



European Geosciences Union General Assembly 2016, EGU
Division Energy, Resources & Environment, ERE

PCM-enhanced lime plasters for vernacular and contemporary architecture

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Abstract

Phase Change Materials (PCMs) have the ability to absorb and release thermal energy, in the form of latent heat, during the melting or solidifying processes respectively. Thus, they may be used as additives in the production of thermally efficient composite building materials, such as plasters. This paper focuses on the design and production of PCM-enhanced lime plasters with significantly low thermal conductivity and increased specific heat capacity. The aforementioned plasters are appropriate for application in southern European climatic conditions. Due to their compatibility with traditional substrate materials, they may also be used for the renovation and retrofitting of existing structures.

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Peer-review under responsibility of the organizing committee of the General Assembly of the European Geosciences Union (EGU)

Keywords: lime; plasters; PCMs; energy efficiency; compatibility

1. Introduction

High energy consumption, due to population growth and much needed interior comfort conditions, has led to large emissions of CO₂ in the past few years. Great efforts to reduce CO₂ emissions have been made since 1997, when the European Union (EU) promised to reduce the amount of greenhouse gas emissions by 8% below the levels of 1990 emissions between 2008 and 2012, and by 20% by the end of 2020 [1].

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The building industry is one of the main consumers of energy; its contribution to global energy consumption reaches up to 40% [2]. While traditional buildings were usually constructed considering the immediate environmental climatic conditions and aiming to keep the interior spaces cool in the summer and warm in the winter, these aspects have been forgotten in modern architecture, which is mostly based on mechanical methods for heating and cooling. The latter have led to huge increases in energy demand and have resulted in an annual growth rate of energy use estimated around 2.3% [3]. As a result, EU Member States today are obliged to take measures to encourage building owners to renovate their properties by upgrading the thermal performance of existing building shells.

Traditional building insulation materials are normally used in thick or multiple layers in order to achieve higher thermal resistances. This results in complex building details, an adverse net-to-gross floor area and possibly heavier load-bearing structures [1]. At the same time, conventional insulation materials are not usually appropriate for traditional building facades. Advanced, sustainable and better performing building insulation materials are therefore needed.

Phase Change Materials (PCMs) are currently used in many different applications, due to their ability to absorb or release energy, in the form of latent heat, during the melting or solidifying process, respectively. The principle of latent heat storage can be applied to any porous building material; nevertheless, current research primarily concerns gypsum wallboards and cementitious composites [e.g. 3].

A PCM-enhanced plaster is a heat storage medium combining an appropriate PCM with a cementitious or non-cementitious matrix to produce a low-cost thermal storage material. Most of the relevant published research work refers to the use of PCMs in composites of cementitious origin, such as concrete and cement mortars [e.g. 4, 5, 6, 7, 8, 9, 10]. Nonetheless, research has also been carried out on composites with traditional binders, such as hydrated or hydraulic lime [e.g. 11].

The present research focuses on the design and production of novel cementless PCM-enhanced lime plasters with improved properties. These plasters have been designed for application in southern European climatic conditions, aiming to meet EU strategic policy targets of reduction in primary energy use in the building sector. The composite materials under study can be used not only in new structures, but also for the renovation and retrofitting of existing buildings. The lime-based nature of their matrix and their properties further extend their applicability to listed and monumental buildings.

2. Materials and Methods

Lime-based composite mixtures with constant workability (170 ± 5 mm) were designed and produced in the laboratory (Table 1). In all mixtures, the binder/aggregate ratio was 1:3 w/w, since this has been found to be the prevalent ratio in ancient and traditional lime composites, both in Cyprus and in other areas of the world [e.g. 12, 13]. The aggregate fraction used in the mixtures consisted entirely of local 0-2 mm crushed calcarenite sand. Semi-quantitative XRD analysis of this sand indicated calcite as the predominant mineral, with concentrations reaching up to 60%; albite (25%), quartz (15%) and chlorite (traces) were also present in the sample tested [14].

Table 1. Mix design of laboratory composites. All quantities are measured by mass.

