Application of latent-heat-storage building envelope systems for increasing energy efficiency in the building sector

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Abstract

The construction of latent-heat-storage building envelope systems often involves an application of interior and/or exterior plasters with enhanced thermal storage properties. In this paper, cement-lime plasters with incorporated phase change material (PCM) are designed and the effect of the applied PCM on their heat storage capacity is analysed using the measurement of basic physical, mechanical and thermal parameters. Among the basic physical properties, bulk density, matrix density and total open porosity are measured. Mechanical resistivity of the developed plasters is characterized by compressive and flexural strength and dynamic Young's modulus. Thermal conductivity and thermal diffusivity are measured using the transient pulse method. The temperature dependent specific heat capacity is accessed using differential scanning calorimetry (DSC) in cooling, as well as heating regime. On the basis of the experiments performed, the supposed improvement of the energy efficiency of characteristic building envelope system where the designed plasters are likely to be used is evaluated by a computational analysis. The results of computer simulations are very promising for the future use of the designed system in the building sector.
Keywords: latent heat storage, phase change materials, plasters, computational modelling, thermal performance.

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1 Introduction

The rapidly growing world energy use has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts (ozone layer depletion, global warming, climate change, etc.). The global contribution from buildings towards energy consumption, both residential and commercial, has steadily increased, reaching figures between 20% and 40% in developed countries, and in USA and EU it has exceeded the other major sectors: industrial and transportation. For this reason, energy efficiency in buildings is today a prime objective for energy policy at regional, national and international levels [1].

For the improvement of energy efficiency of buildings, there is necessary to focus on advanced technical solutions of building design resulting in building envelopes with high thermal resistance and sufficient thermal stability. Specific attention must be paid not only to the technical solution of the building enclosure, but also to the particular inbuilt materials, especially to their thermal properties.

Application of latent heat storage building envelope systems using phase-change materials (PCMs) represents an attractive method of storing thermal energy and has the advantages of high-energy storage density and the isothermal nature of the storage process. In this method, thermal energy is stored by a PCM during the solid–liquid phase-change process, and the stored energy is released when it changes from the liquid to the solid [2]. Suitable PCMs incorporated into the building structures make possible to maintain the internal temperature of buildings closer to the desired comfort temperature for a longer period, without any other additional energy for cooling and heating. There is a large number of PCMs (organic, inorganic and eutectic), which can be identified as PCMs from the point of view of the melting temperature and latent heat of fusion [3, 4]. For an application in the regulation of the heat storage of building structures, such materials must be used that exhibit the phase transition in the temperature range corresponding to the thermal climatic loading of buildings. According to the literature, paraffinic wax is the most often used commercial organic heat storage PCM having the melting temperatures in the interval of 23 to 67°C what is optimal for moderation of interior climatic of buildings [5]. Since the benefits of PCMs for moderating the building's interior climate were proven by several experimental studies, new types of plasters with incorporated PCM based on microencapsulated paraffinic wax are designed and tested in the presented paper. Besides the detailed experimental analysis, the plasters thermal performance is evaluated using a computational analysis.

2 Experimental

2.1 Studied materials

The plasters were prepared using the dry plaster mixture Baumit Manu 1, which consisted of hydrated lime, cement, sand and additives. The commercial dry plaster mixture was modified by PCM admixture at mass dosages of 8 and 24% referred to the mass of the original dry plaster mixture. Because of the negative effect of PCM admixture on plasters workability, the water dosage was increased to maintain the same workability for all tested mixtures. As PCM admixture, the polymer microencapsulated paraffinic wax produced by BASF was applied. Plasters composition is given in Table 1.

Table 1: Composition of researched plasters.

Plaster	Water (kg)	Dry plaster mixture (kg)	PCM (kg)
Reference plaster (RP)	1.5	6.3	0.000
Plaster with 8 mass% of PCM (P8)	1.95	6.3	0.504
Plaster with 24 mass% of PCM (P24)	2.35	6.3	1.512

2.2 Basic characterization

Among the basic physical properties, the bulk density, matrix density, and total open porosity were measured. Bulk density was accessed on the gravimetric principle from the measured sample size using digital length meter and its dry mass. For this measurement, 5 cubic samples of side 100 mm were used. The matrix density was determined also on helium pycnometry principle. Matrix density was measured by helium pycnometry using apparatus Pycnomatic ATC (Thermo Scientific). At the application of Pycnomatic ATC, a well dried sample of studied material was weighed and placed in a calibrated reference chamber of known volume. Helium was first loaded at known pressure in a calibrated reference chamber and then expanded into the sample chamber. Once the pressure was stabilized, experimental data were collected and the material volume was accessed. The accuracy of the gas volume measurement using this device was ± 0.01% from the measured value, whereas the accuracy of used analytical balances was ± 0.0001 g. On the basis of bulk density and matrix density measurements, the total open porosity was calculated [6]. The relative expanded uncertainty of applied testing method was 5%.

