Innovative Structural Concretes with Phase Change Materials for Sustainable Constructions: Mechanical and Thermal Characterization

A. D'Alessandro[1](✉), A. L. Pisello[2,3], C. Fabiani[2], F. Ubertini[1],
L. F. Cabeza[4], F. Cotana[2,3], and A. L. Materazzi[1]

[1] Department of Civil and Environmental Engineering, University of Perugia, Perugia, Italy
antonella.dalessandro@unipg.it
[2] Department of Engineering, University of Perugia, Perugia, Italy
[3] CIRIAF - Interuniversity Research Center, University of Perugia, Perugia, Italy
[4] GREA Innovació Concurrent, Universitat de Lleida, Lleida, Spain

Abstract. New phase change materials (PCMs) are promising fillers for the realization of multifunctional concretes, combining good mechanical properties with enhanced thermal storage capabilities within building envelope. These materials are currently receiving a growing interest in the scientific literature. Encapsulated PCMs result particularly suitable for applications in concrete. This paper presents a research on concretes doped with different contents of PCMs, up to the 5% of the total weight. Physical, mechanical and thermal experimental tests were carried out, in order to investigate the physical properties, the stress-strain behaviour, the ductility, the compressive strength, as well as the thermal conductivity, the diffusivity and the specific heat capacity of the novel concretes. The results of thermal tests demonstrated the effective enhancement of the thermal inertia of the materials, while mechanical tests showed performances compatible with structural applications. Overall, new multifunctional concretes with PCM inclusions appear promising for achieving sustainable and lightweight concrete structures.

Keywords: Phase change materials · Structural concretes
Cement-based composites · Stress-strain envelope · Thermal properties
Smart materials

1 Introduction

Novel nano- and micro-cementitious materials result a topic of growing interest in scientific literature (Shah et al. 2009; Ubertini et al. 2016). Cement-matrix materials result particularly suitable for a micro-structural modification, due to the presence of components and pores at different scales. The fillers can confer to the materials multifunctional properties, as new or enhanced capabilities (D'Alessandro et al. 2016a; 2016b; Laflamme et al. 2015; Yang and Che 2015). In particular, phase change

M. di Prisco and M. Menegotto (Eds.): ICD 2016, LNCE 10, pp. 172–183, 2018.
https://doi.org/10.1007/978-3-319-78936-1_13

materials (PCMs) possess high heats of fusion and, during the melting or solidifying transitions at a fixed temperature, are capable of storing or releasing energy (Sharma et al. 2009). Their use in building materials permits to optimize thermal-energy efficiency and construction sustainability of constructions (Kalnæs and Jelle 2015; Navarro et al. 2016; D'Alessandro et al. 2016a; 2016b). An optimal phase change material for concrete needs to exhibit appropriate mechanical performances, a proper phase change temperature and a great melting enthalpy. Also, the choice of such materials usually is also led considering other physical, technical and economic aspects, (Cabeza 2015; Fernandes et al. 2015). Research investigations present in literature mainly concern the capability of PCMs to improve the thermal performance of concrete, assessing whether the mechanical properties were severely flawed (Zhang et al. 2004; Lecompte et al. 2015). In order to ensure such acceptable properties, most of these studies focus on the integration of microencapsulated PCMs in cementitious admixtures, thus avoiding leakage problems which could negatively affect the compression resistance of the samples (Konuklu et al. 2015).

The present paper is aimed at investigating the mechanical and thermal performance of concretes with PCMs for structural applications in comparison to ordinary concrete. The paper is organized as follows. Firstly, a literature overview on the use of PCMs as multifunctional additives in concrete is presented in Sect. 1. Materials and samples developed within this work are presented in Sect. 2. The experimental methodology is described in detail in Sect. 3, while test results are presented in Sect. 4 and discussed in Sect. 5. Finally, the paper presents the main findings and conclusions.

2 Materials and Experimental Methods

2.1 Phase Change Materials

The PCMs utilized in the experimentation were Microtek Microencapsulated PCM. They appeared as a white powder (Fig. 1a) with a mean particle size between 17 and 20 µm. The core material inside the microcapsules, consisted of a inert polymer, was a paraffin-wax with heat absorption capabilities and a melting point at 18 °C. The PCM content was about 85–90% with respect to the total mass.

