Asociación Argentina
de Mecánica Computacional

Mecánica Computacional Vol XLII, pp. 1369-1374
A. Caggiano, G. Etse, P. Folino, M. Goldschmit, M. Pucheta, M. Storti (Eds.)
U. Berardi, D. Borelli, A. Caggiano, S. Flores Larsen, P. Folino (Issue eds.)
Buenos Aires, November 11-14, 2025

EXPERIMENTAL RESULTS AND NUMERICAL ANALYSIS OF CAPILLARY WATER ABSORPTION OF LIME-CEMENT MORTARS WITH PCM AND CELLULOSE FIBRES FOR 3DP APPLICATIONS

Laura Ramallo [a], Antonio Caggiano [b,c], Irene Palomar [a], Álvaro Márquez [a] and Gonzalo Barluenga[a]

[a] *Architecture Department, Universidad de Alcalá, Madrid, Spain, dpto.arquitectura@uah.es, https://www.uah.es/es/*

[b] *Dipartimento di Ingegneria Civile, Chimica e Ambientale, University of Genoa, Genoa, Italy, info@dicca.unige.it, https://unige.it/*

[c] *LMNI-CYE, Facultad de Ingeniería, Universidad de Buenos Aires, Ciudad Autónoma de Buenos Aires, Argentina*

Keywords: Moisture Transport Phenomena, Lime-cement mortar, PCM, Cellulose Fibers, FEM, 3D-printing.

Abstract. This study assesses the moisture transport phenomena of 3D printing lime-cement mortars with Phase Change Materials (PCM) and Cellulose Fibers (F) for architectural applications comparing experimental results and numerical analyses. A lime-cement control mortar was designed and cellulose fibers and different percentages of PCM (i.e., 10, 20 and 30%) were added, leading to a total of eight different mixtures. Physical and mechanical characterization tests were performed on mortar samples and capillary water absorption tests were carried out over 24h. Based on the experimental results, a computational nonlinear FE-based Moisture Diffusion model was calibrated to simulate the data.

ISSN: 2591-3522 DOI: 10.70567/mc.v42.ocsid8394

1 INTRODUCTION

The incorporation of phase change materials (PCM) into lime-cement mortars has emerged as a promising strategy to enhance material thermal performance (Palomar et al., 2015 and Mankel et al., 2019). However, the impact of such additives on the hygric behaviour of these composites remains insufficiently explored (Aligizaki, 2005). This study investigates the capillary water absorption of lime-cement mortars modified with microencapsulated PCM and cellulose fibres. Experimental tests were conducted to assess the water uptake behaviour (Palomar and Barluenga, 2018), and the results were used to validate a finite element model —FEM— (Isgor, 2004 and Martín-Pérez, 2001) capable of simulating the moisture transport within non-saturated cementitious materials (Guardia et al., 2020). The combined approach provides insight into the influence of PCM and fibre content on the water absorption dynamics and supports future design of more durable, energy-efficient building materials.

2 EXPERIMENTAL PROGRAM

The aim of this study was to understand moisture transport phenomena of eight lime-cement mortars containing microencapsulated phase change materials and cellulose fibres for architectural purposes. A FEM-based model proposed by Caggiano et al. (2018) was used to dig further in this knowledge.

2.1 Material composition

Eight mixtures were designed using components shown in Table 1. An ordinary Portland cement type I 52,5R (UNE-EN 197-1) supplied by *Cementos Portland Valderribas* and an air lime CL90-S (UNE-EN 459) were selected. A 0-1 mm siliceous sand and a sepiolite nanoclay were used to improve mortar printability. A 0.4 water to binder ratio (w/b) and a polycarboxylate ether-based superplasticizer was used to achieve target mortar consistency. Binder to aggregate ratio was 1,0 : 0,5 : 1,5 by volume (cement : lime : sand). A microencapsulated paraffin wax -Phase Change Material (PCM)- with a particle size ca. 50-300 µm and a melting point of ca. 23ºC supplied by Master Building Solutions —former BASF— was added in a 0, 10, 20, 30% by fresh mortar volume. A 3% by total fresh mortar volume of Cellulose Fibres (F) of 1mm length and 20 µm, supplied by Omya Clariana S.L, were added in.

