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CEMENT COMPOSITES WITH THE ADDITION OF PHASE-CHANGE MATERIALS AS INNOVATIVE CONSTRUCTION MATERIALS FOR MAINTAINING A PLEASANT LIVING ENVIRONMENT

CEMENTNI KOMPOZITI Z DODATKOM FAZNO SPREMENLJIVIH MATERIALOV KOT INOVATIVNI GRADBENI MATERIALI ZA ZAGOTAVLJANJE PRIJETNEGA BIVANJSKEGA OKOLJA

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The aim of this work was to investigate the possibility of the addition of phase-change material (PCM) to mortar mixtures and its effect on the material's mechanical and thermal properties. This work included the preparation of mortar mixtures with two different water-to-cement (*w/c*) ratios as well as various PCM volume-fraction additions. The main objectives were to determine the effect of the *w/c* ratio as well as the PCM addition on the mechanical properties of the mortars after (3, 7, and 28) d of curing. Additionally, we examined the microstructure of the prepared mortar composites and evaluated their thermal behaviour. Microstructural analysis revealed the uniform distribution of PCM microcapsules throughout the mortar matrix, which contributes to the efficient storage and release of thermal energy. Thermal properties were analysed by repeated heating and cooling cycles of the mortar composites. The repeatability of the cyclic testing results showed a reversible melting and solidification phase change of the PCM and indicated the potential use of such composites as an energy-efficient building material. The study highlighted the potential incorporation of the PCM into mortar mixtures to improve their thermal properties while maintaining the mechanical integrity. The research findings provide valuable insight into the development of sustainable building materials with greater energy efficiency and structural reliability.

Keywords: Mortars with PCM addition, thermal analysis, energy efficiency, sustainability

Namen prispevka je bil preučiti vpliv vgradnje fazno spremenljivega materiala (PCM) v maltne mešanice na njihove mehanske in toplotne lastnosti. Delo je vključevalo pripravo mešanic malte z različnimi vodo-cementnimi razmerji *w/c* in prostorninskimi razmerji PCM. Glavni cilji so bili določiti vpliv razmerja *w/c* na mehanske lastnosti malt, ter oceniti vpliv dodatka PCM na upogibno in tlačno trdnost po (3, 7 in 28) d strjevanja. Sočasno smo preučili tudi mikrostrukturo pripravljenih maltnih kompozitov z dodatkom PCM in ocenili njihovo toplotno obnašanje. Mikrostrukturna analiza je potrdila enakomerno porazdelitev mikrokapsul PCM v matrici malte, kar pripomore k učinkovitemu shranjevanju in sproščanju toplotne energije. Toplotno obnašanje je bilo analizirano s cikličnim testiranjem segrevanja in ohlajanja maltnih kompozitov. Ponovljivost rezultatov cikličnega testiranja je pokazala reverzibilno fazno spremembo taljenja in strjevanja PCM ter nakazala na potencialno uporabo takšnih kompozitov kot energetsko učinkovitega gradbenega materiala. Študija je poudarila smiselnost vključevanja PCM v maltne mešanice za izboljšanje njihovih toplotnih lastnosti ob hkratnem ohranjanju mehanske celovitosti. Ugotovitve raziskave zagotavljajo dragocen vpogled v razvoj trajnostnih gradbenih materialov z večjo energetsko učinkovitostjo in strukturno zanesljivostjo.

Ključne besede: Malte s PCM dodatkom, termična analiza, energijska učinkovitost, trajnost

1 INTRODUCTION

The most commonly used primary energy sources in the world are, unfortunately, still fossil fuels. In industrialised countries (including Slovenia), the residential sector is responsible for more than 40 % of the overall energy end-use,[1,2] of which almost 35 % is consumed for heating and cooling. The above facts represent a clearly significant economic cost for individual households as well as adversely affecting the environment due to the way energy is produced.

One of the possibilities for the more efficient use of energy to achieve favourable living conditions in buildings is the greater use of so-called smart materials in construction, which includes materials with a mineral binder (mortars, plasters, and concretes) with the addition of phase-change materials (PCMs).[3] PCMs are a group of functional materials with the intrinsic capability of absorbing, storing, and releasing thermal energy in the form of latent heat[4] during phase transition cycles at their operating temperatures under isothermal conditions. The principle of the PCM is simple. As the temperature increases, the material changes phase from solid to liquid. The reaction being endothermic, the PCM absorbs the heat. Similarly, when the temperature decreases, the material changes phase from liquid to solid. The reaction is

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exothermic, so the PCM releases the heat.[5] The addition of PCM to mortars, plasters, or concretes, therefore, changes the specific heat capacity of the mortar. The use of PCM in mortar would, therefore, reduce the need for the cooling and heating of buildings.