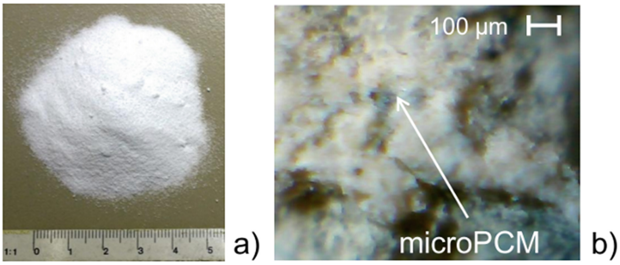

Fig. 1. (a) Appearance of MicroPCM; (b) Microscope enlargement of concrete with 5% of PCM

2.2 Concrete Preparation Procedures

Table 1 shows the components of the normal reference concrete and the concretes prepared with the addition of 1, 3 and 5% of PCMs with respect to the whole mass of the composite. The water/cement ratio was 0.45 for all the admixtures, except for 5% PCM-concrete, with a w/c ratio of 0.5, necessary to obtain similar workability. The cement was type 42.5, pozzolanic. The aggregates were constituted by sand and gravel with nominal dimensions from 0 to 4 mm and from 4 to 8 mm, respectively.

Table 1. Mix design of normal reference concrete and concretes with PCMs.

Components (kg/m^3)	Normal concrete	Concrete with PCM		
		1%	3%	5%
Concrete	524	511	486	447
Water	234	228	218	223
Sand (0–4 mm)	951	927	882	817
Gravel (4–8 mm)	638	622	592	548
PCM	-	24	71	102
Plasticizer	2.6	2.6	2.4	6.8
W/C ratio	0.45	0.45	0.45	0.5

The sample preparation process consisted in the preliminary mix of cement, sand, gravel and PCMs (Fig. 2a), and the subsequent addition of water and plasticizer (Fig. 2b). Then, the dough was mixed and carefully poured into oiled moulds, in order to avoid the separation of the fillers (Fig. 2c). The samples were unmolded for curing after some days (Fig. 2d). After mixing, microPCM capsules appeared intact, since no oil was observed in the composites.

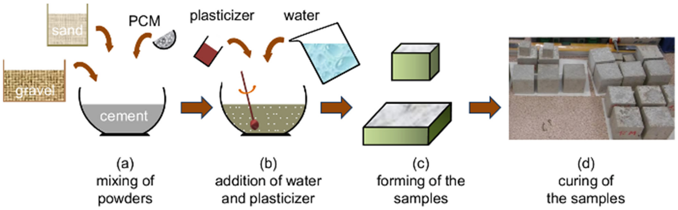

Fig. 2. Preparation process of concretes with PCMs

The samples were cubes with sides of 100 mm, for mechanical tests, and prisms with squared bases of 190 × 190 mm^2 and height of 50 mm, for thermal experiments. Figure 3 represents the structure of the normal and the PCM-concrete, with dispersed microcapsules. An enlarged image of a fragment of hardened concrete with PCMs can be observed in Fig. 1b. The microscope used for the elargements was type Bresser, Biolux NV, with magnifications up to 1280X.

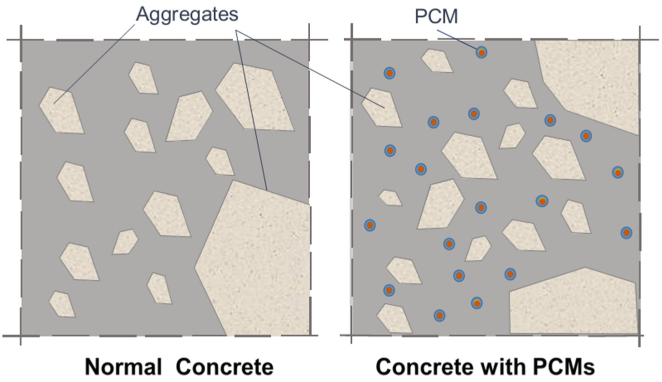

Fig. 3. Schematic representation of the structure of Normal Concrete and Concrete with microPCM

2.3 Experimental Setup

Mechanical Tests

After curing, the sample were measured and weight and then compression tests were carried out, using an Advantest machine, model Controls 50-C7600 (Fig. 4a) with a servo-hydraulic control unit model 50-C9842 (Fig. 4b), instrumented with three LVDT placed at 120° (Fig. 4c). The compressive loads were applied under displacement control, up to the collapse. Both resistance and ductility after peak have been investigated. The test speed was 2 µm/s, in agreement with the EN 12390-3 standard.