		Cement	A.Lime	Sand	Sepiolite	Water	HRWRA	PCM	F
No cellulose fibers	C	700	130	1250	14	330	5,6	-	-
	C10	700	130	1250	14	330	8,4	60	-
	C20	700	130	1250	14	330	13,3	120	-
	C30	700	130	1250	14	330	15,4	180	-
With cellulose fibers	CF	700	130	1250	14	330	5,6	-	2
	CF10	700	130	1250	14	330	8,4	60	2
	CF20	700	130	1250	14	330	11,9	120	2
	CF30	700	130	1250	14	330	15,4	180	2

Table 1: Lime-cement mortars' composition (components in g).

2.2 Experimental methods

Material characterization

Lime-cement mortars' fresh and hardened properties were assed as reported in (Ramallo et al. 2024) and (Márquez et al. 2024), respectively. Apparent Density and Open Porosity —accessible to water— were the experimental parameters considered in this study. Prismatic specimens 40 mm × 40 mm × 16 mm of each mortar mixture were weight at dry, saturated and submerged conditions using a hydrostatic balance according to the European Standard UNE-EN 1015-10.

Water transport phenomena

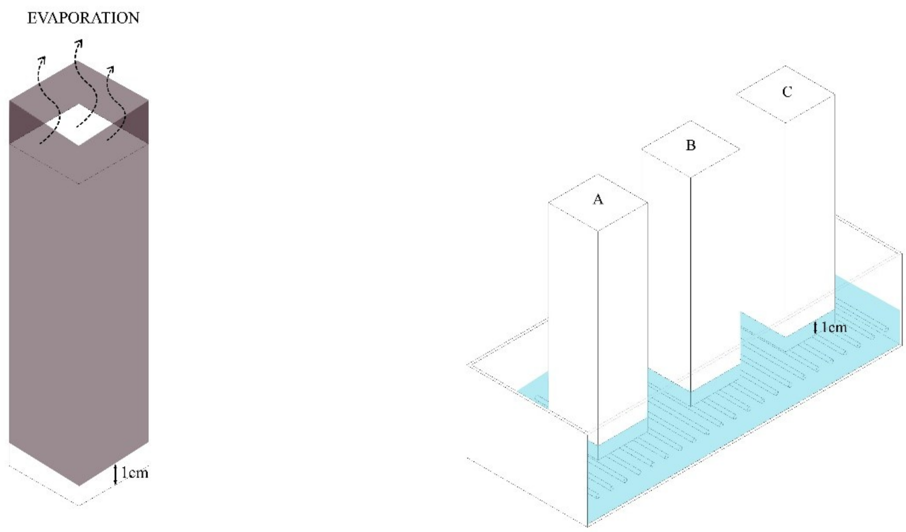

Figure 1. Sample preparation (right) and experimental set-up for the CWA test (left).

Capillary water absorption coefficient (CWA) was calculated according to Palomar et al. (2015), according to the European Standard UNE-EN 1015-18. Three lime-cement mortar samples of each mixture were firstly dehydrated in a stove until constant weight. Then, the four lateral faces of the prisms were covered with a film, leaving the upper face uncovered to let free water evaporation. Samples were placed 10 mm depth in contact with water, and they were weight at different times for 24 hours (Fig.1).

