Thermochromic mortar façade coating: impact on the building energy performance

Revestimiento de mortero termocrómico en fachada: impacto en la eficiencia energética del edificio

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ABSTRACT

Thermochromic materials, with optical properties changing with temperature, optimize the use of solar energy by the building envelope for the improvement of energy efficiency. The purpose of this research is to determine the impact of a thermochromic mortar (TM) façade coating on the building energy performance in a Mediterranean climate. A new calculation methodology is proposed to implement the dynamical optical properties of the mortar in conventional energetic simulation tools. This study considers a coating with variable optical properties that move from 0,65 to 0,60 solar absorptance value, and a transition temperature moving from 20ºC to 35ºC. The mortar shows a dark grey colour for low temperatures and a light colour for high temperatures. The building with TM coating shows a 3 % lower yearly energy demand than the building with non-variable optical properties, with a maximum heating demand reduction reaching 8 %.

Keywords: Building energy efficiency, thermochromic materials, building adaptative façades, variable reflectivity.

RESUMEN

Los materiales termocrómicos, con propiedades ópticas variables con la temperatura, optimizan el aprovechamiento de la energía solar por la envolvente del edificio para mejorar su eficiencia energética. El objeto de este estudio es determinar el impacto de un revestimiento de mortero termocrómico (MT) en fachada sobre la eficiencia energética del edificio en un clima mediterráneo. Se propone una metodología de cálculo para implementar las propiedades ópticas variables del mortero en la simulación energética. Se estudia un revestimiento de MT con absortancia solar entre 0,65 y 0,60, y una temperatura de transición entre 20ºC y 35ºC. El mortero muestra color gris oscuro para temperaturas bajas y color claro para temperaturas altas. El edificio presenta una demanda energética anual un 3 % inferior que con revestimiento de propiedades ópticas no variables. La reducción de demanda de calefacción puede llegar a un 8%.

Palabras clave: *Eficiencia energética de edificios, materiales termocrómicos, fachadas adaptativas de edificios, reflectividad variable.*

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1. INTRODUCTION

Around 40 % of the total energy consumption in the European Union corresponds to buildings. Therefore, the reduction of energy consumption and the use of energy from renewable sources in the building sector constitute an important part of the measures necessary for reducing the Union's energy dependence and greenhouse gas emissions (1).

The demand for heating and cooling in the residential sector represented the 85 % of the total final energy consumption in this sector in 2012. In this respect, space heating provides for the biggest share as it is generally considered as a necessity. On the contrary, cooling supplies are usually lower since all cooling demands are not met and, in some Member States, most consumers accept higher indoor temperatures during warm summers (2). Several studies indicate that this cooling demand is likely to increase significantly in the future, mainly to satisfy unmet demand for thermal comfort and partly because of more extreme weather types with warmer summers, driven by climate change.

In fact, the effect of global warming on the planet is leading to extreme weather conditions, with a gradual desertification of warmer areas. In addition, the urban heat island effect, which implies an increase in the temperature of the urban area in large cities with respect to more opened surroundings or rural environment, has to be considered. The appreciable increase in temperatures reached in recent years requires bioclimatic strategies in buildings capable of adapting to the climate conditions (3).

Another important factor regarding energy consumption in buildings is energy poverty, defined as the inability to keep home adequately warm. The European Union Statistics on Income and Living Conditions (EU-SILC) estimates that in 2013, 11 % of the EU population was unable to keep their homes adequately warm during winter, with similar numbers being reported with regard to the late payment of utility bills (10 %) or presence of poor housing conditions (16 %). In 2012, the survey included a question about level of comfort during summer. In that year, 19 % of the EU population lived in a home that was not comfortably cool in summer time. In those Member States with a specific commitment to eradicate energy poverty, energy efficiency measures are a key part of the overall strategy.

Also important is that energy efficiency strategies must comply with Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings, which establishes a tightening of the minimum energy performance requirements for buildings, pursuing more ambitious objectives such as reaching near zero energy buildings.

The way to limit heating demand is well studied through building insulation and tightness against air infiltrations, while the demand for cooling is usually controlled by the parameters of shading devices linked to the windows of the building envelope.

This trend of energy regulation to make buildings increasingly airtight, inherit building models of cold climates but may be improvable for Southern European countries with Mediterranean climate that lends itself to the use of external conditions to favor the building energy performance. More specifically, the Spanish climate presents significant variations from the north coast area (temperate and rainy climate) to the peninsular meseta (dry climate with extreme temperatures in summer and winter) and the Mediterranean coast or the south of the peninsula (temperate climate with dry and hot summer). This combination of climates demands suitable architectural solutions, even with a different response from the building against the outside environment at cold winters and hot summers.