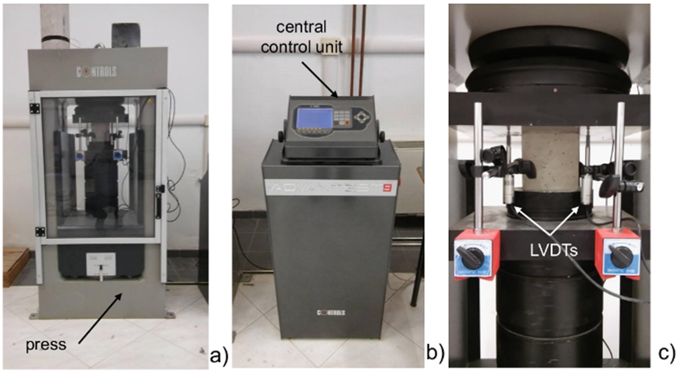

Fig. 4. Experimental setup for mechanical tests: (a) testing machine; (b) central control unit; (c) cubic concrete sample instrumented with LVDTs

Thermal Tests

The thermal investigations of the prismatic samples were carried out by means of Transient Plane Source (TPS) method, using a Hot Disk 2500 system, in accord with the ISO 22007-2 standard and an ATT DM340SR climatic chamber equipped with 12 PT100 thermocouples. In the environmental chamber the samples were insulated by XPS panels: just the upper side was exposed to the controlled environment of the chamber (Fig. 5a). Each sample was instrumented with four PT100: one on bottom surface, one on the upper surface and two probes on the lateral sides. The thermal program consisted of five subsequent segments, 8 h long, with linear varying temperature between 26 °C and 10 °C and a fixed RH value of 50%. The thermal tests in the climatic chamber were aimed at investigating the melting temperature of the PCMs within the concretes and the phase change enthalpy. The Hot Disk tests were carried out in a single sided configuration, installing a superinsulating material on the other side of the probe. These tests were aimed at assessing the thermal conductivity and the thermal diffusivity of the concretes, and to derive the specific heat.

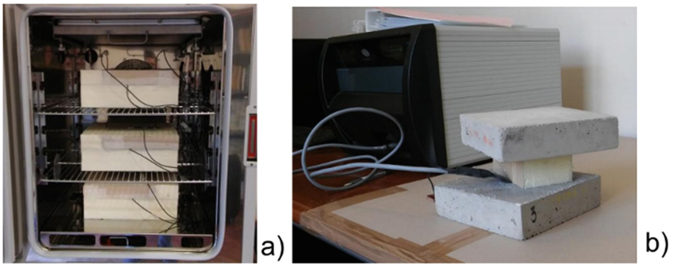

Fig. 5. (a) Prismatic samples in the climatic chamber; (b) setup of the hot-disk

3 Mechanical Tests

The mass density of concretes with PCMs decreased with the increase of the filler content.

In particular, 5% PCM-concretes demonstrated a density reduction of about 11% with respect to normal concrete (Fig. 6a). So, they resulted suitable for the realization

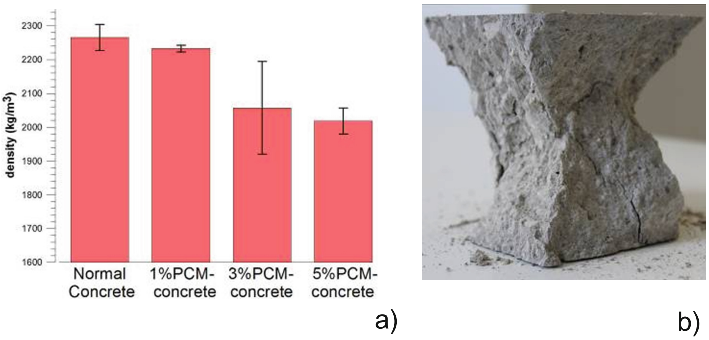

Fig. 6. (a) Variation of density in concrete samples with different amounts of PCM; (b) sample of 5% PCM-concrete after compressive test

of lightweight concretes. Figure 6b represents the fracture pattern of a specimen of 5% PCM-concrete after compressive test: it exhibits a bi-pyramidal fracture, indicating a good behavior of the material.