According to chemical origin, PCMs are divided into i) organic, ii) inorganic and iii) materials of eutectic origin.[6–9] The organic materials that exhibit phase-changing properties are paraffins and fatty acids. PCMs of organic origin are satisfactorily stable, chemically inert, affordable, mostly of natural origin and have a fairly high latent heat of fusion/crystallisation. Their main disadvantage is a relatively poor thermal conductivity and, in the case of paraffin PCMs, flammability.[10] Inorganic PCMs are mostly hydrates of inorganic salts. These PCMs show relatively high latent heat of fusion/crystallisation and have relatively good compatibility with inorganic composite matrices; however, their price is higher than organic PCMs, and the phase transition usually results in a large volume expansion, which is the main limitation for their use in mortar as rigid systems.[11] Eutectic PCMs are a mixture of two or more organic or inorganic compounds, which, depending on the phase diagram under a given composition and thermodynamic conditions, form a liquid or solid. The main advantage of using eutectics is that they allow the properties of PCMs to be adjusted.[12] The selected PCM in construction must meet the following properties: 1) chemical inertness, 2) thermal resistance, 3) high specific heat capacity, 4) good thermal conductivity, 5) high latent heat, and 6) the phase-transition temperature must be in an area suitable for its application.[13,14] To ensure chemical inertness, the PCM is usually not added directly to the mortar but is encapsulated prior to admixing (indirect method of PCM incorporation).[2,15] This reduces the potential impact of the PCM on hydration reactions during the solidification of the mortar mix, as well as subsequent chemical reactions during the ageing of the mortar.

In construction, regarding the temperature range of the phase transition, the use of encapsulated organic PCMs, especially paraffins, is mostly considered. For many paraffins, the solid/liquid phase transition is precisely in the temperature range favourable for human living temperatures. Also, paraffins do not cause corrosion of reinforcement in mortar. It is evident from the scientific literature that the functional properties of mortars can be changed with the addition of PCMs.[13] The hydration of cement is an exothermic reaction that can lead to the formation of cracks in the core of the mortar element and, consequently, the weakening of the mortar. It has been reported that the addition of PCM delays the development of the temperature profile due to hydration and lowers the maximum hydration temperature.[16] Some authors are also of the opinion that the addition of a PCM reduces the damage to mortar due to freezing and thawing cycles.[17] The addition of microencapsulated PCMs, in contrast, reduces the workability and flowability of mortar, but there are no definitive answers in the literature on the acceptable amount of PCM to be added, as well as the method and timing of PCM addition to keep the mortar workable.[18] The addition of micro-encapsulated PCM further reduces the density of the mortar, as PCM in mortar partially replaces higher-density material (e.g., aggregate), which can consequently affect the mechanical properties of the mortar product (e.g., compressive strength). The compressive strength of mortar is an essential element to consider when designing a structure. Specifically, mortar withstands compressive loads well and is thus used as a load-bearing component of the structure. In the case of PCM addition, it is therefore highly desirable to minimise the loss of compressive strength of the mortar. The prevailing opinion in the literature is that the cracking of microcapsules and, consequently, the increased porosity of the mortar with an addition of encapsulated PCM contributes mostly to the reduction of compressive strength.[19] However, the reduction in the strength of the mortar with the addition of PCM has not yet been definitively investigated, but it is assumed that the reduction in compressive strength of the mortar is related to the amount of added PCM. Despite the latter, the compressive strength of mortar with the addition of PCM is still believed to be suitable for use in structural applications. Furthermore, the addition of a PCM is also expected to affect the thermal properties of mortar, both its thermal conductivity and specific heat capacity. Most studies find that the addition of micro-encapsulated PCMs reduces the thermal conductivity of mortar.[20] The reasons for this effect are the increase in porosity due to entrapped air caused by the addition of a PCM as well as the partial replacement of the aggregate with PCM particles, which, in principle, have poorer thermal conductivity. In contrast, the addition of micro-encapsulated PCMs increases the heat capacity of the mortar, especially in the PCM melting temperature range due to the latent heat of the PCM phase transition.

It is also worth mentioning the influence of the addition of a PCM on the resistance of the mortar during fire. Organic PCMs are certainly combustible. However, some literature studies suggest that the addition of a PCM in the initial stages of a fire even lowers the temperature of the mortar, which further suggests that the time required for the building construction material to decay during a fire is actually longer.[21]

The aim of the proposed project is to critically evaluate the possibility of using selected PCM based on encapsulated wax for the preparation of special mortars as modern building materials in construction.