Exterior coating materials of buildings have a significant contribution to energy efficiency and warming of urban areas through the use of solar energy (4, 5). Such use depends directly on the optical properties of the exterior surface of the building, which include its reflectance and absorptance over the entire wavelength range of solar radiation (6, 7). In fact, there are different technological approaches to optimize the use of solar energy in building envelopes by innovative materials with adequate solar optical response

While cold climates require dark building coatings for maximum solar absorption, mild climates of southern Europe requires light building coatings for the maximum solar reflection. According to Pisello et all, in all the scientific contributions developed since the 70s, cool coatings demonstrated to have a non-negligible impact in warm Climate at both single-and inter-building scale, significantly improving indoor and outdoor thermal comfort with reduced building energy consumption. A large and exhaustive group of works was also dedicated to real world applications, where cool coatings demonstrated to play a key role in optimizing building energy efficiency and indoor thermal comfort conditions (8).

Also, Zinzi (9) studies cool materials for façade applications in residential buildings, focusing on the performance in the Mediterranean region, where cooling energy uses and urban heat islands are critical issues. The study shows the potentiality of this technology in terms of energy performance and impact on indoor thermal comfort. This author also concludes that cooling energy uses are reduced by 10−20 % with a novel masonry paint, produced with the inclusion of cool pigments (6) accompanied by a reduction of external surface temperatures above 6∘C with respect to the conventional masonry paint during the peak irradiation hours.

Reversible thermochromic materials are of special interest for applications in building envelopes. For cold external conditions these materials present a dark colour and low solar reflectance (high absorptance), thus increasing surface temperature. The same material reversibly turns to a light colour and high solar reflectance (low absortance) for warm conditions, thus reducing the surface heating of the envelope. This dynamic optical solar response of the material is useful to improve building energy efficiency (10).

There are also studies that compare the effect of cool materials with thermochromic materials on the energy efficiency of buildings. According to Krarti (11) the reviewed literature shows that conventional static cool roofs can provide cooling energy use savings during hot seasons, but may also cause significant heating penalties during cold seasons. That is the reason why static cool roofs are most beneficial in climates with a long cooling season and a short heating season. On the other hand, a switchable reflectance coating would especially be useful in climates with similar heating and cooling season

length, or in heating dominated climates with a large swing in temperatures between heating and cooling seasons.

There is a minimal reported analysis on the potential energy savings for switchable reflectance roofs. The limited available literature in potential energy savings for switchable reflectance roofs shows that they can provide 11 % additional energy use savings compared to static cool roofs. The methodology used to determine the material dynamic performance has been based on the combination of two states of the coating, one for summer and another for winter. Thus, a thermochromic coating, as an approach for the optimization of building envelopes, can become meaningful in the extreme seasonal weather of some areas of Southern Europe that demand different behavior for winter and summer.

This paper studies the impact of a thermochromic façade coating on the energy efficiency of buildings within a climate with extreme conditions both in summer and in winter. A calculation methodology for the implementation of the variable optical properties of thermochromic coating in a conventional energetic simulation tool is proposed that better represents the material performance with respect to that found in previous works. Using this methodology, the impact of a thermochromic mortar of façade coating on the building energy demand is determined by comparison with a conventional mortar coating with constant optical response. The evolution of the external surface temperature throughout the year is also analyzed.

2. METHODOLOGY AND CALCULATION

To study the effect of optical properties of façade coating material on the building energy efficiency energetic simulation has been performed assuming an uninsulated façade wall north oriented that, according to previous works (12), is more suitable for the use of thermochromic mortar coating.

2.1. Climatic zone

As argued in the introduction, thermochromic façade coatings for energy efficiency improvement are especially meaningful in extreme seasonal weathers that demand different behavior for winter and summer. This is the case of the climate in some areas of Spain and other Southern European countries.

According to the climatic classification established in the Spanish Building Code, Energy Saving Basic Document, section 1 "Limitation of energy demand" (13), the climatology of the Iberian Peninsula is divided according to summer climatic severity and winter climatic severity. The indicator of winter climate severity establishes five types of climates in the peninsula: A, B, C, D and E, being climatic zones A those with less severe climate in winter, and climatic zones E those with more severe climate. The indicator of the climatic severity of summer establishes four types of climates: 1, 2, 3 and 4, being climatic zone 1 that with a less severe climate in summer, and the climatic zone 4 that with a more severe climate.

Thus, to select a climate with extreme conditions in both seasons, summer and winter, climatic zones C and D must be considered, combined with zones 3 and 4. The climatic zone D3, corresponding to the climate of Madrid, has been chosen

for the present study because it has more extreme temperature peaks, with higher average temperatures in summer and lower average temperatures in winter.

The city of Madrid is located at an altitude of 667 m above sea level, whose climate can be considered as a transition between the cold semi-arid climate and the Mediterranean climate. The average temperature in the period 1981-2010 is around 15 °C. The winters are moderately cold, with average temperatures in January around 6 °C, minimum around 0°C, with frequent frosts and occasional snowfalls. On the contrary, the summers are hot, with average maximum temperatures between 32 and 33.5 °C. The daily thermal amplitude is important, reaching over 10 °C. The annual thermal amplitude is also high, around 20°C.

