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Energy Efficiency of Novel Interior Surface Layer with Improved Thermal Characteristics and Its Effect on Hygrothermal Performance of Contemporary Building Envelopes

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Received: 12 March 2020; Accepted: 16 April 2020; Published: 17 April 2020



Abstract: Facing the consequences of climate change and fuel price rises, the achievement of the requirements for low-energy consumption of buildings has become a challenging issue. On top of that, increased demands on indoor hygrothermal conditions usually require the utilization of additional heating, ventilation, and air-conditioning (HVAC) systems to maintain a comfortable environment. On this account, several advanced and modern materials are widely investigated as a promising way for reduction of the buildings' energy consumption including utilization of passive heating/cooling energy. However, the efficiency and suitability of passive strategies depending on several aspects including the influence of location, exterior climatic conditions, load-bearing materials used, and insulation materials applied. The main objective of this study consists of the investigation of the energy performance benefits gained by the utilization of advanced materials in plasters by computational modeling. Results obtained from a computational simulation reveal the capability of the studied passive cooling/heating methods on the moderation of indoor air quality together with the reduction of the diurnal temperature fluctuation. Achieved results disclose differences in terms of energy savings for even small variation in outdoor climate conditions. Additionally, the effectivity of passive cooling/heating alters considerably during the summer and winter periods. Based on the analysis of simulated heat fluxes, the potential energy savings related to improved thermal properties of the applied plaster layer reached up to 12.08% and thus represent an interesting passive solution towards energy sustainability to meet the criteria on modern buildings.

Keywords: plaster; thermal energy storage; computation simulation; recuperation heat; passive cooling; climate

1. Introduction

A major share of energy demands is allocated to the maintenance of the indoor thermal comfort for building inhabitants [1]. On this account, the development of new insulation systems attracted much attention during the few last decades [2,3]. Efforts paid to this field resulted in the design of new insulation materials and the optimized composition of building envelopes for a better thermal performance of buildings required for the maintenance of sufficient indoor thermal comfort [4]. Among the other factors, the thermal comfort poses one of the main factors influencing occupants´ wellbeing, health, and working productiveness, thus need significant attention [5]. Since humans spend most of

their time indoors, the particular importance of maintenance of the indoor environment becomes more important in order to mitigate Sick Building Syndrome consequences [6].

Regarding the concept of the ideal energy conservation of buildings, the envelope plays a crucial role in the temperature delay of the outside temperature variations with a significant impact on indoor thermal comfort [7]. The concept can be applied for cases when the thermal storage and insulation play a suitable role in the delay of the outdoor temperature fluctuations, thus the temperature can be maintained without any additional heating or cooling devices [8–10]. This issue is mostly related to the significantly outdated building envelopes of older houses with poor thermal performance and thus high energy demand.

Despite the number of studies aimed at the investigation of thermal properties of phase change materials (PCM), only minor attention is paid to the suitability, compatibility, and effectivity of PCMs with various masonry types or applied insulation layers [11–13]. The volumetric thermal capacity of building materials, together with the different thermal conductivity has an inevitable impact on the utilization of PCM latent heat [14]. The thermal mass of applied building materials can contribute to the overall building heat storage capacity and thus a building envelope's thermal performance [15,16]. The overall positive effect according to Johra et al. [12] can be clearly seen especially in the case of lightweight building structures and the application of PCMs on such structures poses an auspicious solution for improvement of thermal inertia. On the other hand, a higher risk of overheating was found in the case of low-energy houses when PCM is applied to the interior side [17–19].

The adaptability of applied PCM in various climate regions represents another substantial task associated with its efficiency and viability from the economical point of view [20]. According to the performed study focused on PCM viability in a hot and humid climate in Iran, the cost-effectiveness of such materials is poor, thus the application struggles with financial indicators [21]. Contrary to the hot and humid Iranian climate, the benefits of PCM incorporation into gypsum boards were achieved in continental/subtropical climate with dry winter in the South Korean region [13]. The importance of PCM selection and adaption for certain climate types was accessed through the simulation of monthly energy savings in U.S. locations likewise [22]. Here, substantial differences in the PCM effectivity application in Chicago, Los, Angeles, Miami, and Phoenix highlighted divergent temperature fluctuations, especially during the summer and winter periods. Notwithstanding this, the lack of studies focused on the effectivity of PCM solution in mild climate limits a broader material application [23].

