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Smart reversible thermochromic mortar for improvement of energy efficiency in buildings

G. Perez [a,*], V.R. Allegro [a], M. Corroto [b], A. Pons [c], A. Guerrero [a]

[a] *Institute of Construction Science Eduardo Torroja – CSIC, C/Serrano Galvache, 4, 28033 Madrid, Spain*
[b] *Otifa, Alcorcón, Spain*
[c] *Institute of Optics – CSIC, C/Serrano, 144, 28006 Madrid, Spain*

HIGHLIGHTS

- First smart reversible thermochromic mortar (SRTM) for dynamic building coating.
- Mortar composition favours stability and physical/organic activity of pigments.
- Solar absorptance decreases a 19% upon heating SRTM beyond its transition temperature.
- Suitable optical, physical, mechanical properties for energy efficiency improvement.

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ABSTRACT

A smart reversible thermochromic mortar based on ordinary white Portland cement and organic microencapsulated thermochromic pigments is presented in this work. Chemical and morphological composition of the mortar assures chemical stability and proper physical and organic activity of the pigments within the cementitious matrix. The optical properties of the mortar change with temperature at the transition value of the pigments (31 °C). For higher temperatures, the material shows a light colour and high reflectance in the visible range, while for lower temperatures it shows a dark grey colour associated to a low reflectance. Infrared spectroscopy and electron scanning microscopy results confirm the chemical and morphological stability of the microencapsulated pigments within mortar samples cured for 28 days. Finally, physic-mechanical properties of fresh and hardened mortar demonstrate the suitability of this innovative material as a dynamic building coating for improvement of energy efficiency.

1. Introduction

Important efforts are devoted nowadays in different research fields to the development of smart materials with properties controlled by external stimuli. Specifically in the field of construction materials, smart self-healing concretes obtained with different strategies show the ability to seal by themselves cracks appearing at the microscopic level with no human external intervention [1]. As another example, self-sensing concrete can monitor stress, strain, crack and damage by itself through the measurement of electrical resistance without the need of embedded, attached or remote sensors [2]. In both cases, the smart construction materials increase durability and service life of infrastructures, improving safety and reducing economic and social costs associated to failures and repair actions.

Chromogenic materials with optical properties reversibly changing upon changes of external parameters are also of interest as smart construction materials. In fact, electrochromic and thermochromic glazing are under development with variable response to solar radiation controlled by changes in an externally applied voltage and in external temperature, respectively. This type of dynamic materials may improve energy efficiency and reduce environmental impact of buildings through a proper control of the flow of visible light and solar energy through the envelope [3].

In the case of thermochromic materials, important development has been achieved in glazing with devices based on vanadium dioxide thin films that allow less solar energy passing through the glazing at high temperature than at low temperature, thus reaching indoor comfort with lower energy consumption. Most recent studies suggest that the use of VO_2 nanoparticles may significantly improve the performance of thermochromic glazing and give rise to their practical implementation in buildings [3].

* Corresponding author.
E-mail address: gperezaq@ietcc.csic.es (G. Perez).

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Recent publications demonstrate the feasible implementation of thermochromic properties in different types of construction materials, as asphalts for roads construction [4], bricks [5], elastomeric roof coatings [6] and coatings for buildings' envelopes [7].

In most cases, the thermochromic behaviour is based on organic pigments in powder or slurry form, which are encapsulated in organic microcapsules with diameter around 15 μm or lower in order to protect them from the surrounding chemicals in the specific base material. Their optical properties change from a coloured state for temperatures below a transition temperature to colourless when heated beyond this value and reversibly to coloured state when cooled again. This translates into a high solar absorption (low reflectance) in the material for cold conditions giving rise to an increase of its surface temperature. On the contrary, the material shows a low solar absorption (high reflectance) for warm conditions that avoids a high increase of its surface temperature. This smart variation of the optical response are especially interesting for application of thermochromic materials in buildings envelopes, as in both external conditions, cold or warm, the properties of the material help improving energy efficiency of the building.