2.3 Moisture Diffusion model proposed

The simulation of the capillary water absorption in lime-cement mortars with PCM and cellulose fibres was performed following the moisture diffusion approach proposed by Caggiano et al. (2018). Strong nonlinear behaviour was assumed due to the dependence of water content and local porosity (Guardia et al., 2020; Caggiano et al., 2018; Yang et al., 2021; Fachinotti et al., 2023) and was run afterwards in FEM-based implementation.

$$D_\theta = \frac{C\,\gamma_{lv}\,cos\theta_c}{25B\mu}\frac{\phi^2}{(\phi-\theta)\,ln^2(1-\frac{\theta}{\phi})}\left[1-\left[1-\ln\left(1-\frac{\theta}{\phi}\right)\right]x\left(1-\frac{\theta}{\phi}\right)\right]^2 \quad (1)$$

As equation (1) shows, B [m^{-1}], the Raleigh-Ritz pore size distribution constant was modified in each mixture to adjust experimental to simulation results. C is an empirical constant [—], γ_{lv} [N m^{-1}] is the liquid-vapor interfacial energy, θc is the equilibrium contact angle between the liquid and the solid [degrees], ϕ the open porosity [m^3 /m^3] and μ the dynamic viscosity of water (Zhou, 2011 and Maekawa, 2014).

3 RESULTS AND DISCUSSION

The results reported in this section show how the microencapsulated phase change material (PCM) and cellulose fibers (F) affect the capillary water absorption phenomenon, and how the FEM-model adjusts to the experimental results obtained in the laboratory.

3.1 Experimental results

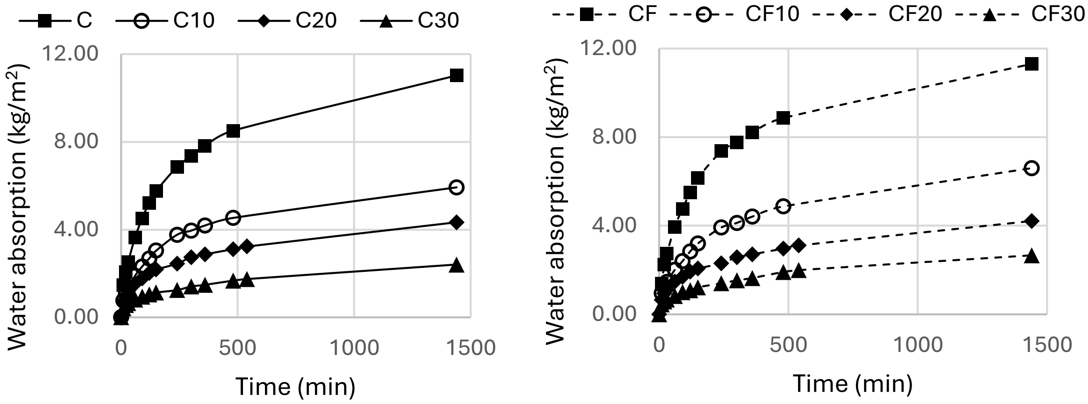

Figure 2. Water absorption experimental results of the lime-cement mortars with PCM (left) and PCM+F (right).

As Figure 2 depicts, the more PCM is added to the control mortar (C), the less water is absorbed. There is a significant change in water transport behaviour when PCM is added. As the percentage grows, water absorption decreases proportionally falling to 2 kg/m^2 when 30%PCM is reached. Although slightly higher values were reached combining lime-cement mortars with cellulose fibres (CF), a similar behaviour is observed when PCM is added.