A proper understanding of building envelope response to the varying outdoor conditions represent another substantial task [24,25]. The influence of various climate, diurnal or seasonal temperature fluctuation climate characteristics were found as essential for beneficial and economically effective PCM applications [26]. On the other hand, the definition of optimal ambient conditions needs to be done to meet with the criteria of building inhabitants [27].

Most of the recent studies dealing with the energy savings are strictly focused only on the investigation of the heat transfer and optimization of the available technologies, materials, and methods which can be effectively applied in the construction industry. Besides a moderation of the temperature, the overall quality of the indoor environment is also connected to the level of the relative humidity [28]. Recent studies highlighted the significance of the level of the relative humidity and the need to regulate it to avoid negative consequences associated with mold growth, the health of buildings occupants, deterioration of furnishing, etc. [29]. The maintenance of the indoor hygrothermal conditions is usually carried out by heating, ventilation and air-conditioning systems which are responsible for increasing energy consumption [30,31]. Advanced modern building materials can moderate indoor temperature and moisture fluctuations and mitigate the loading peaks [32,33]. Furthermore, the fabrication of advanced materials significantly affects the hygroscopicity of novel materials and thus their moisture-buffering capability [34–39].

Overcoming of the described issues poses just one aspect of efficient PCM utilization in the building industry. Overbridging problematic issues associated with PCMs implementation provides a

more precise evaluation of the temperature and moisture coupled effect. The proper understanding of building envelope response to the varying outdoor conditions represent another substantial task.

Taking into account the aforementioned points, the analysis of newly developed form-stable PCM (FSPCM) was carried out together with a numerical simulation accessing the hygrothermal performance of plaster with enhanced thermal storage properties. Within this paper, the influence of construction material on thermal storage effectivity as well as the difference in the thermal performance in the particular seasons and locations were studied by the help of computational modeling. The possible benefits provided by the PCMs' application based on the energy consumption reduction effect were calculated.

2. System Description

2.1. Materials

In this study, FSPCM prepared from diatomaceous earth as a supporting material and dodecanol as PCM medium with the desired temperature of the phase change was used. The details of the material fabrication of FSPCM are described in [38]. For better clarity, the applied plaster was modified by 0, 8, 16, and 24 wt.% of FSPCM and denoted as RP, P8, P16, and P24, respectively. Summarized results describing the phase change temperatures and phase change enthalpy are given in Table 1. The experimental thermophysical analysis of such plasters was done in the previous study [40].

Table 1. Phase change temperatures of studied plasters and specific enthalpies.

Material	Phase Change Temperature (°C)				Latent Heat of Fusion/Freezing (J/g)	
	Heating		Cooling		Heating	Cooling
	Onset	Endset	Onset	Endset		
RP	-	-	-	-	-	-
P8	22.46	24.68	20.68	18.63	4.63	4.89
P16	22.13	24.91	20.81	18.98	10.11	10.28
P24	22.68	25.86	20.75	19.66	15.20	15.38

In order to access the effectivity of building envelopes modified by PCM, the computational simulation of typical load-bearing material was carried out. The thermophysical properties of applied building materials are given in Table 1. Within the computer simulations, the studied plasters were applied in a thickness of 20 mm on the interior surface of the structural wall built by ceramic bricks with a thickness of 450 mm equipped by a 100 mm layer of mineral wool. Since the material parameters of ceramic brick were not measured within the presented work, we adopted the results from the previous research as accessed in Table 2 [41,42]. The detailed scheme of studied wall assembly used in the computational simulation is given in Figure 1.

Table 2. Parameters of applied materials.

Material Parameter	Ceramic Brick	Mineral Wool
Bulk density ($kg \cdot m^{-3}$)	1831	70
Matrix density ($kg \cdot m^{-3}$)	2581	2260
Total open porosity (%)	27.9	96.9
Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.59	0.036
Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	825	810
Water vapor diffusion resistance factor (-)	22.1	2.62