Mixture	Binder (B)		Aggregates (A)	Workability (mm)	Water/Binder	PCM Additive (% B+A)
	Hydrated Lime	Hydraulic Lime				
AREF	1	-	3	175	0.88	-
HREF	-	1	3	175	0.86	-
APCM	1	-	3	171	0.90	5
HPCM	-	1	3	173	0.92	5

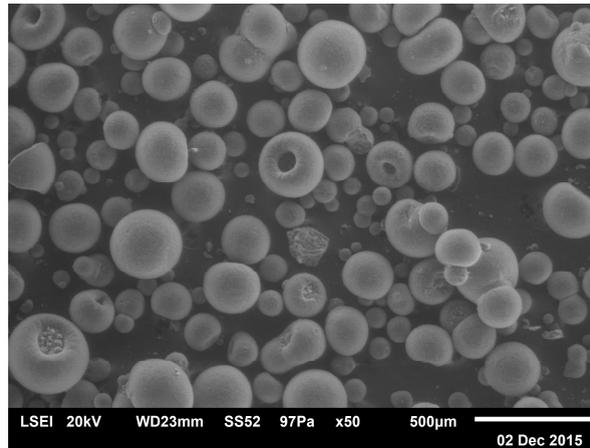


Fig. 1. SEM image of BASF Micronal DS 5038 X PCM.

Two of the mixtures (AREF and HREF) were designed as reference samples, while in the other two (APCM and HPCM) a commercial PCM (BASF Micronal DS 5038 X) was added. The aforementioned PCM is microencapsulated in powder (dry) form (Figure 1) and has its main melting and crystallization peaks at about 25°C and 24°C respectively. The latent heat capacity (solid content) of this PCM is approximately 100 kJ/kg, while its total thermal storage capacity (solid content, integral 10-30°C) is around 142 kJ/kg; the material's bulk density is 300-400 kg/m³ and its particle size is ca. 50-300 µm.

In the AREF and APCM mixtures, hydrated lime (CL70-S) supplied by Hellenic Mining Public Co. was added, while in the HREF and HPCM mixtures, hydraulic lime (Chaux Blanche Nathural 3.5) supplied by Lafarge was used. The PCMs were added to APCM and HPCM composites while mixing. The quantity of PCM in each case corresponded to 5% w/w of the total binder and aggregate content. Both mixtures with 100% hydrated lime binder (i.e. AREF and APCM) were cured in a room with stable temperature (23±5) °C. The mixtures with hydraulic lime (i.e. HREF and HPCM) were covered with water-saturated burlap and were cured in closed plastic containers at (23±5) °C.



Fig. 2. Measurement of thermal properties using the ISOMET 2104.

The thermal properties of each mixture were determined using a single specimen with dimensions 175×150×30 mm (Figure 2). The measurements were based on the analysis of the temperature response of each test specimen to heat flow impulses, using the ISOMET 2104 instrument supplied by Applied Precision. All measurements were carried out at three different areas of the specimen's smooth surface, resulting in values of thermal conductivity, volumetric heat capacity and thermal diffusivity.

Open porosity and apparent density were measured on prismatic specimens (40×40×160 mm) by vacuum saturation, using water as the wetting liquid. Water capillary absorption was also measured on the same specimens, following the method described by Hall and Hoff [15].

Prismatic specimens (40×40×160 mm) were further tested under flexural load (three-point bending) in accordance with EN 1015-11 [16]; the mean flexural strength was estimated using the results from three test specimens. The mean uniaxial compressive strength of each mixture was also determined using the six half-prisms obtained from the three-point bending test. Prior to the strength tests, the same prismatic specimens were used for the determination of the dynamic modulus of elasticity, by measuring the ultrasound speed propagation through them. All the tests took place at 28-, 56-, and 90-day intervals from the production day.

3. Results and Discussion

3.1. Thermal properties

The results of the thermal properties are summarized in Table 2. The specific heat capacity of the composites was calculated by dividing the volumetric heat capacity value, measured directly using the ISOMET 2104, with the apparent density value (see Table 3).