2 EXPERIMENTAL PART

2.1 Materials

The cement mortar samples were prepared using dolomite aggregate from the north-east part of Slovenia, cement CEM I 42.5N (EN 197-1) and superplasticiser

Table 1: Chemical composition of CEM I 42.5N

SiO_2 (*w*/%)	Al_2O_3 (*w*/%)	Fe_2O_3 (*w*/%)	CaO (*w*/%)	MgO (*w*/%)	SO_3 (*w*/%)	Na_2O (*w*/%)	K_2O (*w*/%)	Cl (*w*/%)
19.68	4.82	2.88	63.49	1.54	2.74	0.34	0.72	0.06

Table 2: Designation and composition of samples.

Sample name	used cement	aggregate size fraction	*w/c* ratio	superplasticizer addition /%	PCM addition / φ/%
Ref	CEM I 42.5N	0/4	0.46	1	/
A 0.46-5	CEM I 42.5N	0/4	0.46	1	5
B 0.46-10	CEM I 42.5N	0/4	0.46	1	10
C 0.53-5	CEM I 42.5N	0/4	0.53	1	5

Cementol Hiperplast 481 in accordance with [22]. The aggregate was produced by crushing the parent rock. Only a 0/4 mm fraction was used for the specimens' preparation. Water absorption of the aggregate was 0.8 %, and its density was 2810 kg m^{-3}. The result of a quantitative X-ray analysis showed that the aggregate was composed predominantly of the minerals dolomite (98.1 %) and calcite (representing only ≈1.9 %). The Blain-specific surface area of used cement is 3388 cm^2 g^{-1}, and its density is 3.05 g cm^{-3}. The chemical composition of the used CEM I 42.5N is given in **Table 1**.

The chosen PCM was based on encapsulated paraffin wax with a melamine-formaldehyde membrane. The melting point of the wax in the used PCM is between 25 °C and 29 °C, and its heat storage capacity is in the 160–185 J g^{-1} range. The particle size of the encapsulated PCM is 2–10 μm (**Figure 1**). During the preparation of the cement mixture, the PCM was added as an aqueous dispersion (slurry with 28.2 % PCM content).

2.2 Samples preparation

During the experimental work, four samples were prepared: a reference mortar sample without added PCM and three mortar samples with added PCM (**Table 2**). In the case of the reference sample and two mortar samples with added PCM, the water-to-cement (*w/c*) ratio used was 0.46, and the addition of the PCM slurry into the cement mixture was 5 φ/% or 10 φ/% for samples A 0.46-5 and B 0.46-10, respectively. Additionally, in order to alter the workability of the fresh mortar paste, the C 0.53-5 sample was prepared with a water-to-cement ratio of 0.53 and 5 φ/% of added PCM. After the casting of mortar bars with dimensions of (40 × 40 × 160) mm, the samples were cured in an environment with a relative humidity higher than 90 % and a temperature of 20 ± 1 °C for (3, 7 and 28) d.

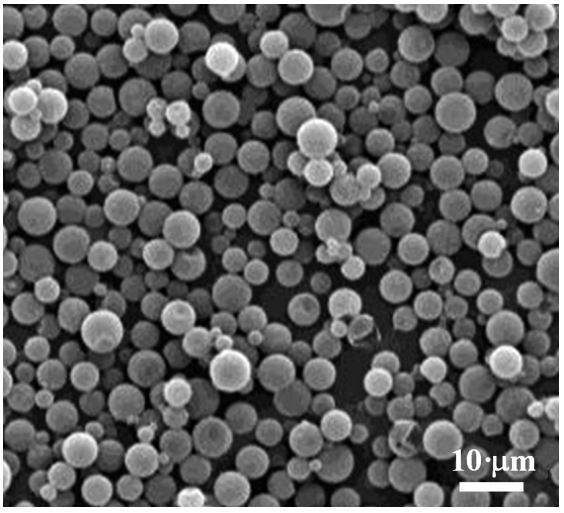

Figure 1: SEM image of used PCM

2.3 Methods

Microstructure characterisations of the samples were performed using electron microscopy (FE-SEM Zeiss Ultra Plus microscope equipped with EDS Oxford X-Max SDD 50 mm^2 detector and INCA 4.14 5 X-ray microanalysis software). To better distinguish the phases present in the samples, back-scattered electrons (BSEs) were used for SEM imaging and the Cameo+ option in Inca software, which allows the emitted X-ray light to be presented in the visible part of the spectrum.