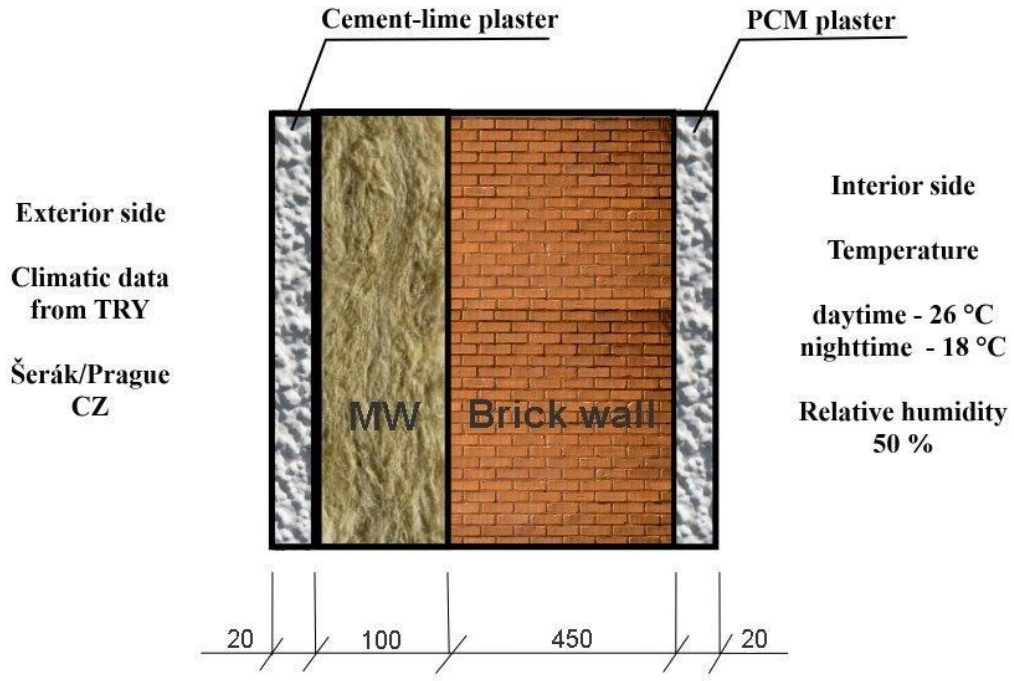


Figure 1. Scheme of computational simulation for brick/mineral wool construction.

2.2. Boundary Conditions

The particularly studied structures were exposed to alternating temperatures of 18 and 26 °C. In the temperature regime, the wall was exposed to 18 °C for 5 h, to 26 °C for 13 h, and back to 18 °C for another 2 h, while each change of interior temperature took 2 h to avoid temperature step jumps. Thus, one complete cycle took one day, and the loading cycles were repeated for 365 days. The exterior environment was simulated using test reference years (TRY) in order to simulate the real fluctuations of environmental loads. TRY includes hourly weather data of temperature, relative humidity, wind speed and direction, solar radiation and precipitation.

In this study, two locations in the Czech Republic were chosen, Prague and Šerák. However, the Koppen and Geiger climate classification often used [43] does not distinguish any differences between the selected locations despite the harshness of the Šerák region compared to Prague (see Table 3), thus more detailed characterization has to be used. To provide a comparison of both locations in the Czech Republic, the damage function enumerating a number of indicative freeze/thaw cycles was used as is shown in the isopleth map (see Figure 2).

Table 3. Averaged climatic data for Prague and Šerák region.

Location	January	February	March	April	May	June	July	August	September	October	November	December
Prague–temp. (°C)	1.83	2.53	4.83	9.33	15.19	18.03	19.61	19.09	15.02	8.94	5.62	1.56
Šerák–temp. (°C)	−4.36	−2.31	−3.18	2.12	7.06	11.04	11.59	12.33	7.55	3.51	−1.66	−3.98
Prague–RH (%)	77.2	72.4	67.6	60	57.9	57.9	66.1	62.7	72.4	75.5	78.2	77.6
Šerák–RH (%)	82.8	86.4	82.7	77.9	73	76.1	82.6	83.7	83.1	87.9	93	87