3.2 Moisture diffusion model results

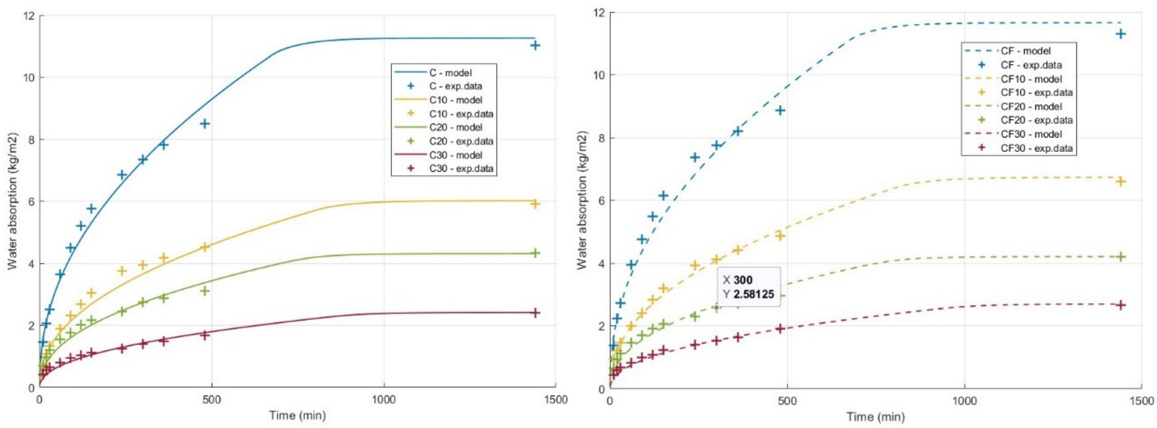

Figure 3. Water absorption model results of the lime-cement mortars with PCM (left) and PCM+F (right).

Figure 3 depicts the water absorption experimental results obtained in the laboratory (crosses) of the eight lime-cement mortars and their model results after running the FEM code (continuous and dash line). It was possible to obtain a perfect model adjustment modifying B (Raleigh-Ritz pore size distribution constant) for every mortar, as Table 2 shows.

		PCM (%)	CWA ($kg/m^2 \cdot s^{0,5}$)	OP (%)	Dap (g/cm^3)	B (m^{-1})
No cellulose fibers	C	0	0,76	17,14	2,02	$0,77 \times 10^7$
	C10	10	0,39	16,67	1,94	$2,41 \times 10^7$
	C20	20	0,27	16,26	1,87	$4,25 \times 10^7$
	C30	30	0,14	8,83	1,85	$2,5 \times 10^7$
With cellulose fibers	CF	0	0,81	16,62	1,99	$0,49 \times 10^7$
	CF10	10	0,4	17,00	1,93	2×10^7
	CF20	20	0,26	15,85	1,88	$4,2 \times 10^7$
	CF30	30	0,15	9,55	1,87	$2,8 \times 10^7$

Table 2: Lime-cement mortars' properties and parameters related to hygric behaviour.

It was observed that the Raleigh-Ritz pore size distribution constant (B) was inversely proportional to the Water Absorption Coefficient (CWA), the Open Porosity (OP) and the Apparent Density (Dap), thus, the percentage of PCM content.

4 CONCLUSIONS

An experimental and mathematical study on the hygric effect of a microencapsulated phase change material (PCM) and cellulose fibres (F) on a lime-cement mortar for 3DP applications was carried out. The main conclusions of the study were:

- PCM content directly influenced water absorption behaviour, reducing it drastically when a 10% was added. Then, the reduction became proportional to the PCM percentage.
- F slightly increased water absorption behaviour.
- A perfect model adjustment to experimental results was reached modifying B (Raleigh-Ritz pore size distribution constant) for every mortar.
- B was inversely proportional to the other lime-cement mortars physical properties.

ACKNOWLEDGEMENTS

The authors acknowledge with thanks the Grant for training of Lecturers (FPU-UAH 2023) funded by Universidad de Alcala awarded to Ms. Laura Ramallo.

