Cementitious plasters for façade finishing with phase change materials and thermochromic pigments

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Abstract. Exterior building surfaces are exposed to considerable thermal stresses and UV radiations that significantly reduce their durability. Additionally, solar and thermal energy affect energy transfer through the building envelope that impacts indoor comfort and energy demands. Thus, improving the performance of exterior finish materials in regulating exterior surface temperatures would impact the overall performance of buildings. The aim of this research is to develop a responsive cementitious finish plaster for building façade applications to act as a filter for variable solar and thermal loads. The proposed cement plaster is combined with phase change materials (PCMs) and thermochromic (TC) pigments to control solar radiation and surface temperatures dynamically on the exterior façade. This paper presents the prototype development and optical characterization of the prototypes. The objective is to investigate the interaction between different PCM and TC pigments in regulating surface temperatures. Three different melting temperatures for the PCMs were tested in consideration of two different colours of the TC paint. Twelve samples were produced with 2.5% mass fraction of PCM and TC pigment each. The emissivity of the samples was measured using infrared thermography. The results showed that a high emissivity in high temperatures and a low emissivity in colder temperatures could be achieved.

1. Introduction

Building envelope is the interface between the exterior and interior environments which impacts the indoor environmental comfort and energy demands as it controls the transfer of energy and mass. In addition to energy and mass flow through the building envelope, new climate challenges impose a more careful consideration of the long-term performance and durability of building envelope components and materials. The exterior finish layer in buildings is exposed to considerable environmental loads, namely thermal and UV radiation that over long-term exposure leads to optical degradation and thermal stresses [1]. The temperature fluctuations experienced on the exterior surface of finish materials not only decreases the durability of the material but also impacts the heat transfer through the building envelope that could impact indoor thermal comfort and energy demand in buildings [1-3].

In recent years several strategies and building materials have been introduced and used for exterior building applications for passive regulation of the environmental loads exposed to external finish surfaces to increase their long-term performance. The application of cool or reflective coatings with high solar reflectance and emissivity have been extensively studied in the literature [1,4]. While the application of reflective coatings on exterior roof or wall surfaces helps in reducing surface temperatures in the summer and decreases cooling loads, their use in temperate climates with cold winters could lead to a heating penalty due to reduced beneficial solar heat gain on the surfaces [1,4]. This factor also limits the use of such reflective coatings year around [5,6].

Recently, several strategies to optimize the performance of reflective coatings have been evaluated such as combining reflective coatings with phase change materials (PCMs) [6,7]. This combination has been proposed to benefit from the large heat storage capacity of PCMs to buffer the peak temperatures and decrease the thermal fluctuations which directly affect the durability of the finish materials. While this approach assists in regulation of thermal energy, the optical energy remains a
challenge. Another approach that is gaining attention is the use of dynamic coatings with variable optical properties using thermochromic (TC) coatings or paints [5,8]. TC paint changes its colors in response to temperature, allowing a change in its optical properties at a specific transition temperature. The solar reflectance and emittance of the TC paint are increased with higher temperatures as it turns to whiter shades, and as the temperatures go down, the solar absorptivity of the paint is increased. This mechanism allows for better annual control of solar radiation on external surfaces [5,8].