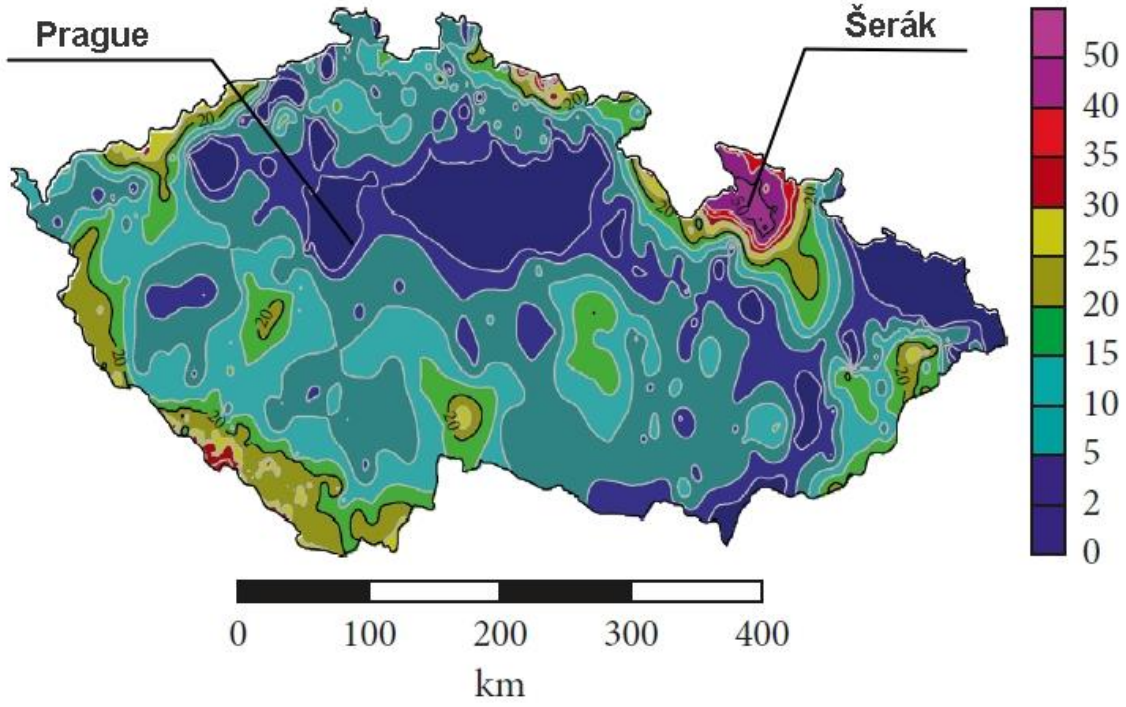


Figure 2. Freeze/thaw cycles map of the Czech Republic.

2.3. Computational Analysis

The objective of the computational modeling was to investigate the effect of studied plasters with FSPCM on the energy performance and the surface temperature distribution of selected typical building wall assembly and to analyze potential improvements that may result from the application. For that reason, the data obtained from laboratory experiments were used as input parameters and 1-D simulation of heat and moisture transport through the building wall exposed to the dynamic exterior and interior environment was conducted.

Computational Model

The description of heat and moisture transport in studied materials was based on the modified version of Künzel's mathematical model [44]. The motivation for such a modification was to improve the numerical stability of the original model as well as to increase output accuracy and reduce computational time. The balance equations for heat and moisture mass in one-dimensional transport problem are defined as:

$$\frac{\mathrm{d}H}{\mathrm{d}T}\frac{\partial T}{\partial t} = div(\lambda \ \mathrm{grad}\ T) + L_{\mathrm{v}} div\left(\delta_{\mathrm{p}} \ \mathrm{grad}\ p_{\mathrm{v}}\right), \tag{1}$$

$$\left[\rho_{\mathrm{w}}\frac{dw}{dp_{\mathrm{v}}} + (n-w)\frac{M}{RT}\right]\frac{\partial p_{\mathrm{v}}}{\partial t} = div\left[D_{\mathrm{g}} \ \mathrm{grad}\ p_{\mathrm{v}}\right], \tag{2}$$

where H (J·m^{-3}) is the enthalpy density, T (K) the absolute temperature, λ (W·m^{-1}·K^{-1}) the thermal conductivity, L_{v} (J·kg^{-1}) latent heat of evaporation of water, δ_{p} (s) the water vapor diffusion permeability, p_v (Pa) the partial pressure of water vapor in the porous space, ρ_w (kg·m^{-3}) the density of water, w (m^3·m^{-3}) the moisture content by volume, n (-) the porosity of the porous body, M (kg·mol^{-1}) the molar mass of water vapor, and R (J·K^{-1}·mol^{-1}) is the universal gas constant. D_g (s) is the global moisture transport function defined as

$$D_{\mathrm{g}} = B \cdot D_{\mathrm{w}}\rho_{\mathrm{w}}\frac{dw}{dp_{\mathrm{v}}} + A \cdot \delta_{\mathrm{p}}, \tag{3}$$

where *A* and *B* are the membership functions defining the transition between particular phases of water. For more information on membership functions A and B please refer to Maděra et al. [44].