The thermal properties of the PCM-enhanced composites (APCM and HPCM) prove the potential of PCMs in enhancing the thermal performance of traditional lime-based plasters. This agrees well with the literature, whereby the addition of microencapsulated PCMs in lime-based mortars is shown to lead to reduced heat losses and improved thermal insulation properties [e.g. 11, 17]. In fact, Vaz Sá et al. [17] noted a 50% decrease in the thermal conductivity of hydraulic lime mortars with the addition of 25% w/w PCM. Some other researchers [e.g. 18] have also recorded similar percentages of decrease in thermal conductivity values for hydraulic lime mixtures with 20% w/w of the total mass of the dry components PCM addition. The modified hydraulic composite (HPCM) investigated in the present study shows a significantly lower (by 55%) thermal conductivity, compared to the respective reference plaster (HREF), despite the fact that the quantity of PCM additive in it was merely 5% w/w of the total binder and aggregate content. A lower thermal conductivity is also recorded for the modified hydrated composite (APCM), when the latter is compared to the hydrated reference plaster (AREF); the decrease here, however, is much less pronounced.

Increased specific heat capacity values are also shown in Table 2 for both PCM-enhanced laboratory mixtures (APCM and HPCM). Ventolà et al. [11] noted enhanced specific heat capacity values for lime-based mixtures with PCM additives as well. The aforementioned authors mention that the increase in specific heat capacity correlates positively with the PCM content.

Table 2. Thermal properties of laboratory composites at the age of 90 days after production.

Mixture	Thermal Conductivity (W/mK)	Specific Heat Capacity (10 ² J/kgK)	Thermal Diffusivity (10 ⁻⁷ m ² /s)
AREF	0.69	8.12	4.62
HREF	0.94	8.87	6.30
APCM	0.61	9.64	3.85
HPCM	0.42	10.20	2.92

The thermal diffusivity (i.e. the ability of the composites to conduct thermal energy, relative to their ability to store it), of the PCM-enhanced plasters is also significantly lower, thus further confirming the improvement in their thermal performance. Other researchers [e.g. 19] have also noted similar results with lime-based composites.

3.2. Physical properties

Table 3 summarizes the physical properties of the composites under investigation. Lower density and higher porosity values are generally observed for the PCM-enhanced mixtures (APCM and HPCM), when compared to the relevant reference composites (AREF and HREF). This finding agrees with the results reported by a number of other researchers [e.g. 11, 17, 19, 20, 21, 22]. Lucas et al. [20], in particular, reported increases in the porosity of lime-based mixtures with the inclusion of 5% PCM additive. Such increases in the porosity of the PCM-enhanced composites may be attributed to the higher water demand of the mixtures in the fresh state to reach the desired workability (see Table 1) [11, 19, 20, 23, 24, 25] and may well be correlated with the better thermal performance of the hardened products observed (Table 2) and discussed earlier (section 3.1). The increased water demand of the PCM-enhanced composites in the fresh state is attributed to the fineness of the PCM additive and to the absorption of the polymeric wall of the microcapsule. It is worth mentioning that increased porosities may also affect the performance of the end-product against artificial weathering [23].

Table 3. Physical properties of laboratory composites.

Mixture	Porosity (%)			Apparent Density (g/cm ³)			Capillary Absorption Coefficient (mm/min ^{1/2})		
	28d	56d	90d	28d	56d	90d	28d	56d	90d
AREF	31.3	28.6	29.8	1.82	1.82	1.83	1.95	0.97	0.69
HREF	34.7	34.1	33.4	1.67	1.67	1.68	1.56	1.15	0.52
APCM	33.3	33.9	33.4	1.65	1.65	1.65	1.41	0.61	0.44
HPCM	30.6	31.3	40.0	1.37	1.39	1.40	0.45	n/a	0.21

The capillary absorption coefficients of the composites decreased with the addition of PCM. Pavlik et al. [26] and Cunha et al. [24] also recorded decreased capillary absorption values when microencapsulated PCMs were added to lime-based mixtures. In fact, Pavlik et al. [26] observed a significant decrease (ca. 50%) in the capillary absorption value of a hydraulic lime composite, when a similar PCM to the one used in this study (BASF Micronal DS 5008 X) was added to a mixture at a quantity of 10% w/w of the total mass of dry components. This is analogous to the decrease observed here in the case of the hydraulic composite HPCM, albeit for the addition of 5% w/w of the total binder and aggregate content PCM additive. It is worth mentioning that a decrease in the capillary absorption value of a plaster is of great importance, since it may well be an indication for better expected durability against weathering in the long-term.