The annual precipitations are around 400 mm, with a minimum value in summer, characteristic of Mediterranean climates. The average humidity throughout the year is around 57 %, with a large oscillation between cold seasons, much more humid, and the hot ones, which are very dry.

2.2. Building geometry and construction

A single-family semi-detached house has been chosen as a building model in this work, which is a typical building type in the Spanish building stock, with single-family housing in row accounting for almost 20 % of the total housing built (14, 15). This building type is especially appropriate for the present study as it usually shows a higher heating and cooling demand than collective housing (multi-apartment buildings). In fact, according to SPAHOUSEC report (16) the total consumption of a single-family home in Spain is twice that of block housing, with heating consumption four times higher. Moreover, it has been stated that half of the single-family homes do not have a heating system (17), which implies a lack of comfort in the cold times of the year.

The housing building has two floors, with a total living space of 82 m². It has an envelope area of 211 m² enclosing a volume of living space of 222 m³. The windows percentage on the façade is 15 % and also an opaque north façade is studied. The compactness of the building is 1 m, which is the result of dividing the volume of living space by the envelope area. An image of the model is shown in figure 1.

Figure 1. Building model. Single-family semi-detached house.

The spaces distribution in the model corresponds to the typical one of a terraced single-family house, where some spaces have a single orientation and others have two. The building has been oriented North-South for the main façades, in order to analyse the northern spaces energy demand without the influence of solar radiation on the exterior surface wall. The influence of the direct solar radiation on the façade with thermochromic coating causes high increase of surface temperature, being in certain periods higher in the winter months than in summer. This makes the variable optical properties of the thermochromic mortar not favorable to the required demand in each season of the year (18).

The areas of the building are distributed as shown in figures 2 and 3.

As a façade type, a double-masonry wall was used with a non-ventilated intermediate air chamber. The exterior coating is conformed by a one coat mortar for external use.

The thermal transmittance (U) and solar factor (g) of the envelope elements in the building model, shown in table 1, are the guideline values indicated in the Energy Saving Document of the Spanish Building Code (13), except for the north oriented wall, without insulation, whose thermal transmittance is 1,29 W / m²·K.

Table 1. Envelope termal transmitances.

UWall (W/m²·K)	URoof (W/m²·K)	UFloor (W/m²·K)	UWindow (W/m²·K)	g (-)
1,29	0,22	0,34	2,00	0,57

2.3. Simulation model

The analysis of the energy demand in this study is based on simulations using Design Builder software (version 4.7.0), which integrates the calculation engine of Energy Plus. This tool runs the calculation of the model thermal balance in transient regime, and provides a range of environmental performance data such as energy consumption, comfort conditions, and other parameters related to building energy performance.

The calculation parameters introduced for the calculation are a heating mode air temperature set-point of 18ºC, and a cooling mode air temperature set-point of 25ºC.The schedule used for heating and cooling systems simulations is the one corresponding to dwellings from Design Builder Library, where every zone has its corresponding type of activity schedule. The climate data are the one corresponding to Madrid, included in Design Building library and no external shading devices have been considered.

As commented previously, the study is focused on the impact of optical exterior surface properties on building energy performance. The optical properties for opaque materials required by the simulation tool are: visible absorptance, solar absorptance and emissivity (thermal absorptance). The visible and solar absorptance of a thermochromic mortar based on black organic microencapsulated pigment (10) are considered as determined following UNE-EN 410: 1998 standard (19) from experimental reflectance spectra. The optical response of the mortar has been calculated at specific surface
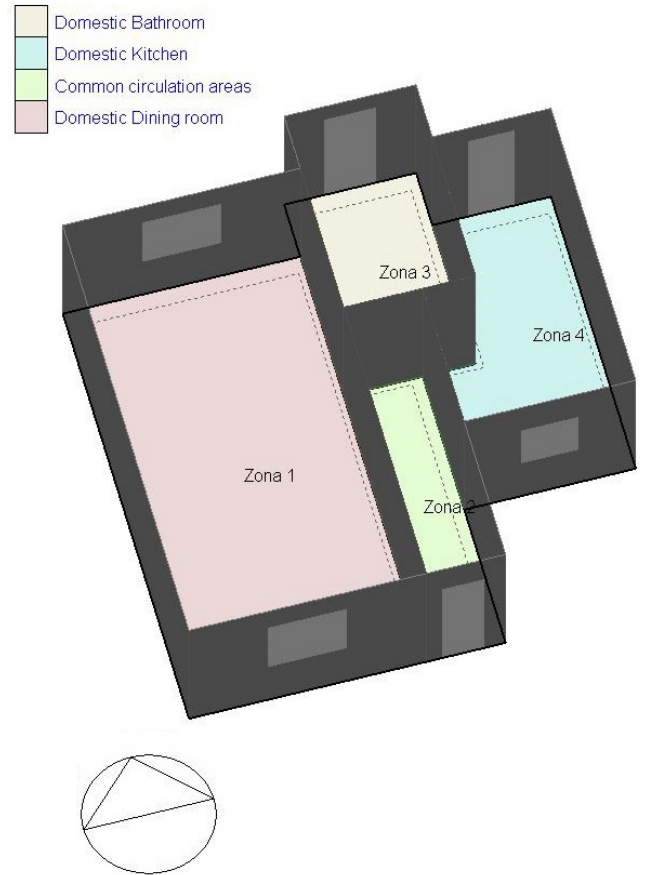