The workability tests of the fresh mortar mixtures (including mortars' flow tests and density) were carried out in accordance with the SIST EN 1015-3:2001 standard method.[23] Porosity tests of the fresh mortar mixture were measured in accordance with the SIST EN 1015-7:1999 standard.[24] The flexural (3 parallel samples) and compressive (6 parallel samples) strengths of the cast and cured mortar bars were determined according to the EN 1015-11 standard[25] by using universal testing machines Roel-Amsler with capacities of 100 kN and 500 kN, respectively. The E-modulus of ready-mixed mortars with PCM addition was measured using a Proceq Pundit PL-200 ultrasound according to the method described in [26]. The freeze-thaw tests of the cast and cured mortar bars with de-icing salts were performed using an alternative method described in the CEN/TS 12390-9 standard.[27] In each test, 20 freeze/thaw cycles were conducted. Each cycle lasted 24 h and consisted of 16 h of freezing at a temperature of –15 ± 2 °C followed by 8 h of thawing at a constant temperature of 20 ± 2 °C. After every fifth cycle, the samples were removed from the solution, cleaned with running water to remove all

the particles that fell off the surface and dried. Such surface dry samples were weighed in order to calculate the mass of the lost material.

All thermo-analytical tests were recorded using a Metter Toledo DSC1/778/700 module. Each test was performed on approximately 5 mg of crushed mortar sample in synthetic air (20 mL min^{-1} 20 φ/ % O_2 and 80 φ/ % Ar) following consecutive steps in a temperature program: 1) dynamic cooling from room temperature to –10 °C (cooling rate β = 2 K min^{-1}), 2) isothermal step at –10 °C for 2 min, 3) dynamic heating from –10 °C to 50 °C (β = 2 K min^{-1}), 4) isothermal step at 50 °C for 2 min, 5) dynamic cooling from 50 °C to –10 °C (β = 2 K min^{-1}), 6) isothermal step at -10 °C for 2 min and 7) dynamic heating from –10 °C to 50 °C (β = 2 K min^{-1}).

3 RESULTS AND DISCUSSION

3.1. Mechanical properties of mortars

The mechanical properties of mortars are of prime importance in construction. Some basic characteristics of fresh mortars, as obtained on a flow table, are presented in **Table 3**. It is evident that the ability of fresh mortars to flow is mainly influenced by the *w/c* ratio in the fresh mortar mixture and very little by the amount of added PCM. Such results are expected since a higher *w/c* ratio dilutes the system and thus lowers its viscosity. Consequently, with a higher *w/c* ratio, the workability of the mortar increases, and such systems can be mixed, placed, consolidated, and finished more easily with minimal loss of homogeneity. Additionally, the measured porosity values further imply that a higher *w/c* ratio also reduces the aeration of the mortars. In this regard, the PCM addition has very little effect. In contrast, the addition of PCM has a significant effect on the bulk density of the prepared fresh mortars. When compared to the reference sample (without added PCM), the bulk density of the prepared fresh mortars decreases with increasing volume fraction of the PCM additive. The main reason for such an observation is the fact that PCM, as an organic phase, has a lower density than any other solid phase in mortars. Since PCM partially replaces other solid components in the mortar composite mixture, it also lowers its bulk density.

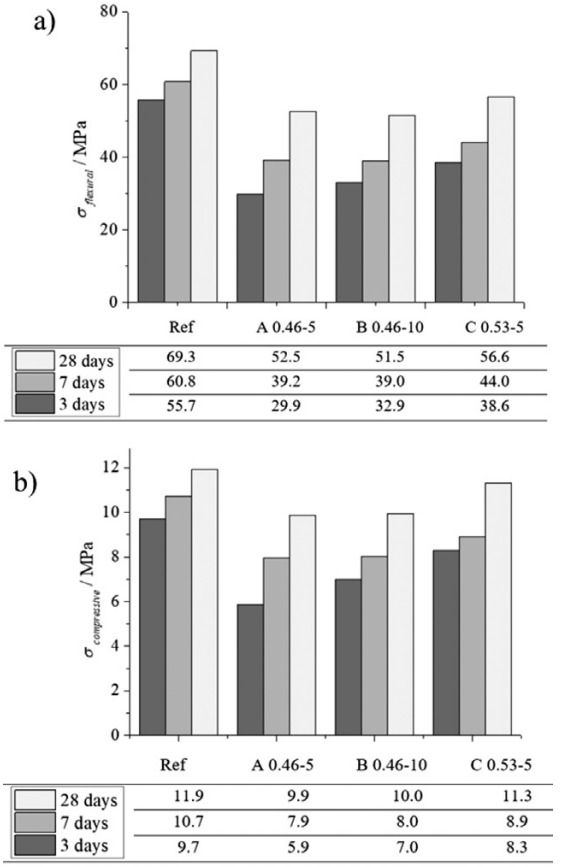

Figure 2: a) Compressive and b) flexural strength of cast and cured mortars

Table 3: Basic characteristics of fresh mortars as obtained on a flow table.