For the description of phase change in the material, a fixed-domain method was used. The fixed-domain method treats both solid and liquid phases as one continuous medium and the interface condition becomes implicit in a new form of the equations described, particularly in this paper, by the effective specific heat capacity c_{eff}. Such a solution does not require re-meshing, which makes the implementation quite simple [45]. The effective specific heat capacity c_{eff}, which is defined as the slope of specific enthalpy vs. temperature function, was obtained in the experimental part of this research using a DSC device. The basic thermophysical obtained by the DSC device were shown in Table 1. However, to apply the fixed domain method, the effective specific heat capacity c_{eff} needs to be identified in the entire temperature range and substituted to the heat balance Equation (1) instead of dH/dT. The measured specific heat capacities of studied plasters for both heating and cooling are shown in Figures 3 and 4.

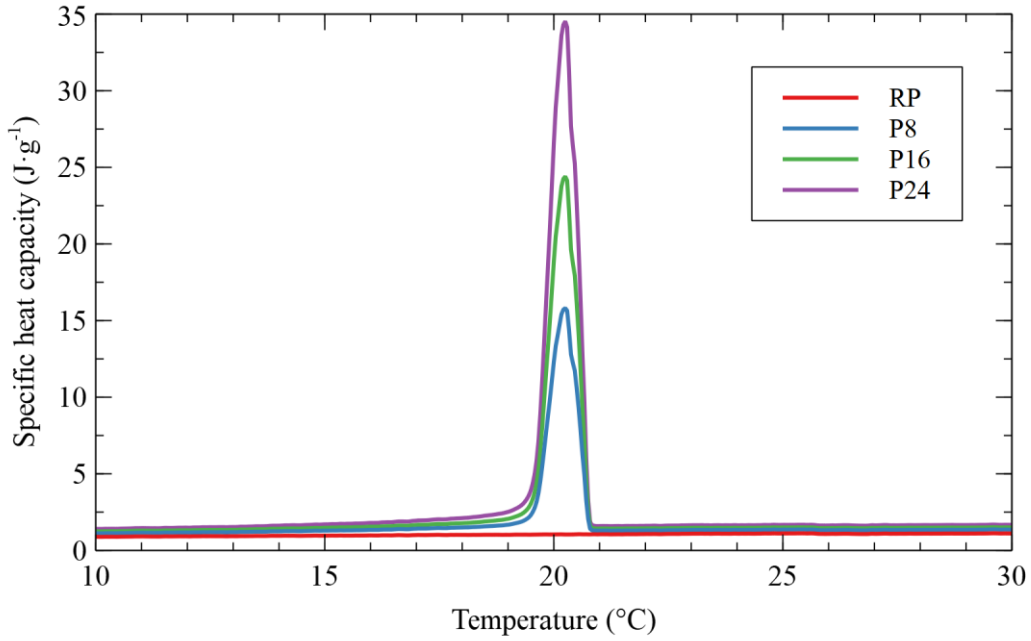


Figure 3. Temperature-dependent specific heat capacity of studied FSPCM plasters during cooling.

The computational solution of the two differential equations with the effective specific heat capacity model was done using the HMS simulation tool, which uses the general finite element package SIFEL (Simple Finite Elements) [46] as the main solver. The HMS tool is used for the creation of the computational problem and pre-processing It allows generating the computational mesh, assigning materials to the with different properties to the mesh elements, assing boundary conditions to the nodes and edges and parameters, and finally for setting the computing parameters.

HMS encodes the parameters of the simulation into the input file that is processed by the SIFEL package. SIFEL uses the final element method to solve computational problems. The utilization of HMS with the SIFEL tool has been successfully used and validated in the recent past [47].