Financial support was provided by the project CALTHED (grant number TED2021-132585B-100) funded by the Spanish Ministry of Science and Innovation (MCIN/AEI/10.13039 /501100011033) and by the project HORIZON-TMA-MSCA-SE_2021 "BEST-Bio-based Energy-efficient materials and Structures for Tomorrow" (grant number 101086440) funded by the European Commission (DOI: 10.3030/101086440). This work reflects the views and opinions of the authors only, and neither the European Union nor the granting authority can be held responsible for any use that may be made of the information contained herein. Some of the materials were supplied by TOLSA GROUP S.A, Master Builders Solutions, Omya Clariana S.L. and Cementos Portland Valderrivas

REFERENCES

Aligizaki K (2005). Pore Structure of Cement-Based Materials. London: CRC Press

BASF (2013). BASF Datasheet. Micronal PCM DS 5040 X, 11/2013

Caggiano A, Schicchi DS, Mankel C, Ukrainczyk N, Koenders EAB (2018). A mesoscale approach for modeling capillary water absorption and transport phenomena in cementitious materials. *Computers & Structures*, 200: 1–10

Fachinotti, V. D., Peralta, I., Toro, S., Storti, B. A., & Caggiano, A. (2023). Automatic generation of high-fidelity representative volume elements and computational homogenization for the determination of thermal conductivity in foamed concretes. *Materials and Structures*, *56*(10), 179.

Guardia, C., Schicchi, D.S., Caggiano, A. *et al.* On the capillary water absorption of cement-lime mortars containing phase change materials: Experiments and simulations. *Build. Simul.* **13**, 19–31 (2020).

Isgor OB, Razaqpur AG (2004). Finite element modeling of coupled heat transfer, moisture transport and carbonation processes in concrete structures. *Cement and Concrete Composites*, 26: 57–73

Maekawa K, Chaube R, Kishi T, (2014). Modelling of Concrete Performance: Hydration, Microstructure and Mass Transport. London: *CRC Press*.

Mankel C, Caggiano A, Ukrainczyk N, Koenders E (2019). Thermal energy storage characterization of cement-based systems containing Microencapsulated-PCMs. *Construction and Building Materials*, 199: 307–320

Martín-Pérez B, Pantazopoulou SJ, Thomas MDA (2001). Numerical solution of mass transport equations in concrete structures. *Computers & Structures*, 79: 1251–1264

Márquez, Á., Ramallo, L., Varela, H., Barluenga, G., Puentes, J. 3D Printing Architectural Applications of cement-lime mortars with microencapsulated Phase Change Mate-rials (PCM). In: *Digital Concrete 2024* - Supplementary Proceedings (2024).

Palomar, I., Barluenga, G., Puentes, J. Lime–cement mortars for coating with improved thermal and acoustic performance, *Construction and Building Materials*, Volume 75, 2015, Pages 306-314, ISSN 0950-0618.

Palomar I, Barluenga G (2018). A multiscale model for pervious lime-cement mortar with perlite and cellulose fibers. *Construction and Building Materials*, 160: 136–144

Ramallo, L., Barluenga, G., Palomar, I. Thermal evaluation of low-carbon lime cement mortars with PCM for 3D printing architectural applications. In: *78th RILEM Annual Week & RILEM Conference on Sustainable Materials & Structures: Meeting the major challenges of the 21st century - SMS 2024*. Conference Proceedings, RILEM (2024).

UNE EN (2000). UNE EN 197-1. Cement - Part 1: Composition, specifications and conformity criteria for common cements. AENOR.

UNE-EN (2003). UNE-EN 1015-18. Methods of test for mortar for masonry - Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar, AENOR.

UNE-EN (2007b). UNE-EN 1015-10:2000/A1. Methods of test for mortar for masonry - Part 10: Determination of dry bulk density of hardened mortar, AENOR

UNE EN (2011). UNE EN 459-1. Building lime - Part 1: Definitions, specifications and conformity criteria. AENOR.

Yang, S., Ukrainczyk, N., Caggiano, A., & Koenders, E. (2021). Numerical phase-field model validation for dissolution of minerals. *Applied Sciences*, *11*(6), 2464.

Zhou J (2011). Performance of engineered cementitious composites for concrete repairs. *PhD Thesis*, Delft University of Technology, the Netherlands.