Domestic Bathroom
Domestic Kitchen
Common circulation areas
Domestic Dining room

Figure 2. Rooms layout scheme: 1st floor.

Domestic Bedroom
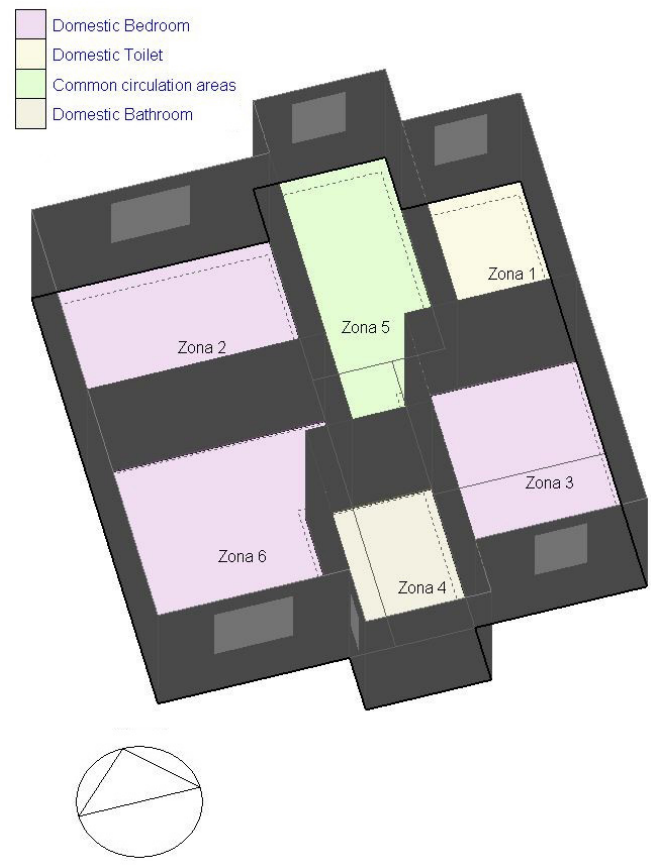Domestic Toilet
Common circulation areas
Domestic Bathroom

Figure 3. Rooms layout scheme: 2nd floor.

temperatures of 20ºC, 25ºC, 30ºC and 35ºC (table 2) that cover the range at which the pigment is expected to show thermochromic variation. The maximum difference of optical response of the mortar in this temperature range is 0.04, and 0.06 in the case of solar and visible absorptance, respectively. The emissivity values have been taken from the Design Builder database (version 4.7.0).

Table 2. Optical properties of thermocromic mortar at different temperatures.

Temperature	Absorptance	
	Solar	**Visible**
20ºC	0,65	0,70
25ºC	0,64	0,70
30ºC	0,63	0,69
35ºC	0,60	0,63

3. IMPLEMENTATION OF VARIABLE OPTICAL PERFORMANCE IN CALCULATIONS

In order to analyze the effect of the thermochromic material coating with variable optical properties on the external surface temperature of the wall and the building energy demand, a simulation procedure has been proposed in Design Builder tool with the following steps:

Step 1 – System heating loads and cooling loads have been obtained by four simulations, corresponding to the fixed optical properties of the thermochromic mortar coating for the temperatures of 20ºC, 25ºC, 30ºC and 35ºC (table 2).

Step 2 – Building heating and cooling demands have been obtained from the output files provided by Design Builder for each of the previously simulated cases: hourly demand, for heating and cooling separately, throughout the year for each space and data of the exterior surface temperature of the north façade wall. The North wall has been chose because it is where the surface temperature is closest to the outside ambient temperature, not being altered by the incidence of external solar radiation as in other orientations.

Step 3 – To implement the dynamic performance of the thermochromic mortar in the building, the demand assigned to each hour is the value previously obtained with the fixed optical properties corresponding to the exterior surface temperature in the north façade provided by the simulation tool.

The heating demand of the building with thermochromic mortar coating ($D_{TC, Heat}$) is thus obtained from the total sum of the hourly demand, according to equation [1]:

$$[1] \qquad D_{TC,Heat} = \sum_{h=1}^{h=8760} D_{TC,Heat(h)}$$

Being $D_{TC, Heat (h)}$ the heating demand (kW·h) of the building with thermochromic mortar coating for the hour h, which is obtained from the previously calculated demand for the models with fixed properties coating at 25ºC and 20ºC ($D_{25,Heat(h)}$ and $D_{20Heat(h)}$ respectively), depending on the value of the surface temperature, as indicated in table 3.