This paper is part of a broader research that aims to investigate the potential of a dynamic cementitious finish plaster for external building applications to regulate variable solar and thermal loads in a temperate climate year around. This cement plaster is combined with PCMs and TC pigments to control surface temperature fluctuations using two different mechanisms. Controlling the solar radiation using the optical properties of the TC paints and increasing the thermal stability of the plaster using PCMs by maintaining the surface temperatures for longer periods. Cementitious plasters are a prominent exterior finish material for building facades used in different building types. Several studies have been performed on the combination of cement plasters with either PCMs or TC pigments or coatings. For instance, a white cement coating combined with a black TC slurry was developed and tested for exterior finish coat applications that showed a change in solar reflectance leading to 19% lower solar absorption when heated beyond the transition temperature [9]. Another study also applied TC powder to white Portland cement paste with different colors that showed a 3 °C higher surface temperature than the regular cement paste in cold temperatures [10]. Combining cement plaster with PCMs has been extensively investigated in different studies to improve the thermal performance of the plaster. A comprehensive review has been provided by Rao et al. [11] on the combination of PCMs with cement mortars and plasters, outlining the trend of research mainly focused on adding PCM to cement plaster for energy efficiency purposes. Reporting on their enhanced ability to regulate temperature fluctuations exposed on exterior surfaces. Wang et al. [12] developed microencapsulated PCMs with thermochromic capability that demonstrated good thermal and solar control in addition to better thermal stability that could be used for multiple applications. More potential outcomes could be achieved by combining TC paint and PCMs to simultaneously benefit from optical and thermal regulation on typical finish materials for both new and retrofit façade applications.

The objective of this research is to develop different configurations of TC-PCM cement plasters and characterize their optical and thermal performance in relation to different mixture configuration. This paper presents the first phase of this research on the process of sample development, the mixing of the cement plaster with TC pigments and PCMs. Finally, the thermal emittance of the samples is evaluated.

2. Development of the cement plaster with PCMs and thermochromic samples

Microencapsulated PCMs and TC pigments were considered in this study to be readily mixed with the cement plaster base. Organic microencapsulated PCMs from Microtek Labs were used with three different melting temperatures ($T_{mp}$) of 18 °C, 24 °C, and 28 °C. The leuco dye TC powder pigments from LCR Hallcrest were selected with the transition temperature (TT) of 31 °C in two different colors of blue and red. In this case, the samples change color from blue/red to white as the surface temperature increases above 31 °C and turn back to the darker shade as temperatures go below 31 °C. Table 3 shows the properties of the selected PCMs. The range of the temperatures selected is compatible to the construction sector. The cement plaster mixture was made according to the ASTM C926-18b standard to conform to the mixture ratios of each material and the thickness requirements of plaster for exterior finish coating applications. Table 1 presents the mixture ratios for the cement plaster control sample.

| Material component | Portland cement (Type I) | Lime | Sand | Water to cement ratio |
|--------------------|--------------------------|------|------|----------------------|
| Ratio              | 1                        | 0.75 | 2    | 0.4                  |
| Amount (gr)        | 100                      | 75   | 200  | 40                   |

Regular Portland cement Type I and lime were considered as the cementitious materials, and sand was used as the aggregate. Considering the different melting temperatures and the two colors considered for
the TC pigments, twelve samples were made, including the control sample. Samples were made into small tiles with dimensions of 10 cm x 10 cm with a thickness of 1.2 cm, common in plastering applications. Given the different range of material configurations, the samples were made individually which includes the cement plaster base. The composition of each sample was made according to the weight of each constituent to ensure repeatability with the lowest error in the sample production.

Table 2 shows the content ratio of each material used in the twelve samples in this study. The addition of the PCMs and the TC pigments were based on a mass fraction of 2.5% of the cement plaster base tile. The initial water to cement ratio of 0.4 was considered for all the samples, however, considering the workability of the plaster more water was added gradually. The amount of water added was recorded individually for each sample to monitor the consistency of water ratios in the sample production. It should be noted that in order to mix the TC pigments and ensure even dispersion in the cement plaster, the pigments were first diluted in water. Based on the ratio calculations, the total amount of TC pigments in the samples was 1.4 grams, and the amount of PCM applied was 6.9 grams.  