Sample name	ability to flow / mm	bulk density / kg m^{-3}	porosity / %
Ref	106	2402	3.9
A 0.46-5	103	2387	4.0
B 0.46-10	104	2276	3.8
C 0.53-5	172	2290	3.6

Figure 2 shows the evolution of the flexural and compressive strengths of the cast and cured mortar composites in the time periods of (3, 7, and 28) d. As expected, both compressive and flexural strengths increase over time for all the samples. When comparing the reference and the PCM samples, it is evident that the flexural and compressive strengths of the samples with the addition of PCM are lower. At the age of 3 d, sample A 0.46-5 reaches close to 54 % of the compressive strength of the reference sample, sample B 0.46-10 reaches ≈59 % of the reference strength, while sample C 0.53-5 reaches ≈69 % of the reference mixture compressive strength. At the age of 7 d, the compressive strength of the reference samples is around 61 MPa, and the samples with the added PCM achieve an average of around 67 % of that value. At the age of 28 d, the reference sample reaches a compressive strength of 69.31 MPa, while the compressive strengths of the samples A 0.46-5, B 0.46-10 and C 0.53-5 are 52.51 MPa, 51.54 MPa and 56.61 MPa, respectively, which is around 77 % of the reference value. The fact that the C 0.53-5 sample exhibits relatively higher strength values during the early stages of curing compared to the A 0.46-5 and B 0.46-10 samples can be attributed to the better workability of the C 0.53-5 sample.

Regarding flexural strength, the gap between the reference sample and the samples with added PCM is smaller than the compressive strength. At the age of 3 d, the samples with added PCM reached, on average, 72 %

(28 % gap) of the flexural strength of the reference mixture. After 7 d of hardening, this difference is down to 23 %, and at the age of 28 d, the gap in flexural strength is, on average, only 13 %.

The above numbers suggest that the reference sample hardens faster than the PCM samples; however, the gap in compressive or flexural strength between the reference and the PCM samples gradually becomes narrower with hardening time. It is, therefore, rational to expect that prolonged curing time will bring the compressive and flexural strengths of the PCM samples even closer to the reference value.

One of the fundamental parameters when designing mortar or mortar structures is the elastic modulus (E_c). In general, it is defined as the ratio of the applied stress to the corresponding strain. Not only does it demonstrate the ability of the mortar to withstand deformation due to an applied stress, but also its stiffness. In other words, it reflects the ability of the mortar to deflect elastically and is thus a good overall indicator of its strength. From this definition, it is also possible to connect the evolution of E_c with progressing mortar or mortar hardening. According to the results presented in **Figure 3**, the addition of a PCM to the mortar mixtures affects their E_c values (E_c is calculated through the velocity measurements of longitudinal ultrasound waves v_{US}). It is evident that the reference mixture starts hardening 3.55 h after casting. The mixture with added 5 % PCM (A 0.46-5) starts hardening within 4.40 h, while the B 0.46-10 mixture starts hardening another 35 min after the A 0.46-5 sample. Additionally, the C 0.53-5 sample with 10 % PCM and 0.53 *w/c* ratio behaves similarly to the A 0.46-5 sample with regard to hardening time and, thus, E_c evolution.

As expected, the dynamic modulus of elasticity after 48 h is the highest for the reference mixture, around ≈45 GPa. After the same time period, mortars with a PCM addition exhibit lower E_c values ranging between ≈32.2 GPa and ≈32.4 GPa. Furthermore, regarding the E_c values during this early curing time, the gap between he reference sample and the mortars with added PCM appears to widen. The latter suggests that the initial mortar hardening is a more complex process if the PCM is added to the mixture and that the PCM capsules affect the stress-strain behaviour and, thus, the deformation of mortars under load.

Successive freeze-thaw cycles and the disruption of paste and aggregate can cause some immediate microstructural changes and, eventually, permanent mortar damage. The main reason for such an observation is the fact that the liquid-to-solid phase change of water results in a volume expansion of about 9 %. As the water in the mortar freezes, it produces pressure in the pores of the mortar. If the pressure developed exceeds the tensile strength of the mortar, the cavity will dilate and rupture. Therefore, the freeze-thaw resistance is one of the many parameters which define mortar durability and should be carefully studied.