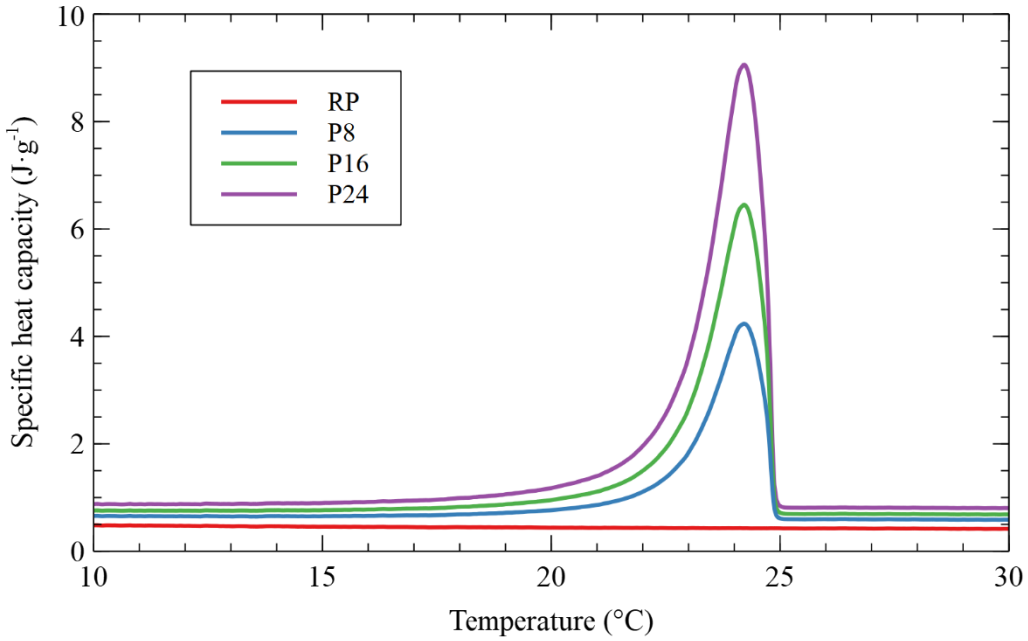


Figure 4. Temperature-dependent specific heat capacity of studied FSPCM plasters during heating.

As a result of computational simulations, temperature and relative humidity variations for the studied building envelopes are obtained. From those performances, the energy balance can be determined by calculation of the heat flux densities, i.e., heat fluxes per square meter of the wall each time. The assessment of energy performance of the wall was done on the basis of the overall heat fluxes $q(t)$ for two points of investigation: (i) on the interior surface of FSPCM plaster; and (ii) on the interface between FSPCM plaster and load-bearing material. The heat fluxes were determined as:

$$q(t) = \lambda_{\mathrm{p}}(w,t)\frac{\Delta T_{\mathrm{e}}(t)}{\Delta x_{\mathrm{e}}}, \tag{4}$$

where $\lambda_p(w,t)$ (W·m^{-1}·K^{-1}) is the moisture-dependent thermal conductivity of the interior plaster element in the point of the investigation, Δx_e (m) is the thickness of the element in the main direction of the heat flux, and ΔT_e (K) is the temperature difference between the opposite sides of the element in the main direction of the heat flux. The heat transmission was calculated as an integral of the heat flux given by Equation (4) over time with respect to the direction of the heat flux. The heat fluxes in the direction to the exterior were accounted as a specific heat loss, whereas the heat fluxes in the direction to the interior space were accounted as a specific heat gain.

3. Results

First, for estimation of the benefit induced by the FSPCM admixture, an evaluation of the energy consumption calculated for the unit area of the wall per annum was done. Second, the influence of the FSPCM admixture was demonstrated on the basis of the evaluation of the temperature change delay during the loading periods.

3.1. Energy Simulation Analysis

In this section, the thermal performance of studied wall type exposed to different climatic conditions at two locations in the Czech Republic is presented. Here, monthly energy savings delivered by improved thermal storage capability of studied plasters are quantified according to Equation (4) and discussed. As the dominant direction of heat flux represents heat losses mostly, the energy savings were expressed with respect to heating demands. Additionally, to provide a deeper insight into energy

balance and thermal response of studied plasters, the amount of heat stored in the FSPCM plaster and released back to the interior was analyzed as well.