3.3. Mechanical properties

Table 4 shows the influence of PCM addition on the mechanical properties of the composites under investigation. Lower flexural and compressive strengths correspond to the hydraulic mixture with PCMs (HPCM), compared to the respective reference composite (HREF). This is entirely in line with the physical properties presented in Table 3 (e.g. higher porosity value) and it may also be partly attributed to the higher water demand of the PCM-enhanced hydraulic composite in the fresh state. Similarly inferior mechanical properties for lime-based mixtures with PCM additives are reported elsewhere in the literature [20, 22].

In contrast, the addition of PCM does not seem to affect the mechanical properties of the hydrated lime composite (APCM), despite adverse evidence found in the literature [20, 22]. In fact, the compressive strength of APCM notably improved with the addition of PCMs. Other researchers [e.g. 22, 23, 27] have also noted that the addition of PCM in hydrated lime mortars, albeit in quantities 10-30% w/w of the total mass of solid particles, does not seem to affect negatively their mechanical properties (i.e. flexural and compressive strength). Cunha et al. [27] in fact found that the addition of 20% (of the total mass of solid particles) microencapsulated PCM in a hydrated lime mortar increased the flexural strength of the hardened composite by 450%. This may be attributed to the spherical shape of the PCM-additive particles, which contributes to a more condensed microstructure [21].

The dynamic modulus of elasticity appears consistently and significantly reduced after the addition of PCMs in both the hydraulic (HPCM) and hydrated (APCM) composites. This agrees well with the measurements carried out by Vieira et al. [18] and it is also in line with the physical properties (e.g. higher porosities) reported in Table 3. The reduction in the dynamic modulus of elasticity ranges between ca. 30 to 35%, at the age of 90 days after the production of the mixtures (Table 4).

Table 4. Mechanical properties of laboratory composites.

Mixture	Flexural Strength (MPa)			Uniaxial Compressive Strength (MPa)			Modulus of Elasticity (GPa)		
	28d	56d	90d	28d	56d	90d	28d	56d	90d
AREF	0.6	0.7	0.7	1.1	1.5	1.4	4.9	4.9	4.7
HREF	0.9	1.5	1.6	4.7	8.9	8.9	6.1	6.0	5.5
APCM	0.6	0.7	0.7	1.4	2.0	1.9	2.7	3.1	3.3
HPCM	0.7	0.8	1.1	3.3	4.2	5.5	2.1	2.8	3.5

4. Conclusions

The effect of PCM addition on the thermal, physical and mechanical performance of traditional lime-based plasters has been presented in this paper. The results suggest that commercial microencapsulated Micronal DS 5038 X PCM, supplied by BASF, has the potential to enhance the thermal properties of traditional hydrated and hydraulic lime composites, since it leads to reduced thermal conductivity and diffusivity, and increased specific heat capacity. Better thermal performance was observed in the case of the hydraulic modified composite; however, the latter also showed reduced compressive and flexural strengths following the addition of the PCM. In contrast, no significant effect of the PCM additive on the mechanical properties of the hydrated lime composites was observed. Regarding their physical properties, the PCM-enhanced composites showed higher porosity and decreased density values. Nevertheless, their capillary absorption coefficient was reduced; this is very important for the long-term durability of plasters against weathering.

Future work is expected to reveal a viable compromise between the physico-mechanical and thermal properties of PCM-enhanced lime composites, through the testing of various mix designs with different quantities of PCMs. This will facilitate the use of the end-products during the thermal renovation of existing buildings.

Acknowledgements

The authors would like to acknowledge financial support from the Republic of Cyprus through the Research Promotion Foundation (Project KOINA/M-ERA.NET/1012/01).

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