Assessment of the durability of lime renders with Phase Change Material (PCM) additives against salt crystallization

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Abstract

Energy consumption in buildings is mostly associated with the use of heating and cooling systems. Renders with the addition of Phase Change Materials (PCMs) have the ability to absorb and release thermal energy, when the temperature changes accordingly, thus enhancing the thermal comfort and energy efficiency of buildings. Nevertheless, the performance of such renders with traditional binders lacks international experimental data, especially regarding their durability against salt weathering.

This paper focuses on the effect of different percentages of commercial microencapsulated powder PCMs on the properties of hydrated and hydraulic lime renders, investigating at the same time the durability of the end-products against salt crystallization. The aim is to produce energy efficient and durable lime-based renders for the upgrading of contemporary buildings, as well as for conservation purposes.

The modified composites have significantly lower thermal conductivity and increased specific heat capacity at 90 days after laboratory production, thus confirming the great potential of PCMs in enhancing the thermal performance of the aforementioned renders. Comparative tests show that the addition of PCMs has an adverse effect on the mechanical properties of the renders and a noteworthy reduction of their bulk density. Nevertheless, the salt crystallization resistance of the modified renders improves with the percentage of PCM addition, when assessed both quantitatively and qualitatively following 15 full immersion wetting and drying cycles in Na_2SO_4 solution.

Keywords: lime, composites, PCMs, salt crystallization

1. Introduction

Buildings nowadays account for about 40% of the global energy consumption.[1] The continuously augmenting energy consumption in buildings is directly linked to thermal comfort, as well as to the growth rate of population.[2] Therefore, it is imperative that efficient construction technologies and materials are used or developed for the reduction of energy consumption in the built environment and for the preservation of energy resources.

Conventional thermal insulating building materials are usually inappropriate for traditional building envelopes, since normally they are used in thick layers and most of the times they cannot offer the desired results without collateral hitches, such as load bearing problems.[3] The application of latent heat storage is probably one of the most efficient methods for enhancing the thermal behaviour of buildings, since it is based on the phase change enthalpy of a material, which can store heat within a temperature range.[4] Phase Change Materials (PCMs) are widely known due to their ability to absorb and store energy and release it back to the environment, under certain condi-

Mixture	Aggregates	Binder		Additive (% w/w of solids)	W/B	Workability (mm)
		A	H			
REFA	3	1	-	-	1.06	174
PCMA5	3	1	-	5	1.00	176
PCMA10	3	1	-	10	1.13	174
PCMA20	3	1	-	20	1.50	175
REFH	3	-	1	-	0.83	174
PCMH5	3	-	1	5	0.87	176
PCMH10	3	-	1	10	1.05	180
PCMH20	3	-	1	20	1.34	176

Table 1: Mix design of laboratory composites. All quantities are measured by mass. A: hydrated (aerial) lime; H: hydraulic lime.

tions, during the melting and solidifying process respectively.

While the introduction of Phase Change Materials in structural elements often involves the dispersion of PCMs into the matrix, encapsulation of the raw material can prevent leakage without altering the thermal energy transfer efficiency.[5] The incorporation of microencapsulated PCMs in composite construction materials, such as renders, plasters and concrete [6, 7, 8, 9], shows the inordinate interest of the research community in investigating the potential of these additives towards the enhancement of the energy performance of buildings.

Nevertheless, although PCMs have been used as additives in renders, the durability of PCM-enhanced renders has not yet been investigated. Furthermore, additional research is needed on the effects of PCM addition on the physico-mechanical properties of renders, since existing related data is rather inconclusive and contradicting (e. g. some studies report a negative impact on the mechanical properties, whereas others suggest a positive effect).[6, 10]

This study focuses on the effects of PCMs on the performance of lime-based renders, and includes research on the durability of PCM-enhanced lime renders against salt weathering. Due to the lack of a suitable standardized methodology to study the salt weathering phenomenon on renders with traditional binders under laboratory conditions, the concept of full immersion in sodium sulphate (Na_2SO_4) solution and subsequent drying is adopted. It should be noted that this test is considered to be highly aggressive and inconsistent with natural environmental conditions, let alone the fact that in this study it is performed on relatively weak construction materials, such as the lime renders under investigation.