The concrete samples were compared in terms of average compressive strength, R_m, and of characteristic compressive strength, R_{ck}, in order to evaluate their feasibility as structural materials. R_{ck} represents the strength value which the 5% of the tested samples don't achieve. According to literature, it is analytical defined as:

$$R_{ck} = R_m - k \cdot s \tag{1}$$

where s is the standard deviation, and k depends on the number of tested samples. It was assumed equal to 3.40 and 2.75 for PCM-concretes (5 samples) and normal concrete (8 samples), respectively. Also, the coefficient of variation is particular relevant for structural applications because low values of this characteristic result in higher structural reliability:

$$CV = s/R_m \tag{2}$$

All samples with and without PCMs exhibit the typical non-linear stress-strain curve, with decaying branch after peak.

Figure 7 shows the results of all the tested samples without PCM and with microPCM. As expected, the compressive strength of the concretes decreased with the increase of the content of PCMs because of the lower strength of PCM capsules with respect to aggregates.

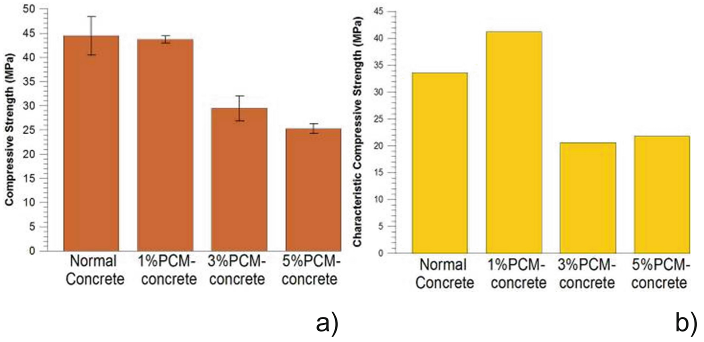

Fig. 7. (a) Average compressive strength with standard deviation, and (b) characteristic compressive strength of the tested concretes with different amounts of PCMs

The characteristic compressive strength shows instead a better performance of concretes with low amounts of PCMs. Microcapsules can provide higher specific area for nucleation sites in cement hydration, and could have a beneficial thermal effect in the composition of the hydration products.

Table 2. Compressive strengths, CV and densities of concrete composites normal and with PCMs

Type of concrete	R_m [MPa]	CV	R_{ck} [MPa]	Density [kg/m^3]	Class
Normal	44.39	0.09	33.52	2265	C25/30
1% PCM-concrete	43.67	0.02	41.16	2233	C28/35
3% PCM-concrete	29.46	0.09	20.60	2057	C16/20
5% PCM-concrete	25.25	0.04	21.80	2018	C16/20

Table 2 reports the average compressive strength resulted from the axial compression tests. The table also shows the values of the coefficient of variation (CV) of the composites, their characteristic compressive strength and their average density. The CV of normal concrete tested in the experimentation is equal to 0.09, within the typical range of ordinary concretes. The CV values of PCM-concretes resulted smaller or equal than 0.09 and demonstrated the good reliability capabilities of the composites for structural applications. Moreover, 1% PCM-concrete possessed a coefficient of variation of 0.02, considerably less than the value of normal concrete. The low dispersion exhibited by resistances of 1% PCM-concrete resulted in an increased structural class from C25/30 of normal concrete to C28/35. Moreover, all concretes with PCMs demonstrated structural properties compatible with the use as structural concretes. Figures 8 represents the single stress-strain curves resulted from the compressive tests at displacement control, for all the normal concrete samples and samples with PCMs. The graphs show clearly the behavior of the materials with increased strain: the peak value represents the maximum compressive resistance, while the post peak branches are representative of the ductility properties. Each type of concrete exhibits a similar behavior even if a decrease of the maximum resistance can be observed. PCMs seem not to affect the ductile capabilities of the concretes. Figure 9 shows the average values of the stress-strain curves for each typology of concrete. The values were obtained by