2.3 Mechanical properties

Mechanical resistivity of researched composites was characterized by compressive strength, flexural strength and Young's modulus. Compressive and flexural strength were measured according to the standard ČSN EN 1015-11 – Methods of test for mortar for masonry – Part 11: Determination of flexural and compressive strength of hardened mortar. The measurements were done on samples cured 28 days in water. Young's modulus was measured on dynamic principle using the pulse ultrasonic device DIO 562 (Starmans electronics) working on the frequency of 50 kHz.

2.4 Heat transport parameters

Thermal conductivity and thermal diffusivity were measured by ISOMET 2114 (Applied Precision) working on a dynamic measurement principle, which reduced the time of measurements to 10–20 minutes [7]. The measuring range of thermal conductivity was from 0.015 W/mK to 6 W/mK. The accuracy was 5% of reading +0.001 W/mK. The measurement reproducibility was 3% of reading in operation temperature range from 0 to 40°C.

2.5 DSC analysis

The measurements were done using apparatus DSC 822e (Mettler Toledo). The following temperature regime was applied: 5 minutes of the isothermal regime (40°C), cooling of 10°C/min from the temperature 40°C to the temperature –10°C, 5 minutes of the isothermal regime (-10°C), heating of 10°C/min from the temperature -10°C to the temperature 40°C, 5 minutes of isothermal regime (40°C). For the low temperature exposure of the studied samples, the cooling device FT 900 (Julabo) was used. On the basis of DSC analysis, the temperatures of the phase transitions and temperature dependent specific heat capacity were identified.

3 Computational

The thermal performance of tested plasters exposed to the climatic conditions changes was evaluated using a computational analysis. Within the performed computer simulations, the particular studied plasters were applied in a thickness of 15 mm on the interior surface of structural wall built from autoclaved aerated concrete P4 – 500 [8]. Material parameters of autoclaved aerated concrete were taken from the material database of Department of Materials Engineering and Chemistry, FCE CTU in Prague [9]. The system is based on PostgreSQL type of database with PHP application, a solution well proven in general computer systems, but also in materials science [10].

For the tested structure, thermal transmittance (U-Value) and thermal resistance (R-Value) were calculated according to [11], assuming the thickness of the autoclaved aerated concrete wall of 375 mm. Thermal resistance of studied structure was calculated using Eq. (1)

$$R = \sum_{i=1}^{2} \frac{d_i}{\lambda_{eff_i}}, \tag{1}$$

where R (m^{2}K/W) is the thermal resistance, d_i (m) the thickness of the particular material and λ_{effi} (W/mK) the effective thermal conductivity of plaster and autoclaved aerated concrete, respectively. Thermal resistance of the whole structure is expressed as

$$R_T = R_{si} + R + R_{se}, \tag{2}$$

where R_T (m^{2}K/W) is the total thermal resistance of structures, R_{si} (m^{2}K/W) the thermal resistance for the heat transfer at the interior surface (0.13 m^{2}K/W) and R_{se} (m^{2}K/W) the thermal resistance for the heat transfer at the exterior surface (for winter period 0.04 m^{2}K/W). Thermal transmittance U (W/m^{2}K) was calculated from Eq. (3)

$$U = \frac{1}{R_T} . \tag{3}$$

At the computational analysis, the particular studied structures were exposed to the following interior temperature regime: the initial interior surface temperature was 22°C, 5 hours of the isothermal regime (18°C), 2 hours linear heating from the temperature 18°C to the temperature 26°C, 13 hours of the isothermal regime (26°C), 2 hours linear cooling from the temperature 26°C to the temperature 18°C, 2 hours of the isothermal regime (18°C). One complete temperature cycle took 24 hours, whereas the above given temperature exposure was repeated six times. The simulated interior temperature is given in Figure 1.