Table 3. Hourly heating demand.

T_{sup} (ºC)	≥ 22,5	< 22,5
$D_{TC, Heat(h)}$	$D_{25,Heat(h)}$	$D_{20,Heat(h)}$

Similarly, the cooling demand of the building with thermochromic mortar coating (DTC,Cool) is obtained from the total sum of the hourly demand, according to equation [2]:

$$[2] \qquad D_{TC,Cool} = \sum_{h=1}^{h=8760} D_{TC,Cool(h)}$$

Being $D_{TC,Cool(h)}$ the cooling demand (kW·h) of the building with thermochromic mortar coating for hour h, which is obtained from the previously calculated demand for the models with fixed properties coating at 25ºC, 30ºC and 35ºC ($D_{25,Cool(h)}$, $D_{30Cool(h)}$ and $D_{35,Cool(h)}$ respectively), depending on the value of the surface temperature, as indicated in table 4.

Table 4. Hourly cooling demand.

T_{sup} (ºC)	≤ 27,5	27,5 < T ≤ 32,5	> 32,5
$D_{TC, Heat(h)}$	$D_{25,Cool(h)}$	$D_{30,Cool(h)}$	$D_{35,Cool(h)}$

The methodology used by other authors (20) only considers the extreme states of the variable behavior of the material, one for cooling season and the other for heating season. In this sense, the methodology proposed in this paper provides results that is more adjusted to the real behavior of the material.

4. RESULTS AND DISCUSSION

4.1. Surface temperature profiles. Colour appearance

Figure 4 shows the variation in colour appearance presented by the experimental thermochromic mortar for increasing values of its surface temperature within the thermochromic variation range. The thermochromic mortar will keep stable colour beyond this range, with the light colour observed at 35 ºC for higher temperatures and the dark colour observed at 20ºC for lower temperatures.

To define the expected effect of this behaviour in the case of applying the thermochromic mortar in a building façade, has been simulated the external surface temperature of the north facing façade of the building model described in section 2.2. Figure 4 shows the temperature profile for a full year

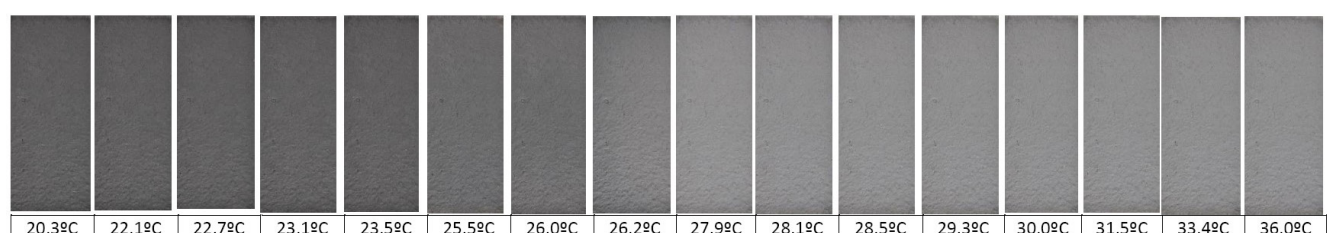| 20,3ºC | 22,1ºC | 22,7ºC | 23,1ºC | 23,5ºC | 25,5ºC | 26,0ºC | 26,2ºC | 27,9ºC | 28,1ºC | 28,5ºC | 29,3ºC | 30,0ºC | 31,5ºC | 33,4ºC | 36,0ºC |

Figure 4. Colour appearance of thermochromic mortar at different temperatures.

obtained for constant absorptance of 0.64 and 0.70 in the solar and visible range, respectively. These optical properties correspond to the thermochromic mortar at 25°C (table 2). According to this figure, there will be certain periods of the year in which the surface temperature will be beyond 35°C, so that the thermochromic mortar will keep its lighter color, while in other periods the surface temperature will be below 20°C and the mortar will keep its darker colour. Finally, in those periods in which surface temperature lie within these values (red lines in figure 5) the façade will change its colour appearance as shown in figure 4, depending on the outside temperature.

These results indicate that the use of thermochromic mortar as façade coating has an interesting aesthetic impact associated to the colour change upon variation of outside temperature that must be taken into account for its application.

4.2. Building energy demand

In order to evaluate the impact of the thermochromic mortar on the building energy efficiency, the single-family semi-detached house described in section 2.2 has been simulated with different optical behaviours of the mortar in its north façade. As indicated previously, this façade is expected to give rise to the maximum benefits from the use of thermochromic mortar coating on the building energy demand.