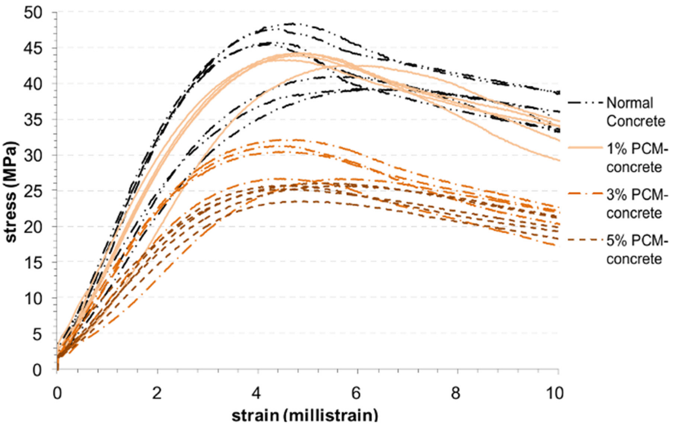

Fig. 8. Stress-strain curves of the complete uniaxial compression tests on concrete without and with PCM up to a strain of 10 με.

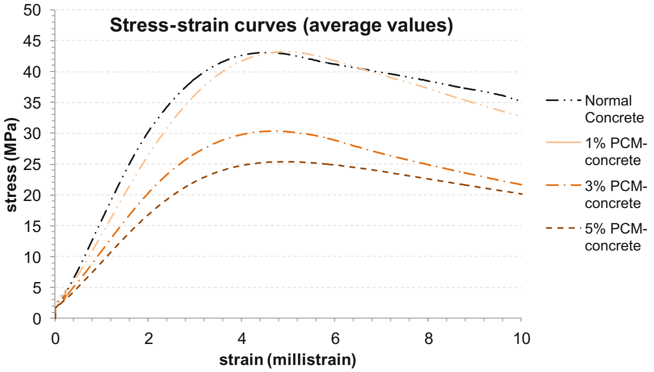

Fig. 9. Average values of stress-strain curves of the complete uniaxial compression tests on concretes without and with PCM up to a strain of 10 με.

calculating the mean stress for fixed strains. The diagrams clearly show that the elastic modulus is greater for the concrete samples with higher compressive strength.

4 Thermo-Physical Tests

The thermo-physical tests were aimed at investigating the phase change materials in dynamic experimental conditions in order to assess the thermal benefits of the addition of PCMs in concrete.

The results coming from the thermal cycles show that all the samples followed the imposed temperature history. The differences between the temperature applied and measured on the concrete samples are due to the high thermal inertia of the cementitious material. Moreover, the samples with PCMs exhibit a peculiar behavior in the temperature range between 17 and 12°C, in the descending ramp, and in the range between 15 and 18 ° C in the increasing ramp (Fig. 10). The deflections resulted in the thermal profile of concrete with 5% of PCMs, with respect to the reference trend of the normal concrete sample, are associated to the phase change taking place in the fillers. Indeed, the paraffin inside the microcapsules has a nominal melting point of 18 °C. The first deflection referred to the solidification of the PCM, while the second one to the melting transition. During these phenomena, the PCM-concretes decrease their temperature at a lower level, since thermal energy is stored in the latent storage material, necessary to break or form molecular bonds in the PCMs. The effect of the presence of PCMs is visible up to about 2 h. Figure 11 represents the thermal behavior of concretes with 1% and 5% of PCMs, compared to the thermal behavior of the reference normal concrete, as recorded within the environmental simulation chamber. Phase change phenomena are clearly visible during cycles, closed to the transition phase temperature of the fillers. As shown in the diagrams, the concrete with the highest content of PCMs exhibited the greater deviation, resulting in a higher amount of energy absorbed and released by the concretes in phase change transition. Such behavior is highlighted also by the presence of a larger area included in the trends. Otherwise, the concretes with 1% of PCMs exhibit a thermal behavior almost linear, very similar to that of normal concrete.