2. Materials and methods

2.1. Materials and sample preparation

Eight lime-based mixtures were designed and produced in the laboratory; two reference mixtures and six optimized ones with the addition of PCMs at different percentages (5%, 10% and 20% w/w of solids). The binder consisted of either hydrated (aerial) lime (A: CL80 supplied by Hellenic Mining Public Co.) or natural hydraulic lime (H: NHL 3.5 supplied by Lafarge). The aggregate fraction consisted of Latouros sand, a local calcarenite fine aggregate with 0-2 mm particle size.[11] A commercial PCM (Micronal DS 5038 X supplied by BASF) was also used; this is microencapsulated in powder (dry) form and has its main melting and crystallization peaks in the range of 24-25 °C. The selected binder/aggregate ratio was 1:3 by weight, based on the prevalence of this ratio in ancient and traditional composites in Cyprus and other areas of the world.[12, 13] The water demand of each mixture was subsequently estimated after achieving a constant workability in the range of 175±5 mm according to EN 1015-3.[14] The water to binder ratio (W/B) along with all the other mix design details are given in *Table 1*.

2.2. Experimental tests

2.2.1. Physico-mechanical and thermal properties

A series of laboratory tests and analytical techniques were used for the determination of the physical and mechanical performance of the samples. All the tests were carried out at different curing times (28, 56 and 90 days); this paper, however, presents only the results recorded 90 days after casting, due to page limitation. Fresh hydrated mortars were stored in a room with constant temperature (23±5) °C and humidity (50±5%), while hydraulic ones were cured in closed plastic containers at constant temperature (23±5) °C and high humidity conditions.

Mercury Intrusion Porosimetry (MIP) was carried out on bulk samples to evaluate porosity (p_o), apparent density (p_a), average pore diameter and pore size distribution. Moreover, the capillary absorption coefficient (s) was measured on prismatic specimens (40x40x160 mm), using water as the wetting liquid. Prismatic specimens were also used for testing the materials under flexural load (three-point bending). Compression strength tests were executed on the fragments of each specimen resulting from the flexural tests. The analysis of the temperature response of the test specimens (175x50x30 mm) to heat flow impulses, following a standardized bulk measurement in accordance with ASTM E1530-11 [15], was used for the determination of the thermal properties of the renders investigated. The test was carried out in the curing room, at a stable temperature of 23±5 °C; this temperature is lower than the phase change temperature of the PCM particles (25 °C).

Level	Description
Perfect	Specimen intact
Good	Very minor damage or minor cracks
Moderate	Rounding of corners and several cracks or detachment of small fragments
Bad	Specimen with several major cracks or broken
Fail	Specimen in pieces or disintegrated

Table 2: Five-level rating classification for visual inspection of the materials resistance to salt crystallization.

2.2.2. Salt crystallization

For the assessment of the renders' resistance to salt crystallization, six specimens (50x50x50 mm) from each mixture were subjected to a maximum of 15 wetting and drying cycles using a 10% solution of Na_2SO_4. The 16th cycle corresponded to a full immersion of the specimens in deionised water for 24 hours and then drying until constant mass was achieved. The test was carried out when the samples had completed at least 90 days of curing. The durability of each specimen after each crystallization cycle was assessed based on two parameters: (i) visual inspection (qualitative evaluation) and (ii) percentage loss in mass (quantitative evaluation). With regard to the qualitative evaluation, a five-level rating classification was devised *(Table 2)*.

3. Results and discussion

The results of the thermal tests *(Table 3)* demonstrate the potential of PCMs in enhancing the thermal performance of lime-based renders.[16, 17] PCM addition causes a significant reduction in the thermal conductivity of the modified end-products, compared to the reference ones. Higher reductions correspond to the renders with the higher percentage of PCM addition.

Increase in the specific heat capacity is further recorded for the modified renders *(Table 3)*; this is also proportional to the PCM content in the mix design. Other researchers[16] also noted a positively correlation between the specific heat capacity and the PCM addition.

The thermal diffusivity of the PCM-enhanced composites is notably lower *(Table 3)*. As in the case of thermal conductivity, this decrease is related to the amount of PCM in the mixture.