The results of the freeze-thaw tests are summarised in **Figure 4**. It is evident that the reference sample, as well as samples A 0.46-5 and C 0.53-5, have practically negligible mass loss after the 10th freeze-thaw cycle. In these three cases, after the 10th freeze-thaw cycle, only minor surface erosion can be visually observed. Further, at the end of the 20th freeze-thaw cycle, total mass losses for samples Ref, A 0.46-5 and C 0.53-5 were measured as 0.87 g, 1.80 g and 1.07 g, respectively. These values are still fairly low, suggesting that relatively low PCM additions only slightly affect the freeze-thaw durability of the investigated mortars. In contrast, the B 0.46-10 sample exhibits an ≈2 g mass loss and a rather rough surface after the first five freeze-thaw cycles. Surface erosion increases noticeably with each further freeze-thaw cycle, resulting in a 17.63 g mass loss after the 20th cycle (which is ≈3 % of the initial mass). The final surface of the B 0.46-10 sample is heavily degraded with numerous craters, voids and cracks, making such mortar inappro-

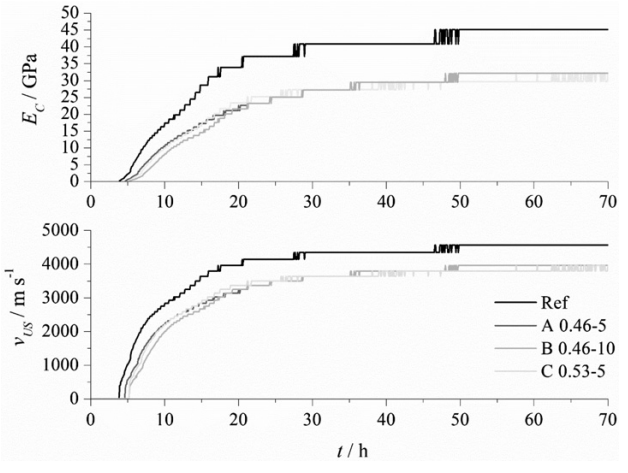

Figure 3: Evolution of dynamic modulus of elasticity (top) and velocity of longitudinal ultrasound waves (bottom) in the prepared mortar mixtures

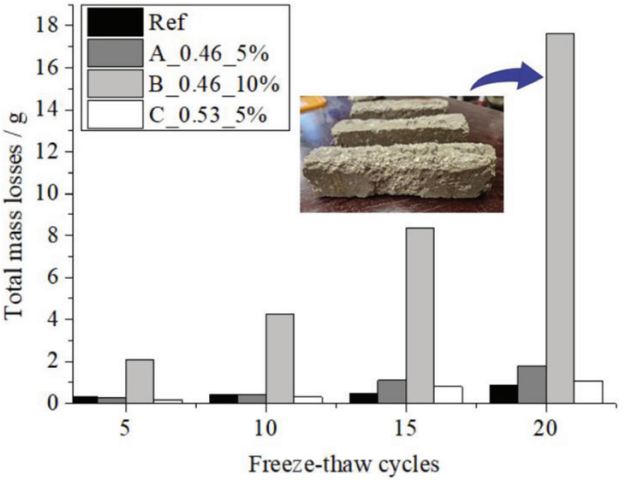

Figure 4: Freeze-thaw tests of mortars with various additions of PCM (the inner picture presents B 0.46-10 mortar bars after the 20th freeze-thaw cycle)

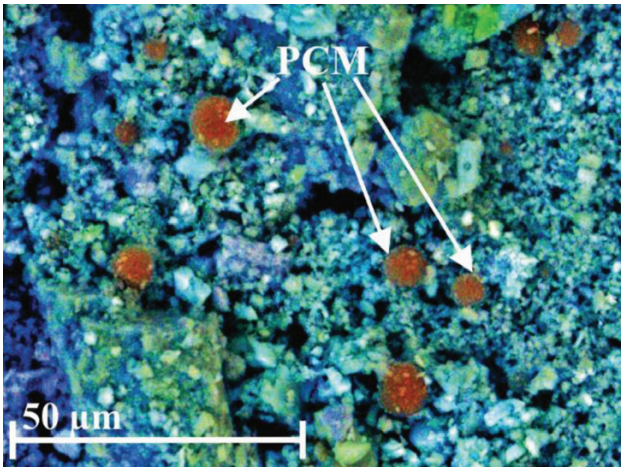

Figure 5: BSE-EDS images of A 0.46-5 mortar composite (PCM capsules are coloured red)

priate to use in extreme weather conditions or limiting its use only for potential applications inside buildings.