The energy demand values have been analyzed separately: heating, cooling and global demand and the demand for five different optical properties at the north façade of the building have been studied:

– TC-20: fixed optical properties of thermochromic mortar coating at 20°C.

– TC-25: fixed optical properties of thermochromic mortar coating at 25°C.

– TC-30: fixed optical properties of thermochromic mortar coating at 30°C.

– TC-35: fixed optical properties of thermochromic mortar coating at 35°C.

– TC-var: thermochromic mortar coating with variable optical properties (calculated with procedure described in section 3).

Moreover, two different situations have been considered: one with a 15 % of windows on the north façade that represents a typical single-family housing façade, and other completely opaque northern façade to maximize the mortar impact. This would be the case of space distribution dwellings, in which there is no façade openings in service areas.

4.2.1. North façade with windows

Figure 6 shows the heating demand obtained for the five possible optical properties considered for a north façade with a 15 % of windows. As expected, the lowest heating demand value, 24,41 kW·h/m2, is presented for the building model with fixed properties at 20°C, with a higher solar absorptance (αsolar=0,65). On the other side, the highest demand corresponds to the model simulated with TC-35 (αsolar=0,60), with a value of 25,26 kW·h/m2 as can be seen in figure 6. The energy demand for the building with thermochromic mortar is 24,49 kW·h/m2, which represents an improvement of 3 % compared to the worst case, TC-35, exceeding only 0.3 % the lowest demand of TC-20.

On the other hand, figure 7 shows that the lowest value of cooling demand for the same building model, is presented for the building with TC-35 fixed optical properties showing the lower solar absorptance (α_{solar}=0,60) with a value of 16,81 kW·h/m². As expected, the highest value is reached for TC-20 case study (α_{solar}=0,65), being 17,63 kW·h/m². The building with thermochromic mortar coating reaches a cooling demand

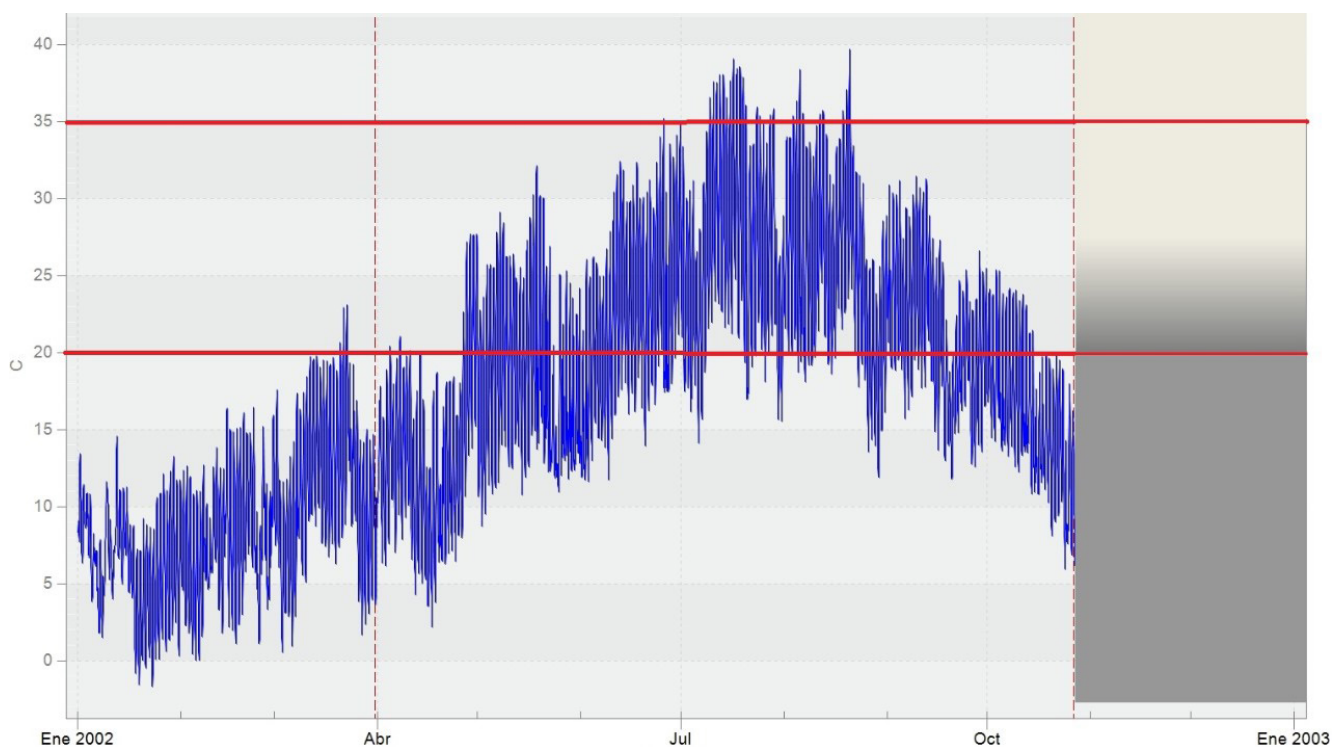Figure 5. Exterior surface temperatures of northern façade.

value of 17,47 kW·h/m², which represents a reduction of 1 % compared to the TC-20 case.