Higher open porosity and lower apparent density values are observed *(Table 3)* for the mixtures with the PCM addition, compared to the reference composites (REFA and REFH); the fluctuation is generally proportional to the percentage of the PCM additives in the mix design. The

Mixture	p_o	p_a	Av. Pore Diam.	s	FS	UCS	λ	Cp	a
	(%)	(g/cm^3)	(nm)	(mm/min$^{1/2}$)	(MPa)		(W/mK)	(10^{2}J/kgK)	(10^{-7} m^2/s)
REFA	30.8	1.65	300.3	2.01	1.32	2.21	0.575	8.147	4.040
PCMA5	32.1	1.53	231.9	1.19	1.03	3.31	0.452	9.200	3.110
PCMA10	34.8	1.51	133.7	0.88	0.91	3.08	0.387	9.663	2.690
PCMA20	33.1	1.44	76.9	0.64	0.72	3.22	0.316	10.361	2.250
REFH	28.8	1.66	69.8	0.82	2.85	10.76	0.687	8.336	4.740
PCMH5	35.9	1.57	90.5	0.06	2.28	8.70	0.570	9.351	3.970
PCMH10	38.1	1.34	108.3	0.23	1.36	5.75	0.426	10.395	2.970
PCMH20	39.0	1.32	96.3	0.39	1.32	3.92	0.309	10.760	2.230

Table 3: Physico-mechanical and thermal properties of laboratory composites measured at 90 days after casting. po: open porosity, pa: apparent density, s: water capillary absorption coefficient, FS: flexural strength, UCS: uniaxial compressive strength, λ: thermal conductivity, Cp: specific heat capacity, a: thermal diffusivity.

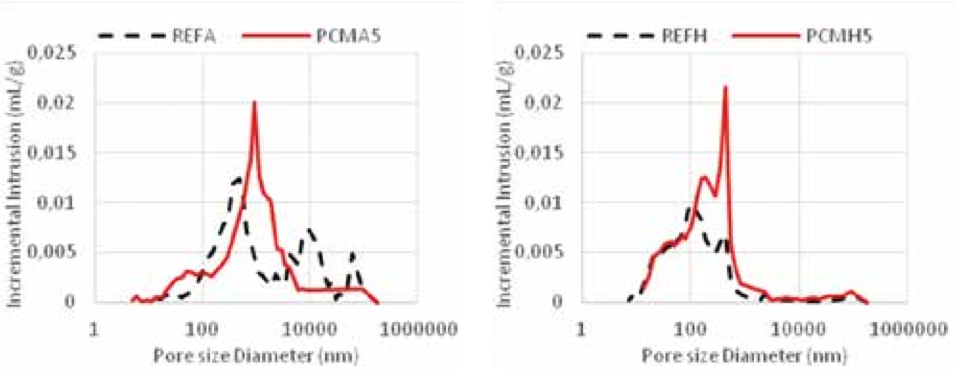

Figure 1: MIP pore size distributions for REFA & PCMA5 (left) and REFH & PCMH5 (right).

relatively higher porosity values can be attributed to the higher water demand of the PCM-enhanced mixtures in order to attain the desired workability[16, 18]; this may, in turn, be associated with the increased volume fraction of solids, the fineness of the microcapsules and the hydrophylic nature of their polymeric wall.

Regarding the capillary absorption results *(Table 3)*, the addition of PCMs seems to lead to significantly reduced values in both the hydrated and hydraulic renders (over 65% and 90% respectively). Similar results were also recorded by other researchers.[19]