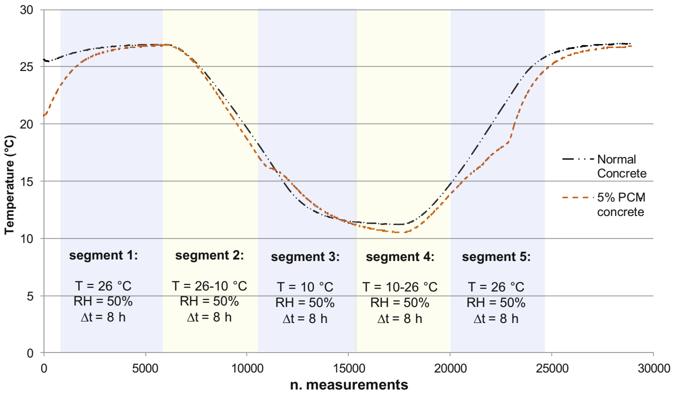

Fig. 10. Normal and 5% PCM-concretes' thermal profiles monitored by the PT100 probe at the bottom of the samples

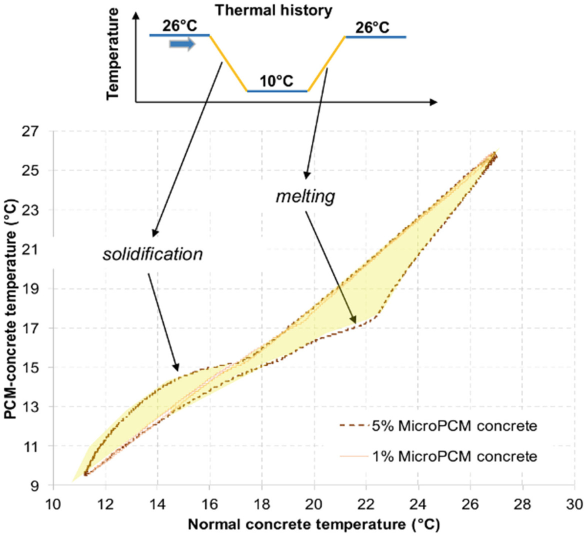

Fig. 11. Thermal profile of 1% and 5% PCM-concrete, as measured within the environmental simulation chamber

Figure 12 depicts the thermal conductivity and the diffusivity measured in the concrete samples with different amounts of PCMs, in comparison with the normal ones. The samples presented a slightly variation of both thermal conductivity and diffusivity in concretes with PCMs, with respect to normal concrete. In particular, the composite materials showed a reduction of the thermal conductivity, probably due to the small and

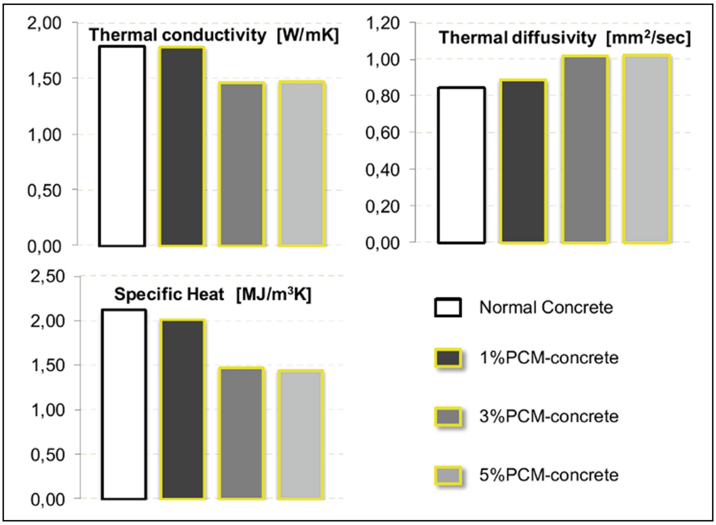

Fig. 12. Thermal conductivity, diffusivity and specific heat resulted by means of hot disk tests on normal concretes and with different contents of PCMs

closed pores created by the addition of the PCM microcapsules. Also, the capability to propagate the thermal wave in transient conditions resulted increased. The specific heat of the different concretes with and without PCMs was also tested, as key parameter influencing the thermal inertia of buildings and typically characterizing both sensible and latent thermal energy storage components. The presence of higher percentages of fillers resulted in a reduction of the specific heat superior to 20%. Indeed, microencapsulated materials seem to produce a noticeable effect on the thermal inertia of concretes.

5 Conclusions

This research was aimed at investigating the multifunctional performance of PCM-concretes for building applications.

