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Development and analysis of advanced inorganic coatings for buildings and urban structures

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ABSTRACT

In recent years a steadily increasing interest has been noticed, concerning the development of advanced materials for both buildings and the urban environment. The aim of the present work is to examine the performance of inorganic coatings as a passive solar technique that contributes to buildings' energy efficiency. A number of inorganic coatings are developed. The materials used for the coatings' developed are characterized using XRD and DTA to verify their composition. Their optical properties, i.e. the solar reflectance and infrared emittance are then measured while the samples were also exposed to the outdoor environment for surface temperature measurements. Finally the energy efficiency of the specific coatings are evaluated in an insulated and non-insulated building using ESP-r modelling tool.

1. Introduction

In recent years there is a steadily increasing interest in the development of advanced materials for both buildings and the urban environment. Those materials target on the one hand to improve the energy performance of buildings, and on the other hand to mitigate the well documented urban heat island phenomenon [1–5].

Recent developments in materials' technology provide extra functionalities leading to the term of "intelligent material" which are characterized by a desired response to some external stimulus, such as temperature, light, humidity, etc. Innovative materials for buildings (coatings, tiles, etc.) and outdoor spaces (new formulations of asphalt, pavements, etc.) have been developed and tested [6–8]. Among these materials we may find cool coatings with specific optical properties, thermochromic, electrochromic and photocatalytic coatings, materials with self-cleaning functionalities, etc. [9–11].

For the development of cool materials and coatings, with increased solar reflectance and/or infrared emittance, various techniques, materials and methods are proposed. Materials that contain transparent polymeric materials, such as acrylic, along with white pigment, such as titanium dioxide (rutile), to make them opaque and reflective are proposed [12]. Other white pigments sometimes used are the anatase form of titanium dioxide, and zinc oxide. These coatings typically reflect 70–85% of the sun's energy. Aqueous dispersions of organic thermochromic pigments are used to develop thermochromic coatings having a transition temperature of 30 °C. The pigmented phase was microencapsulated showing an average particle size of 5 μm [13]. Thermochromic cement at normal temperature is proposed by [7] adding reversibly thermochromic microcapsules in white Portland cement. The research showed that the proposed materials could warm buildings in winter and avoid buildings over-heated in summer.

Even though the tested coatings range from cool materials, thermochromic, phase change materials, etc. nevertheless, weathering and corrosion can effectively diminish their performance [14]. This issue underlines the need for further research among the various materials' used

By taking into consideration the fact that lime renders, mortars and other inorganic coatings have been extensively used for restoration of historic buildings, the aim of this work is to investigate the potential of inorganic coatings as a passive cooling technique. Therefore, the specific work is focused on the development, testing and energy efficiency analysis of inorganic coatings for the building envelope. Various inorganic coatings have proved their endurance [15] and contribution to energy efficiency by various researchers [16,17]. The present work aims to contribute to

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the development and testing of new inorganic coatings. Natural hydraulic lime with pozzolanic additives, dolomite marble, quartz and limestone powder, glass beads and inorganic colour changing coatings are used. The surface temperature of the developed samples is measured using infrared thermography and surface thermocouples. A series of measurements is also performed for the evaluation of the solar reflectance and infrared emittance of the samples. Their contribution to energy efficiency is analyzed and discussed.

2. Materials and methods

The procedure followed during the samples' development resembles the application of coatings in real buildings' construction and retrofit. Some modifications in the procedure were considered necessary in order to shorten the development time. The preparation of the samples is separated into two different stages. The first stage includes the preparation of the substrate. During the second stage, the various coatings are developed and applied in the substrate.

2.1. The preparation of the substrate

The substrate is prepared by mixing 28% Portland cement, 56% limestone and 16% water following the typical composition of construction mortars. The developed substrate is then placed inside the sample holders. The substrate's thickness is almost 2.7–2.8 cm. After the development of the substrate a layer of moistened cotton is placed above the mixture to ensure proper curing of cement for a period of five days.

2.2. Design concepts and technical specifications of coatings

The coatings are developed using different compositions and raw materials. The coatings were poured over the substrate on a single layer with a thickness of 3–4 mm. The sample names and their corresponding composition are tabulated in Table 1. All the samples are cured for one month in stable humidity and temperature conditions (RH = 50 ± 5% and T = 22 ± 2 °C). A smooth and even surface is achieved for all samples by a smoothing process (Fig. 1). The various materials used are described in the following sections.