Table 2. Content ratio of the cement plaster samples.

| Prototype | Cement plaster ratio (%) | PCM Type | Ratio (%) | TC Type | Ratio (%) * |
|-----------|--------------------------|----------|-----------|---------|-------------|
| Cont.-Base| 100%                     | -        | -         | -       | -           |
| Cont-TC-R | 97.5%                    | -        | -         | Red TC paint | 2.5%     |
| Cont-TC-B | 97.5%                    | -        | -         | Blue TC paint | 2.5%    |
| Cont-PCM18| 97.5%                    | Nextek18 | 2.5%      | -       | -           |
| TC-PCM18-R| 95%                      | Nextek18 | 2.5%      | Red TC paint | 2.5%    |
| TC-PCM18-B| 95%                      | Nextek18 | 2.5%      | Blue TC paint | 2.5%  |
| Cont-PCM24| 97.5%                    | Nextek24 | 2.5%      | -       | -           |
| TC-PCM24-R| 95%                      | Nextek24 | 2.5%      | Red TC paint | 2.5%    |
| TC-PCM24-B| 95%                      | Nextek24 | 2.5%      | Blue TC paint | 2.5%  |
| Cont-PCM28| 97.5%                    | Nextek28 | 2.5%      | -       | -           |
| TC-PCM28-R| 95%                      | Nextek28 | 2.5%      | Red TC paint | 2.5%    |
| TC-PCM28-B| 95%                      | Nextek28 | 2.5%      | Blue TC paint | 2.5%  |

* The total ratio for the TC paint refers to the diluted pigments in water which is (80% water (5.5 gr) and 20% pigment (1.4 gr))

To produce the samples, a frame was constructed to make the samples with smooth surfaces and low chances of cracking. Figure 1 shows the construction process and the final cured plaster samples. The cement plaster was mixed by hand and measured carefully before and after the mixing and then inserted into the molds. A thermocouple type T was also inserted within 5 cm inside each sample to measure interior temperatures. Samples were left to cure for seven days in controlled conditions of the lab environment with the indoor temperature of 25 °C and relative humidity of 20%. After the samples cured, as shown in figure 1, the colors can be distinguished between the samples with blue and red pigments, and particularly, the PCM control samples that show a lighter shade.

Table 3. Thermophysical properties of the PCMs used in the cement plaster.

| Material | T_{mp} (°C) | Latent heat (KJ/Kg) | Thermal conductivity (W/m.K) | Specific heat capacity (KJ/Kg.K) |
|----------|-------------|---------------------|-----------------------------|---------------------------------|
| Nextek 18| 18          | 190                 | 0.8                         | 1.44                            |
| Nextek 24| 18-25       | 170-178             | 0.8                         | 1.69                            |
| Nextek 28| 19-27       | 180-190             | 0.8                         |                                  |

The weight of the samples was measured seven days after their production. Considering a volume of 120 cm³ for the tiles, the approximate density of the samples was calculated and is presented in figure 2a. As the figure shows the control sample has the highest density, while the samples containing PCMs and the pigments hold lower densities. No particular trend can be established between the density of the samples and the added materials. However, the samples with both PCM and TC additions have lower densities compared to the control samples with only one of each except for TC-PCM18-B.
To assess the variation between the weight of the samples and the repeatability of the sample production considering the individual production method used, the total weight of the water added to each sample is plotted in figure 2b. As noted, the additional water added to the base 40 grams was in consideration of the workability of the mixture during the production process. This range of added water differs considerably between the samples. The standard deviation for the amount water added to each sample is demonstrated in figure 2b in relation to the average amount of water used which was 94.5 grams. The need for water was higher for samples with the TC pigments, which is due to the initial water used to dilute the pigments into paint before mixing it with the cement plaster base.

Figure 1. a) Mixing of cement plaster samples; b) Materials used in the plaster mix; c) finished tiles.

Figure 2. a) Density of the samples; b) Variation of total weight of the water used in the samples.

3. Optical characterization
The optical properties of materials can considerably influence their surface temperature considering how these properties impact the relation between the surfaces and solar radiation. The thermal emittance of the surfaces was measured in this study. The emissivity of the surfaces is an important parameter that determines the ability of the materials to emit infrared energy which impacts the surface temperature variations during the day and the year. Considering the dynamic nature of the TC and PCM samples in the prototypes which affects their behavior above and below the TT and Tmp, the optical tests were performed at two different temperature ranges. The tests were first performed at the temperature range of 40 °C-45 °C which is above the Tmp of all the PCMs and the TT of TC pigments. The second round of tests was performed at the range of 9 °C-12 °C, that is below the Tmp and TT of the materials.
3.1 Infrared emittance