Such concretes were made by adding increasing amounts of microencapsulated PCMs, from 1% to 5% with respect to the total mass of the material. The fillers had an internal core made of paraffin with melting temperature at 18 °C. Both mechanical and thermo-physical tests were carried out, in order to investigate the multifunctional properties of such materials and their applicability to structural civil engineering. The results of mechanical test demonstrated that PCM-concretes are compatible with structural applications as lightweight concretes. With respect to normal concretes, a reduction up to 11% in weight was observed. Moreover, small additions of PCMs resulted in an increase of the characteristic resistance. At the same time, the prototyped concrete manifested thermal capabilities suitable for building energy efficiency applications. Thermo-physical tests demonstrated that the phase transition is visible in PCM-concretes with higher amounts of fillers, resulting in a mitigation of the temperature fluctuations in the matrices.

Acknowledgements. Acknowledgments are due to the "CIRIAF program for UNESCO" in the framework of the UNESCO Chair "Water Resources Management and Culture". The research leading to these results has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 657466 (INPATH-TES). The authors also thank the Microtek Laboratories, Inc. for providing the capsulated materials. The work is also partially funded by the Spanish government (ENE2015-64117-C5-1-R). Prof. Luisa F. Cabeza would like to thank the Catalan Government for the quality accreditation given to her research group (2014 SGR 123).

References

Cabeza LF (2015) Advances in thermal energy storage systems: methods and applications. Woodhead Publishing Series in Energy, No. 66

D'Alessandro A, Rallini M, Ubertini F, Materazzi AL, Kenny JM (2016a) Investigations on scalable fabrication procedures for self-sensing carbon nanotube cement-matrix composites for SHM applications. Cem Concr Compos 65:200–213

D'Alessandro A, Fabiani C, Pisello AL, Ubertini F, Materazzi AL, Cotana F (2016b) Innovative concretes for low carbon constructions: a review. Int J Low-Carbon Tech 12:289–309

Fernandes F, Manari S, Aguayo M, Santos K, Oey T, Wei Z, Falzone G, Neithalath N, Sant G (2014) On the feasibility of using phase change materials (PCMs) to mitigate thermal cracking in cementitious materials. Cem Concr Compos 51:14–26

Kalnæs SE, Jelle PB (2015) Review. Phase change materials and products for building applications: a state-of-the-art review and future research opportunities. Energ Build 94:150–176

Laflamme S, Ubertini F, Saleem H, D'Alessandro A, Downey A, Ceylan H, Materazzi AL (2015) Dynamic characterization of a soft elastomeric capacitor for structural health monitoring. J Struct Eng ASCE 141(8):04014186

Lecompte T, Le Bideau P, Glouanneca P, Nortershauser D, Le Massonb S (2015) Mechanical and thermo-physical behaviour of concretes and mortars containing phase change material. Energ Build 94:52–60

Navarro L, de Gracia A, Niall D, Castell A, Browne M, McCormack SJ, Griffiths P, Cabeza LF (2016) Thermal energy storage in building integrated thermal systems: a review. Part 2. Integr Passiv Syst Renew Energy 85:1334–1356

Shah SP, Konsta-Gdoutos MS, Metexa ZS, Mondal P (2009) Nanoscale modification of cementitious materials. In: Bittnar Z et al (ed) Nanotechnology in construction 3, pp 125–130. Springer

Sharma A, Tyagi VV, Chen CR, Buddhi D (2009) Review on thermal energy storage with phase change materials and applications. Renew Sustain Energy Rev 13(2):318–345

Ubertini F, Laflamme S, D'Alessandro A (2016) Smart cement paste with carbon nanotubes. In: Loh KJ, Nagarajaiah S (eds) Innovative developments of advanced multifunctional nanocomposites in civil and structural engineering, pp 97–120. Woodhead Publishing

Yang HS, Che YJ (2015) Influence of particle size distribution of fine and micro-aggregate on the microstructure of cement mortar and paste. Mater Res Innov 19:S1–S130

Zhang D, Li Z, Zhou J, Wu K (2004) Development of thermal energy storage concrete. Cem Concr Res 34(6):927–934

Konuklu Y, Ostryc M, Paksoy HO, Charvat P (2015) Review on using microencapsulated phase change materials (PCM) in building applications. Energ Build 106:134–155