2.2.1. Mineral based binders

The binders consist of natural hydraulic lime (NHL), produced by calcining agillaceous or siliceous limestone at temperatures of 900–1200 °C used also in previous studies [17,18]. Natural hydraulic lime conforming to EN459 is typically used for repointing/rendering and building works on most masonry types. Pozzolan or pozzolanic materials react with calcium hydroxide and form hydraulic compounds acting as binders, which enhance the strength gain of hydrated, hydraulic and NHL mortars. In particular, pozzolan additions to a lime which are indicated by the letter Z, following the lime designation e.g. NHL-3.5Z (BS EN 459-1:2001), are also included in this study.

Among the specific characteristics of these materials it can be mentioned the high water permeability and durability to outdoor corrosion [19,20].

Table 1
Composition, codenames of the studied samples.

Sample code	Finishing	Ratio per volume	Type	Group
WCM-DMP	WCM/L/DMP	1/1/2	Render	1
WCM-LMP	WCM/L/LMP	1/1/2	Render	
NHL-DMP	NHL/L/DMP	1/1/2	Render	
NHL-LMP	NHL/L/LMP	1/1/2	Render	
WCM-QUA	WCM/L/QUA	1/1/1.8/0.2	Render	2
NHL-QUA	NHL/L/QUA	1/1/1.8/0.2	Render	
NHL-LMP-GB	NHL/L/LMP/GB	1/1/1.8/0.2	Render	3
NHL-DMP-GB	NHL/L/DMP/GB	1/1/1.8/0.2	Render	
WCM-DMP-GB	WCM/L/DMP/GB	1/1/2	Render	
WCM-LMP-GB	WCM/L/LMP/GB	1/1/2	Render	
P-TC	P	1	Paint	4

NHL: natural hydraulic lime NHL with pozzolanic additives; WCM: white cement Portland; P: plaster; DMP: dolomitic marble; LMP: limestone powered; QUA: quartz sand; GB: glass beads; L: hydrated lime; W: water; TC: colour changing pigment.

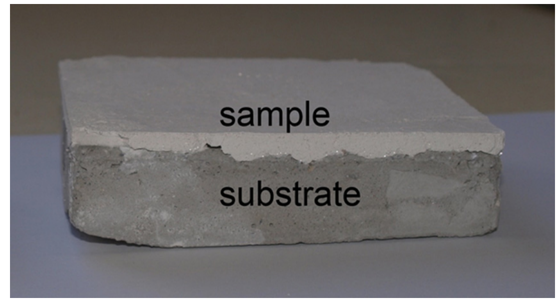

Fig. 1. The sample and substrate.

2.2.2. Aggregates

In this specific work three different types of sands are used as aggregates. The first one which has white colour, is a dolomite marble powder (DMP) [21] originated from Kavala, Greece. The second one which is also white is a limestone powered (LMP) originated from Chania, Greece. Finally the third yellow one is quartz sand (QUA) originated from Chania, Greece.

2.2.3. Inorganic colour changing pigments

Colour changing coatings have been used by various researchers [8,13] to show their ability to contribute to the reduction of the energy demand for cooling as well as for the mitigation of the urban heat island [22]. The inorganic colour changing material used is the bis(diethylammonium)tetrachlorocuprate(II), $[(CH_3CH_2)_2{-}NH_2]_2CuCl_4$ with transition temperature of 43–45 °C and transition colours from green to yellow as depicted in Fig. 2. The tetrachlorocuprate (I1) anion displays this rapid colour change due to a change of the coordination geometry from distorted square-planar to distorted tetrahedral [23].

2.3. Methodology and instrumentation

The mineralogical analysis of aggregates and the synthesized colour changing pigment is carried out by X-ray powder diffraction analysis (XRD) on a Bruker D8 Advance Diffractometer, using Ni-filtered Cu Kα radiation (35 kV 35 mA) and a Bruker Lynx Eye strip silicon detector. The XRD was considered necessary in order to verify the composition of the developed samples and especially of the colour changing pigment that was chemically synthesized in the TUC chemical laboratories. The quantitative XRD analysis is performed by the Rietveld method using the software TOPAS from BRUKER. A crystal structure Data Base from BRUKER is used for the crystalline phases, which are analyzed by the Rietveld method.

The same samples are also subjected to infrared spectroscopic Fourier transform (FTIR) analysis, to differential thermal analysis (DTA) and to thermogravimetric (TG) (DTA–TG). Both FTIR and DTA are considered necessary in order to obtain a verification concerning the chemical bonds and transition temperatures of the developed coloured changing pigment. The FTIR analysis is performed using a FTIR Perkin-Elmer 1000 spectrometer with 4 cm^{-1} resolution in the spectral range of 400–4000 cm^{-1}. The samples