The presence of a PCM in the mortar mixture causes some unique microstructural features. Namely, PCM is an additional solid phase in a mortar composite with its characteristic spherical morphology. The microstructure of the A 0.46-5 sample is presented in **Figure 5**. It is evident that PCM microcapsules are uniformly distributed throughout the mortar. No PCM segregation in the A 0.46-5 hardened mortar further suggests successful material preparation during the components' mixing. Furthermore, all the PCM capsules are still undamaged, meaning that the paraffin wax remains firmly encapsulated within the relatively thin melamine-formaldehyde membrane. The latter is important when such mortar is applied in construction. Specifically, any wax leakage out of the membrane can influence the mortar-hardening process and its strength evolution. The final mortar strength is substantially lowered if the PCM capsules are damaged and the wax spreads throughout the mortar. Since PCM segregation is omitted by more vigorous mixing, while less intense mixing preserves the PCM capsules unharmed, a delicate balance in power input during the mortar preparation must be found.

If mortars with the PCM addition are used as modern building materials with a function to provide favourable living temperatures, the thermal properties of such materials are essential. Specifically, the head capacity and temperature interval of the solid-to-liquid phase transition are two basic characteristics of such modern composites. To evaluate the thermal behaviour of the prepared mortars, a series of DSC tests were conducted (**Figure 6**). The DSC tests included two consecutive cooling-heating cycles in order to verify the repeatability of the measured heat effects. According to the collected DSC results, the reference sample (mortar without PCM addition) exhibits no measurable heat effects within the monitored temperature window (**Figure 6a**). In contrast, the pure PCM sample (**Figure 6b**) shows an exothermic effect during heating and several (two major) consecutive endothermic effects during cooling. The exothermic effect is a consequence of the wax melting during heating, while the endothermic effects are due to subsequent wax solidification during cooling. Several consecutive endothermic peaks during cooling indicate that the wax from the PCM is a combination of different straight-

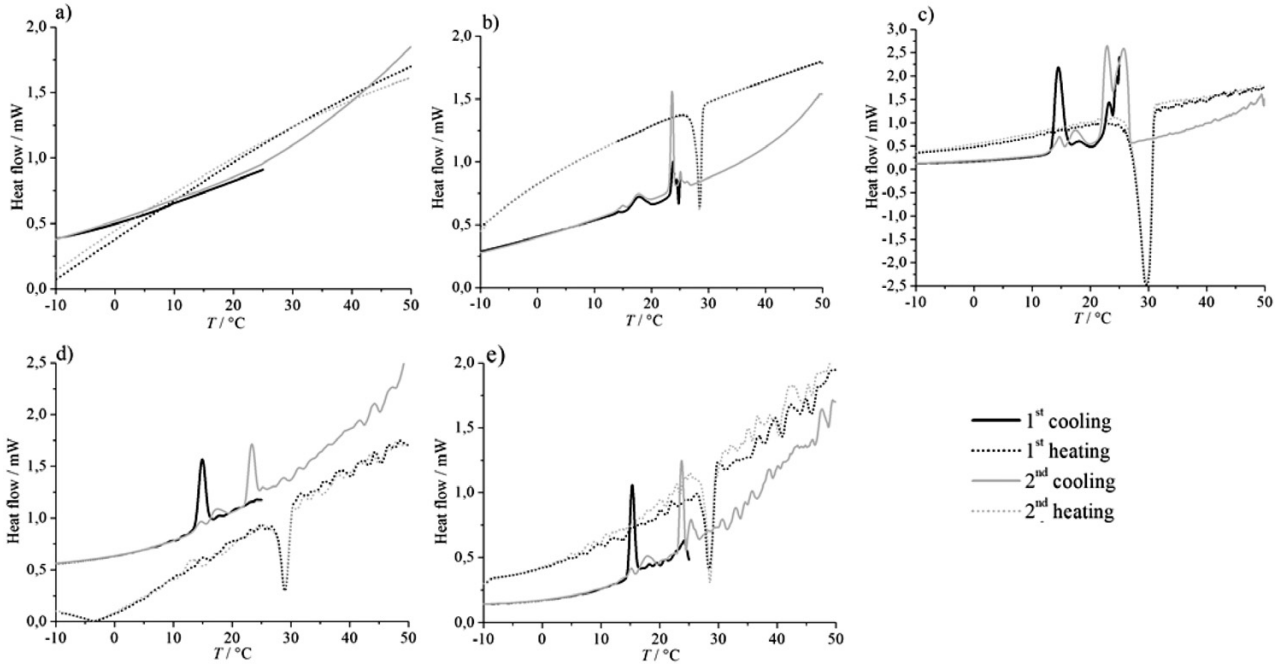

Figure 6: DSC measurements of mortars with various PCM additions: a) the Ref sample, b) the A 0.46-5 sample, c) the pure PCM, d) the B 0.46-10 sample, e) the C 0.53-5 sample

Table 4: Peak temperatures and calculated latent heat capacities of various mortar samples as obtained from the DCS measurements