There are in fact several recent works demonstrating the energy savings associated to the use of such dynamical building coatings as compared to common coatings and to the widely accepted cool materials of similar colours. These cool materials are characterized by a high reflectance in the near infrared range of the solar spectrum thus giving rise to reduced heating of the envelopes due to radiation absorption [8]. This optical response makes them useful for warm climates, while dynamic optical behaviour characteristic of smart thermochromic coatings prove to be especially beneficial in the case of climates with cold winters and warm summers [7,9,10].

For the case of façades, it is more interesting to achieve the thermochromic behaviour in a mortar finishing coating to avoid the need for an additional external coating on top of the mortar. Up to the author's knowledge, only a preliminary work dealing with thermochromic cement-based materials has been published [11]. In that work [11], the authors assess the colour change with temperature of white Portland cement (WPC) pastes with addition of thermochromic pigments synthesized in their laboratory. Thermal tests in a self-made insulated box indicate that, at cold conditions of 10 °C, a temperature 3 °C higher is achieved in a paste with a 10% of black thermochromic pigment and transition temperature about 24 °C than in a paste of raw WPC.

The present work describes the composition and main characteristics of a smart reversible thermochromic mortar based on an ordinary white Portland cement (WPC). Compatibility between the reversibly thermochromic pigments and the cementitious matrix was identified as an important issue in the first stages of the development of this innovative material. In fact, the degradation of three different commercial pigments when added to WPC paste was assessed and the resulting pastes did not show thermochromic behaviour. The highly alkaline environment of the cementitious matrix was identified as the leading degradation factor [12].

An optimized composition is proposed in the present work for the reversible thermochromic mortar that assures the chemical stability of organic encapsulated thermochromic pigments in the mortar matrix. Moreover, the morphological mortar composition is structured to asses a proper physical and organic activity of the pigments within the cementitious matrix, while preserving the necessary physical properties for a final application as building external coating.

Variation of optical properties of the mortar in the solar range upon temperature change, chemical and morphological properties of the hardened material and physic-mechanical properties of fresh and hardened mortar are presented to demonstrate the feasibility of application of this innovative material as a dynamic building coating for improvement of energy efficiency.

2. Materials and methods

2.1. Mortar components and preparation conditions

The thermochromic mortar was based on an ordinary BLII/A-L 42.5 R white Portland cement (WPC), produced in the facilities of El Alto of the Spanish company Portland Valderribas. Cement composition is collected in Table 1 in terms of the main oxides (concentration > 0.2%) as determined by X-ray fluorescence.

A commercial thermochromic pigment Chromazone Slurry Black 31 from LCR Hallcrest Ltd was used for the preparation of the mortars. This is a black coloured reversible thermochromic pigment with transition temperature of 31 °C. Fig. 1 shows the aspect of the slurry changing from a black colour for temperatures below 31 °C to light grey for temperatures beyond this transition value.

The pigment is formed by three components: a pH-sensitive colour former, which determines the colour and donates an electron upon the thermochromic reaction, an electron-accepting colour developer and a hydrophobic non-volatile solvent with a low melting point that defines the transition temperature for the thermochromic reaction. The pigment employed is enclosed in melamine formaldehyde microcapsules as a protection from aggressive environments and the slurry contains a 50% of capsules in aqueous solution.

The composition of the raw mortar (protected under Spanish Application Patent number 201731186) is shown in Table 2. It was structured to asses a proper physical and organic activity of the thermochromic pigment within the cementitious matrix, while preserving the necessary physical properties for the final application as building coating.

A combination of three different calcareous sands with different particle sizes was used for the mortar formulation, in order to

Fig. 1. Aspect of the reversibly thermochromic slurry at a temperature lower (left, at 8 °C) and higher (right, at 50 °C) than the transition temperature of 31 °C.

Table 1
Composition of white Portland cement.

	MgO	Al_2O_3	SiO_2	SO_3	K_2O	CaO	Fe_2O_3
WC	0.35	2.94	17.45	2.35	0.29	61.96	0.27