsilica mortars show similar values to some of the analyzed samples by Kolokotsa et al. [9]. In any case, both reference and microsilica mortars show considerably lower absorptivity than common building materials such as concrete [10], ceramics and cement [35] tiles [27,34] or most of pigmented films [36]. This fact confirms the use of coatings [37,38] or renders in walls in order to improve the performance of constructive systems of façade, especially in summertime conditions.

From the aforementioned, in urban spaces with solar obstruction, a reduction of the solar absorptivity should be preferred so as to improve the energy efficiency in summertime. For the same reason, this strategy should be pointed out if the ongoing trend is a widespread increase of temperatures. However, the suitable solution should be in accordance with the climatic conditions, and a thorough analysis of each specific circumstance would be necessary.

4. Conclusions

Visible and near infrared reflectance of ten types of lime mortars for renders were analyzed in order to determine the influences of the aggregate nature (dolomitic and four types of microsilica dust), content (1:1 and 1:3, by volume), colour (white and pinkish coloured) and roughness (smooth, medium and rough). Reflectances ranged between 72% and 93% which is notably high in comparison to other materials. In addition, substitution of dolomitic dust by microsilica implied an increase of 15–21% and 2–14% in the white and pinkish coloured samples, respectively.

This implies that thermal fluxes in summertime become 24–29 times lower in clear days and 1.9 times lower in cloudy days when compared to the use of the reference mortar. Meanwhile, in wintertime, considering urban spaces with solar obstruction, variation of the absorptivity has almost no influence. Compared to the theoretical analysis previously performed, a lower reduction of thermal fluxes has been achieved due to the comparison of materials with a limited difference. However, if we compared them with a material with high absorptivity in shortwavelength, a reduction of thermal fluxes between 2.5 and more than 100 times is found. From this point of view, the use of these types of renders in the constructive systems of façades considerably improves the thermal performance of them compared to common building materials, especially in summertime conditions.

At the same time, a standard method for reflectance determination with a spectrophotometer was compared to an experimental one with a pyranometer in the same wavelength range. According to the results, a pyranometer can be used as relative reflectance measurement when samples of similar colour and brightness are considered. In the case of white samples, differences of 10% were found between both methods, whereas they reduced up to 3–4% in the case of the coloured ones.

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