Step	1st cooling		1st heating		2nd cooling		2nd heating	
Sample	T_{peak} / °C	ΔH / J g^{-1}	T_{peak} / °C	ΔH / J g^{-1}	T_{peak} / °C	ΔH / J g^{-1}	T_{peak} / °C	ΔH / J g^{-1}
Ref	not detected		not detected		not detected		not detected	
PCM	14.6	–58.2	29.4	183.0	22–17.5	–184.1	29.5	187.0
A 0.46-5	17.8	–2.4	28.5	9.7	22.5–18	–9.7	28.5	9.8
B 0.46-10	14.9	–4.9	29.2	18.6	23–18	–18.9	29.2	18.4
C 0.53-5	15.3	–2.6	28.6	9.6	23.5–18	–9.3	28.6	9.3

chain hydrocarbons rather than a chemically well-defined single organic compound. The latter is further corroborated by the fact that melting and/or solidification intervals are rather wide. Furthermore, the melting (≈29 °C) and the solidification (main peak at ≈23 °C) of the wax are separated by a temperature hysteresis. The latent-heat storage capacities of the encapsulated PCMs are measured as 183.0 J g^{-1}, –184.1 J g^{-1}and 187.0 J g^{-1} during the 1st heating cycle and the 2nd cooling cycle in the 2nd heating cycle, respectively (**Table 4**). Data from the 1st cooling cycle are irrelevant since the cycle is incomplete. If the mortars with PCM additions are tested, the exothermic and endothermic effects due to wax melting and solidification, respectively, are still apparent, however, with much lower latent-heat storage capacity when compared to the pure PCM material. On average, $\Delta H_{melting/solidification}$ of samples A 0.46-5, B 0.46-10 and C 0.53-5 are measured as 9.7 J g^{-1}, 18.7 J g^{-1} and 9.4 J g^{-1}, respectively, which is comparable to the work of Christen et al. [28]. These numbers can be illustrated through a hypothetical calculation. Let us assume a room with dimensions of 3 m × 3 m × 4 m where the ceiling and outer walls are plastered, applying mortar with the PCM addition. A simple calculation reveals that the plastered surface equals 54 m^2. Assuming a 2-cm-thick layer of the applied plaster, we can further calculate the volume of the used plaster to be 1.08 m^3 (≈1.1 m^3). A typical density of mortar varies from 2400 kg m^{-3} to 2900 kg m^{-3}. Since PCMs are a relatively low-density phase in mortar composites, they somewhat lower the final mortar density. Thus, for additional calculations, we may consider the mortar (plaster) density to be ≈2300 kg m^{-3}, resulting in a final mass of ≈2500 kg of used mortar for plastering. The latter further suggests that the latent-heat storage capacities of mortars A 0.46-5, B 0.46-10 and C 0.53-5 are calculated as 6.74 kWh, 12.99 kWh and 6.53 kWh, respectively, if the hypothetical room is plastered. Such relatively high values might substantially reduce the energy consumption for the cooling and heating of buildings as well as increase the thermal comfort for residents. Finally, the use of mortars with PCM addition can aid in constructing buildings that are more energy efficient and environmentally friendly.[29]

4 CONCLUSIONS

The study described the development of some functional properties of mortar mixtures with various additions of a PCM based on encapsulated paraffin wax. All the mortar composites with the PCM addition exhibited gradually increasing flexural and compressive strengths within 28 d of curing time. The composite (C 0.53-5) with a *w/c* ratio of 0.53 reached the highest value. Its flexural and compressive strengths after 28 d of hardening were 82 % and 95 %, respectively, compared to the reference mixture. The elastic modulus of the mortar composites with the PCM addition after 20 h of hardening reached between 60 % and 70 % of the reference value. The freeze-thaw tests suggested that relatively low PCM additions (5 φ/%) negligibly affected the freeze-thaw durability, while an addition of 10 φ/% made mortar completely inappropriate to use in extreme weather conditions. The SEM-EDS microstructural analysis showed that the PCM capsules were undamaged and uniformly distributed in the mortar matrix. Thermo-analytical cycling tests showed repeatable melting/solidification of the PCM, indicating a high potential of mortars with PCM additions for developing energy-efficient building materials. A closer examination of the DSC results revealed that the melting/solidification enthalpy for samples A 0.46-5, B 0.46-10, and C 0.53-5 were 9.7 J g^{-1}, 18.7 J g^{-1}, and 9.4 J g^{-1}, respectively. Assuming that these composites were installed in a room of average dimensions, they could result in up to 20 % savings in heating/cooling energy consumption throughout the year. Overall, the results of this study are an important step toward the development and use of mortar mixtures with PCM additions as a viable approach to improving the thermal performance and structural integrity of building materials.

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