Figure 8 shows the results of total energy demand for the analysed building model in the five cases considered. It is clearly observed that the building energy demand with the dynamical optical properties of the thermochromic mortar coating is the lowest. In fact, the total demand value obtained for TC-var is 41,96 kW·h/m², which is lower than the demand obtained for any of the cases with constant optical properties. This demand reduction represents an annual improvement of 9,5 kW·h and 0,11 kW·h/m².

The results of figures 6 to 8 confirm that the thermochromic mortar coating provides a favorable effect on the building energy demand depending on the different needs of the building each time of the year. Thus, when cooling is demanded, with high temperature outside, the thermochromic coating presents a low solar absorptance, and when the building demands heating it presents a high solar absorptance, contributing in this way to an improvement of the facade energy performance.
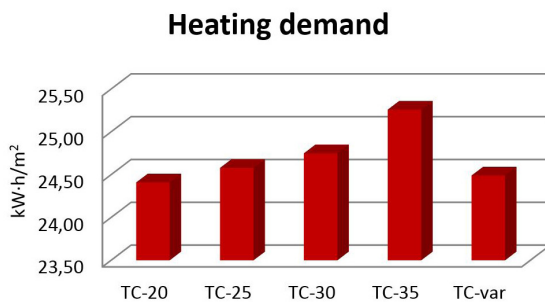
Studies from Zinzi and co-workers (8) show savings in cooling demand by the use of reflective coatings (cool facades) in uninsulated single-family house with values of 0,6 kW·h/m² in the climate of Marseille and 1,8 kW·h/m² in the climate of Athens. These energy savings are higher than those obtained in the present work, but it must be highlighted that they were obtained considering a theoretical increase of 0,1 in solar reflectance, which is twice the experimental value obtained from table 2. Moreover, reflective materials improve cooling demand but can worsen heating demand. Thus, for climates with more extreme temperatures in winter than the climates of Marseille and Athens, cooling savings may be cancelled by demand increase during heating periods by using these cool façade coatings. The use of thermochromic mortar as façade coating material improves the possibility of cool materials in climates with extreme temperatures in summer and in winter, as that of Madrid.

4.2.2. North façade opaque

In the case of the building with opaque northern façade, the best performance in heating demand, figure 9, is observed for the building with fixed properties coating at 20°C, with a value of 24,66 kW·h/m² opposite to 24,75 kW·h/m² for the building with thermochromic mortar coating. This result is qualitatively similar to that obtained for facade with a 15 % of windows (figure 6) but now the thermochromic mortar coating gives rise to a percentage improvement of 8 % with respect to TC-35. This value is significantly higher than the improvement of 3 % obtained in section 4.2.1.

In the case of cooling demand, the percent results are very similar for the façade with and without windows. In the latter, the lowest value of cooling demand corresponding to the building with TC-35 coating takes a value of 14,30 kW·h/m² and the highest value is 15,12 kW·h/m², corresponding to the TC-20 coating (figure 10). The cooling demand of the build-

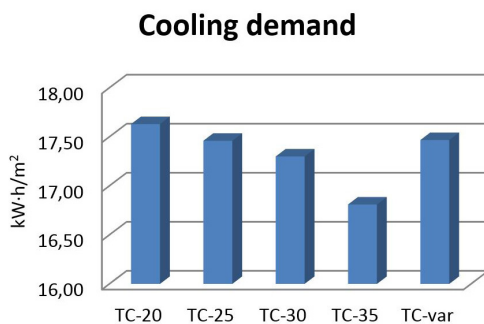Figure 6. Building model 15 % Windows North façade. Heating demand.

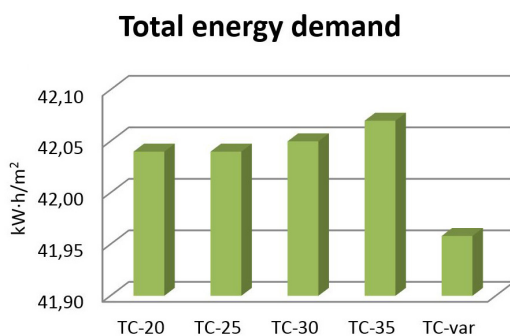Figure 7. Building model 15 % Windows North façade. Cooling demand.