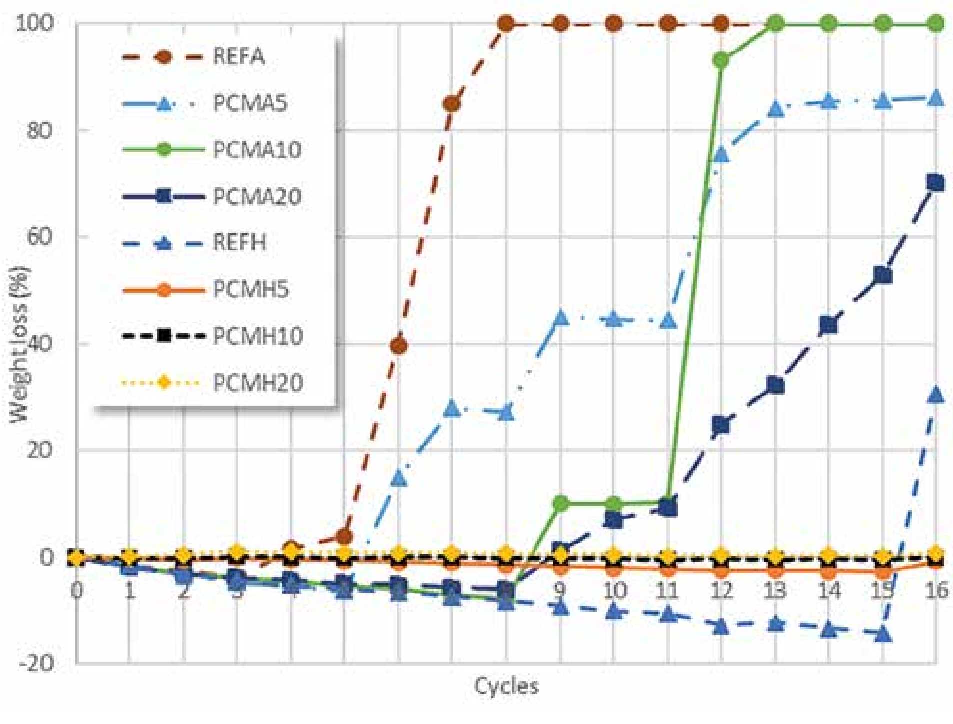

Figure 2: Weight loss of specimens after salt crystallization cycles.

The pore size distributions recorded by MIP *(Figure 1)* show changes in the pore structure of the mixtures with and without PCMs. More specifically, the PCM addition causes a shift of the main peak towards larger pore sizes in comparison with the reference mixtures; in the hydrated mixtures, the main peak shifts from ca. 500 to 900 nm (REFA and PCMA5 respectively) and in the hydraulic ones from ca. 100 to 430 nm (REFH and PCMH5 respectively). Furthermore, in the case of hydrated lime-based renders, the PCM addition causes a decrease of the larger pore volumes (i.e. peaks at ca. 9000 and 60000 nm). Other researchers[10] reported similar changes in the pore structure of PCM-enhanced hydrated lime composites.

Generally lower flexural and compressive strengths are reported for the hydraulic mixtures with the addition of PCMs, compared to the reference composites *(Table 3)*. This agrees well with the higher porosity values observed and may be attributed to the higher water demand of the PCM-enhanced mixtures. Lower flexural strength values are also recorded in the case of hydrated lime renders, compared to the reference materials (*Table 3)*. These observations are in line with other researches reporting on similar lime-based renders[17]. It is worth noting that, despite the fact that PCM addition leads to a decrease in flexural strength, it is found to enhance the compressive strength in the case of hydrated lime mortars. The latter may be attributed to the decrease of the bigger pore volumes recorded by MIP *(Figure 1)*.

The determination of the renders' resistance to Na_2SO_4 attack through quantitative evaluation is given in *Figure 2*, whereas the qualitative assessment of their condition following salt crystallization is presented in *Figure 3*.

Only six mixtures survived all 15 cycles of the artificial weathering test (PCMA5, PCMA20, REFH, PCMH5, PCMH10, PCMH20). Their noteworthy resistance to salt crystallization is primarily attributed to the binder nature (hydraulic lime is associated with enhanced durability