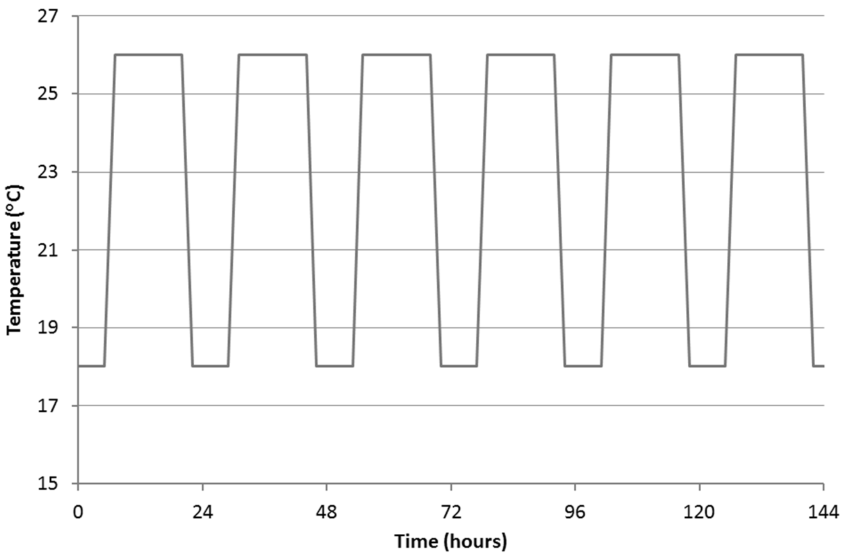

Figure 1: Simulated interior temperature.

The computational analysis was done using computer code SHeM-comp developed at Department of Materials Engineering and Chemistry, Faculty of Civil Engineering, Czech Technical University in Prague. The code is a specialized computer simulation tool for the service life and hygrothermal material behaviour assessment of building envelopes. It is designed as a desktop solution with connectable material and climatic databases [12]. The solution of partial differential equations created by the implementation of the formulated heat, moisture, and salt mass balance equations is accomplished within the batch solver SIFEL [13] using the finite element method.

4 Results and discussion

In Table 2, basic physical properties of tested materials are presented. We can see that using the PCM admixture led to the decrease in both matrix and bulk densities. This finding was not surprising; the polymer capsules' density is lower as compared to the plaster matrix. Total open porosity was for both PCM modified plasters lower than for the reference plaster. This we assign to the high fineness of PCM admixture that ensured the filler effect in the plaster mixtures.

Table 2: Basic physical properties of tested plasters.

Material	Bulk density (kg/m^3)	Matrix density (kg/m^3)	Total open porosity (% m^3/m^3)
RP	1 572	2 416	34.9
P8	1 230	2 129	32.2
P24	1 025	1 667	28.5

Mechanical properties are presented in Table 3. Here, despite the improved total open porosity due to the filler effect, the non-reactive PCM particles yielded lower mechanical resistivity of PCM modified plasters. However, the mechanical properties of these newly developed materials remained still sufficient for an application as interior plaster.

Table 3: Mechanical properties of tested plasters.

Material	Compressive strength (MPa)	Bending strength (MPa)	Young's modulus (GPa)
RP	3.13	0.90	1.91
P8	2.76	0.75	1.88
P24	1.76	0.65	1.40

Heat transport properties measured by the transient pulse method are shown in Table 4. Here, the significant decrease of the thermal conductivity and thermal diffusivity can be observed in dependence on the amount of applied PCM admixture. This material performance can be assigned to the low thermal conductivity of PCM admixture that is equal to 0.08 W/mK at 21°C.

Table 4: Thermal properties of tested plasters.

Material	Thermal conductivity (W/mK)	Thermal diffusivity (10^{-6} m^2/s)
RP	0.54	0.36
P8	0.39	0.27
P24	0.18	0.12

Specific heat capacity of tested materials accessed as a function of temperature is presented in Fig. 2. One can see a high increase of specific heat capacity at the temperature of phase change. Here, the higher amount of incorporated PCM admixture provided the material with a significantly improved heat storage capacity. The measured temperature dependent specific heat capacities were used as input data for computational modelling of plasters performance in the simulated temperature regime of interior climate.