Figure 8. Building model 15 % Windows North façade. Total energy demand.
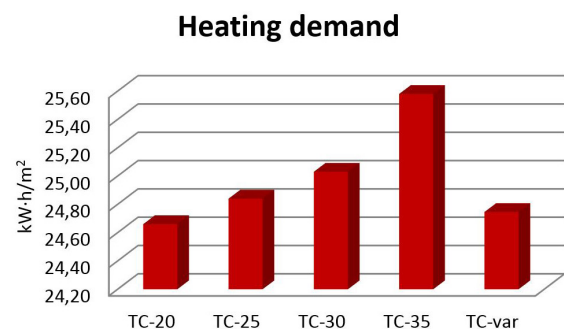

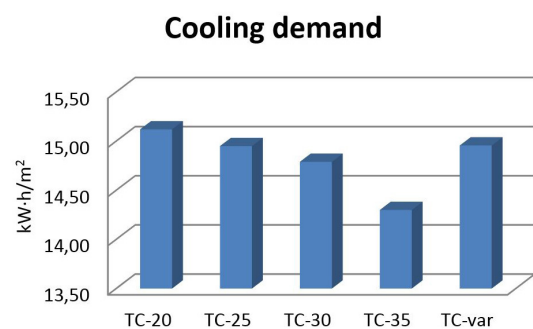Figure 9. Building model with opaque northern façade. Heating demand.

Figure 10. Building model with opaque northern facade. Cooling demand.

ing with thermochromic coating has in this case a value of 14,96 kW·h/m², which represents an improvement percentage of 1% compared to TC-20 case, same as for the façade with 15% of windows.

The annual balance of energy demand for the case of opaque northern façade (figure 11) shows the lowest value for the building with thermochromic mortar coating, with a value of 39,70 kW·h/m², which means that it improves the building's energy performance with respect to the coatings with fixed optical properties with an annual reduction of 116,29 kW·h.
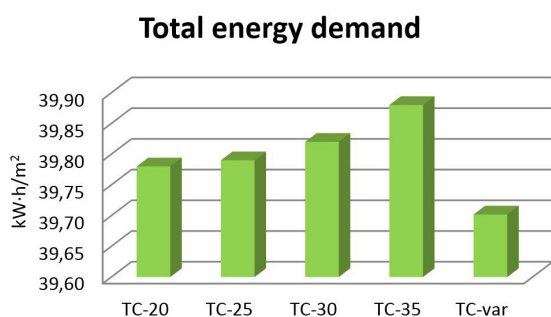
Total energy demand

Figure 11. Building model with opaque northern façade. Cooling demand.

The obtained results imply that the thermochromic mortar coating in the north orientation façade supposes a reduction of the energy demand as compared to conventional coatings of fixed optical properties, for buildings located in climates similar to the one of Madrid, with moderately extreme winters and summers. Moreover, this reduction is more noticeable the smaller the window percentage in façade.

5. CONCLUSIONS

The impact of a thermochromic mortar façade coating on the building energy efficiency has been analysed. The mortar shows variable optical properties within a temperature transition range from 20ºC (solar/visible absorptance of 0.65/0.70) to 35ºC (0.60/063). Energetic simulation is performed for a single-family semi-detached house with the thermochromic mortar at the north facing uninsulated façade. The analysis applies for a climatic zone corresponding to Southern European countries with extreme conditions in both seasons, summer and winter.

The main results of this work are the following:

– A new methodology is proposed to determine hourly energy demand values of a building model with variable optical properties of the façade exterior coating, depending on the exterior surface temperature. This methodology is based on energy demand data obtained from simulations with fixed optical properties corresponding to thermo-

chromic coating in several temperature values within its transition range.

– The simulation results show a reduction in total energy demand values for the use of thermochromic mortar with respect to evaluation with fixed optical properties coatings, due to the capacity of the material to adapt to the outside temperature. The reduction obtained in terms of total demand, moves between 9,5 kW·h – 116 kW·h, depending on the percentage of windows in the façade.

– Higher reductions are obtained in heating demand between 3-8% lower considering the thermochromic mortar than with a coating of fixed optical properties. Cooling demand does not show significant improvements because the climate studied does not present temperatures above the change temperature of the thermochromic material. This makes cooling demand always more favorable with fixed properties materials with high reflectance, although these materials would increase the heating demand in winter.

Concluding, the results for the two simulated cases, building with windows to the north façade and building with opaque north façade, show the potential of the thermochromic mortar as façade coating material to reduce building energy demand. The demand with the greatest reduction impact has been the heating for the studied climate (Madrid-D3), which presents extreme conditions both in summer and in winter, considering the results can be extrapolated to climates of similar conditions.

For future research, we propose two strategies. First, for further improvement of the building energy efficiency is considered interesting to extend the study with a thermochromic mortar façade whose temperature of change is around 10ºC below the material studied which has a change temperature around 25-30ºC. This way, the range of temperature change is more balanced with respect to the extreme temperatures of the climate studied. Second, it would be interesting increase the percentage of pigment in the thermochromic mortar, that could provide a wider range of change in the optical properties, and with it a greater impact on building energy efficiency, although it would be necessary to value the stability of the material in terms of its properties of resistance and durability

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