The emissivity of the samples was experimentally estimated using infrared thermography in accordance with the ASTM E1933-14 non-contact thermometer method. A Fluke handheld infrared camera with an infrared spectral band of 7.5 $\mu$m to 14 $\mu$m and an accuracy of $\pm$2 °C was used. A black electrical tape with $\varepsilon = 0.95$ was attached to the center of the tiles as the surface modifying or control material. The tests were performed in a controlled lab environment and the images were taken from a height of 60 cm. The samples were first heated in an oven to reach the temperature of 45 °C and then removed. The infrared images were taken consecutively of each sample to be assessed for the emissivity measurements as the samples cooled to 40 °C. The temperature of the sample was measured on an area adjacent to the tape and compared to the temperature of the tape - considered as the actual temperature. The surface temperature of the sample was then adjusted accordingly to match the actual temperature of the tape to find the emissivity of the tile surface. After the images were taken from the heated samples, they were put in a freezer to reach a surface temperature of 9 °C. The same process was repeated to take at least four images of each sample to get the final average emissivity value as the samples reached 12 °C. Figure 3 shows an example of an infrared image taken from sample Cont-PCM18 in both heating and cooling cycles. The area of the black tape attached to the tiles can be clearly distinguished in the images.

![Figure 3. a) Sample Cont-PCM18 at 40 °C; b) Sample Cont-PCM18 at 12 °C.](image)

Figure 3 shows the emissivity values obtained from the infrared tests on all the samples. At 45 °C, it is ideally expected that the TC pigments are at their colorless phase, and the PCMs are melted, conversely at 9 °C, the TC pigments would be at their specified colored phase and PCMs would have solidified. While the emissivity of the samples varies in small increments, the total range of the emissivity is higher at 45 °C compared to the values recorded at 9 °C. The total range of emissivity values in the heating cycle from 40 °C to 45 °C in all the samples is from 0.952 to 0.981.

![Figure 4. Emissivity values for the cement plaster samples.](image)

The emissivity of the control sample at 40 °C is higher than the majority of the samples. Only the emissivity values of the Cont-PCM18 and Cont-TC-B samples were higher than the control sample in the heating cycle. While no specific correlations can be made, the samples containing PCM24 on average showed lower emissivity values in the heating cycle. Considering that emissivity is a more prominent factor at night and colder temperatures, the lower emissivity at colder temperatures indicates
the capability to retain heat and reduce the radiation heat exchange between the surface and the sky. In this case, a better performance is observed in control samples without PCMs and with only TC pigments that show lower emissivity values at 9 °C. This could be related to the solidification cycle of the PCMs. The control TC sample with red pigments, has the lowest emissivity of $\varepsilon = 0.9492$. The pattern between the blue and the red pigments is not linear, and these two colors show different behavior when combined with different melting temperatures of the PCMs. In-depth analysis of surface and interior temperatures of the samples in different daily and monthly conditions would provide more information on how each material configuration can regulate the surface temperature fluctuations. Additionally, the phase change cycle of the PCM and the color change of the TC paint must be studied in detail.

4. Conclusions

The paper introduced a new cement plaster with dynamic optical and thermal properties using TC pigments and PCMs. The process of prototype development was described, and it was shown that producing the samples using weight ratios for each constituent is an appropriate method for repeatable sample production. The measured emissivity values showed a non-linear relation between the different TC colors and PCM melting temperatures in both high and cold temperatures. However, the emissivity of TC-PCM samples was lower for some samples than the control sample at 9 °C, and conversely at 45 °C, comparable or higher emissivity values than the control sample were obtained. This shows that the intended purpose of the materials to control high surface temperatures with high emissivity and low surface temperatures with low emissivity can be achieved. The solar reflectance and the thermal characterization are currently investigated to further analyze the performance in different temperature and solar radiation ranges and to investigate the pattern between PCM T_m and TT of the TC paint.

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