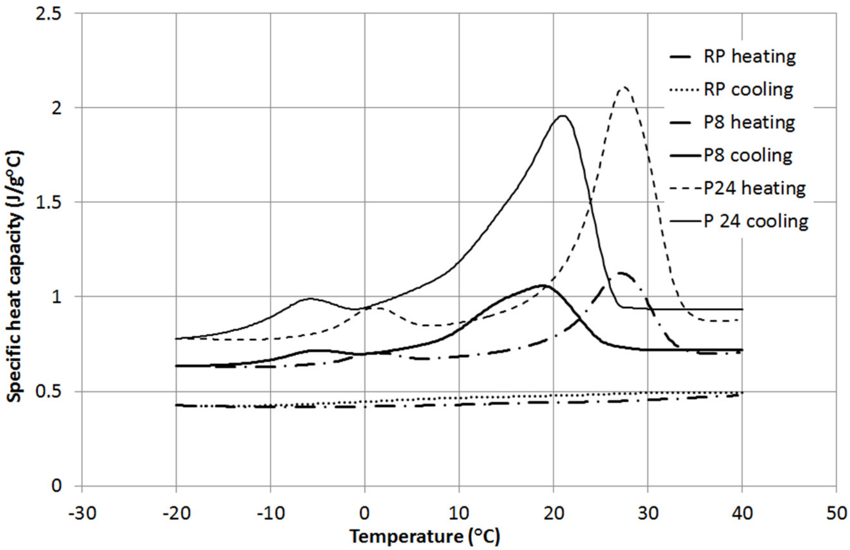

Figure 2: Temperature dependent specific heat capacity.

Thermal parameters of simulated building envelope are given in Table 5. We can observe a slight improvement of both thermal resistance and thermal transmittance from the point of view of thermal insulation performance of the modelled wall. Nevertheless, all studied variants of the envelope met the requirement on thermal transmittance value that is according to the standard ČSN 73 0540-2:2011 for an exterior wall equal to 0.3 W/m^2K.

Table 5: Thermal parameters of simulated structure.

Applied interior plaster	U (W/m^2K)	R (m^2K/W)
RP	0.287	3.49
P8	0.286	3.50
P24	0.282	3.54

However, this was not the main reason for the application of PCM admixture. The contribution of PCM admixture to the thermal performance of the studied building envelope is shown in Figure 3 in more detail. Here, the plaster temperature during 3rd day of simulation is given. It is evident that the application of PCM admixture decelerated both warming and cooling of the plaster layer, as compared to the reference plaster. During the cooling process of P24 to 18°C, the deceleration was approx. 5 hours compared to the plaster RP, whereas the minimal temperature during heating was 18.7°C. For the heating to 25°C, the monitored deceleration was approx. 1 hour. Finally, during the last cooling to approx. 19°C, the deceleration was 1.5 hours. In summary, the total one-day deceleration of plaster temperature was 7.5 hours. This documents the proper function of PCM admixture incorporated in modified plaster mixtures, and makes the designed plasters promising materials for the achievement of energy savings in the building sector.

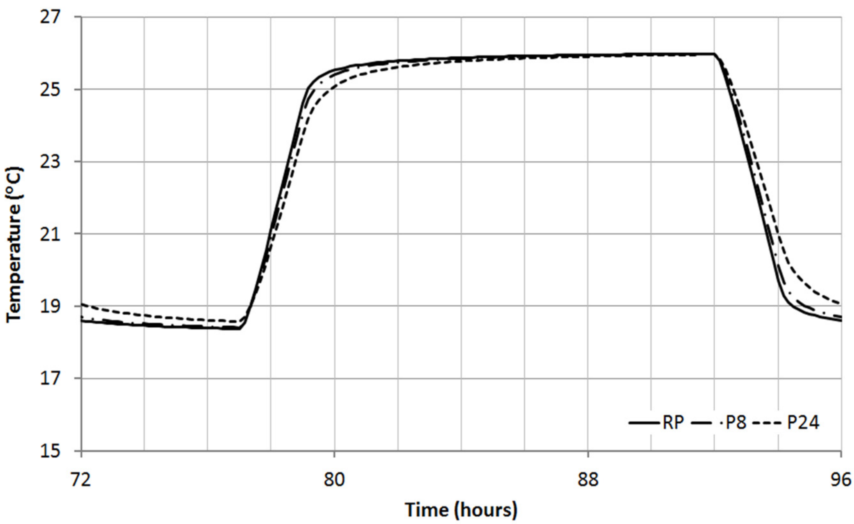

Figure 3: Plaster temperature during the 3rd day of computer simulation.

5 Conclusions

The goal of the presented work was to evaluate the effect of microencapsulated PCM admixture on the improvement of the heat storage capacity of a commercially produced lime-cement mortar and proved its applicability in latent-heat-storage building envelope systems for increasing the energy efficiency in the building sector. At the experimental and computational investigations, two modified plasters with different portions of incorporated PCM admixture based on polymer microencapsulated paraffinic wax were developed and tested. The obtained results proved that the temperature-induced phase change of PCM can be used for release and storage the thermal energy in building materials and structures and can be beneficially utilized for saving the energy spent for the achievement of the indoor thermal comfort.

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