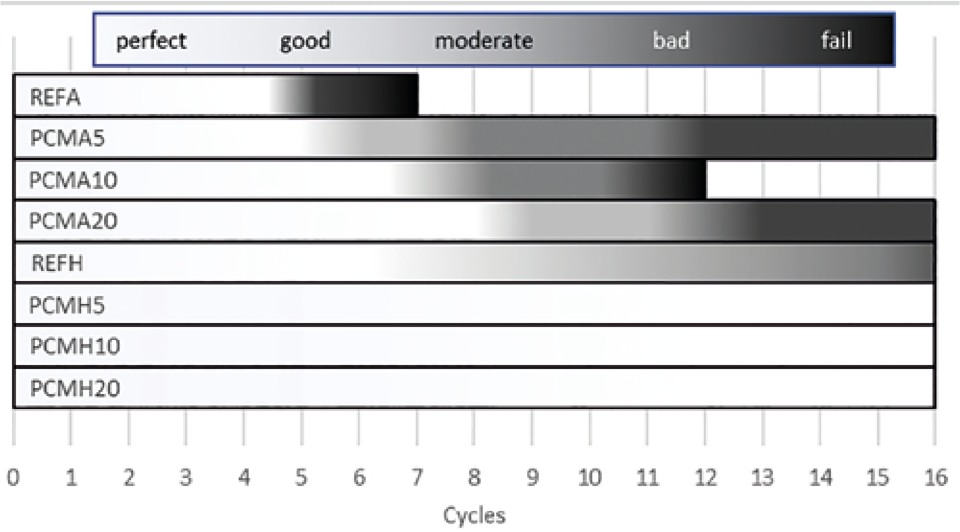

Figure 3: Qualitative evaluation of salt resistance by visual inspection of render mixtures. For explanation on the scale used see Table 2.

compared to hydrated lime). At the same time, PCM addition in the case of hydrated lime renders seems to lead to better durability results; it is worth noting that, in the case of hydraulic composites, the PCM-enhanced specimens completed the durability test without any weight loss. It is therefore evident that better durability results correspond to the PCM-enhanced renders, when compared to the reference mixtures. This is found to be in good agreement with the materials' capillary absorption results, as well as with their high values of porosity and the shift of the main peak of pore volume towards bigger pore sizes *(see Table 3 and Figure 1)*; this may have led to less damage linked to high crystallization pressures due to crystal growth within the pores.[20] It is worth noting that the increase observed in salt crystallization resistance is in constrast to the decrease reported in flexural strength; the latter is possibly attributed to localised flaws in the specimens containing PCMs, however further investigation using enhanced microscopy (e.g. SEM) is needed to confirm this.

The positive effects of PCM addition on the durability of the lime renders investigated in this study is confirmed by the outcomes of the visual inspection *(Figure 3)*. All PCM-enhanced hydrated renders show a better performance against salt weathering, compared to the reference. In the case of hydraulic renders, and despite the fact that the mixture without PCMs (REFH) survived until the end of the crystallization test, the addition of PCMs is associated with efficient damage prevention, since all relevant specimens (PCMH5, PCMH10, PCMH20) are found intact after the end of the test.

4. Conclusions

PCMs significantly reduced the thermal conductivity and thermal diffusivity, while they increased the specific heat capacity of the modified composites. The modification in thermal properties is proportionally linked to the amount of PCMs added to the mixture. This demonstrates the potential of PCMs in enhancing the thermal performance of lime-based renders.

The relatively higher open porosity and lower apparent density values of the PCM-enhanced mixtures are associated with the fact that mixtures with higher PCM content require higher amounts of water to reach the desired workability. Nevertheless, PCM addition significantly reduced the capillary absorption coefficient in both hydrated and hydraulic renders. Noticeable changes in the pore size distribution were also reported since PCM-modified renders were characterized by a shift of the main peak of the pore size distribution towards bigger size pores.

PCM enhancement had in general an inverse effect on the mechanical properties of the end products. However, PCM addition benefited the compressive strength in the case of hydrated lime mortars; this can be attributed to the decrease of pore volumes in the relatively larger pore sizes.

The alterations in several physical values (e.g. lower capillary absorption) due to the addition of PCMs led to noticeable changes in the salt crystallization resistance of the mixtures. Better durability results corresponded to the modified composites when compared with the reference mixtures. This is probably due to the reduced amount of salt absorbed owing to the low capillary absorption of the PCM-enhanced composites; a noteworthy increase of the salt crystallization resistance may also be attributed to the hydraulic binder. Visual inspection of the samples studied confirmed the enhanced performance of PCM modified renders.

The results of this research are overall positive in terms of producing innovative thermally upgraded, yet durable, lime renders. Therefore their incorporation in the construction industry of southern European countries for upgrading the energy efficiency of contemporary buildings and for conservation purposes is deemed promising.

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