The ceramic bricks masonry is the most often used construction material in the residential sector in the Czech Republic as well as several other countries in the European region. Due to its poor thermal performance, the application exterior insulation layer made of mineral wool can be found to meet the criteria on sufficient thermal performance. As is clearly seen in Figures 5 and 6, the utilization of the plaster enhanced by FSPCM resulted in a reduction of heat losses during a whole year. Evidently, more distinct changes can be noted within the winter period, while during summer only minor improvements were observed. The energy savings were obtained for both locations and exceeded 13% during January, February, March, and December in Prague (in the case of P24 plaster), while in Šerák the savings about 13% were achieved only in January. This finding is inevitably associated with lowered heating demands as a result of a latent heat utilization capability of the applied FSPCM plaster layer. Within the summer period, delivered savings thanks to the FSPCM plaster layer slightly exceeded 8% in both locations and do not exhibit significant differences even during the spring or autumn. The application of plasters with lower PCM content gradually decreased monthly savings in both cases.

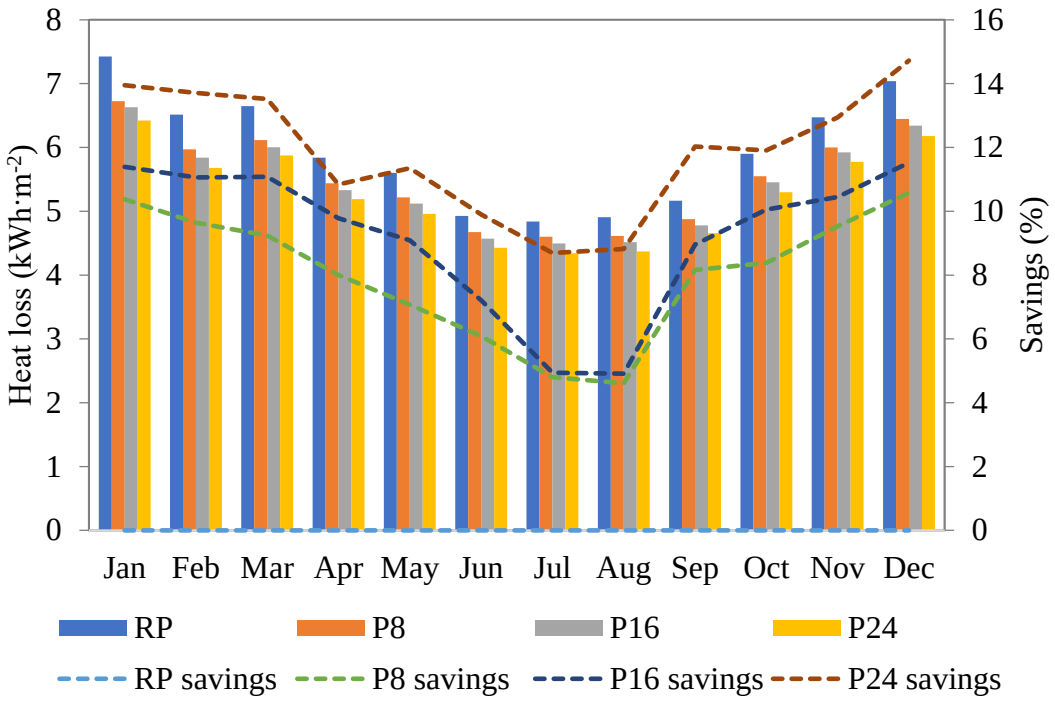


Figure 5. Monthly heat losses and energy savings in Prague.

Considering the obtained annual energy savings as shown in Table 4, a more pronounced effect of applied FSPCM plaster was delivered in Šerák, thus the harsher region with substantially lower winter temperatures. Looking at the achieved annual energy savings, the maximum energy savings in Šerák of about 12% was reached when P24 was applied, while P16 and P8 reached only 9.5% and 8.3%, respectively. Somewhat lowered annual energy savings in Prague indicate a less heating reduction compared to the Šerák region. Namely, the annual energy saving in Prague regions varied from 7.09% to 11.36% dependent on a dosage of FSPCM contained in the applied plaster. Obtained results comply with the work of Tuncbilek et al. [48] who reached the thermal load decrease of about 17% by PCM-integrated bricks. On the other hand, an adverse effect related to higher cooling energy demand during summer diminished overall benefits. The particular importance should be, apart from the seasonal effects, devoted to wall orientations since the saving performance may differ substantially [49]. The analysis aimed at the evaluation of energy performance in various regions indicates a high

sensitivity of energy savings to outdoor climate conditions, however, such conclusions were verified predominantly in hot climates as further noted by Park et al. [13] or Wang et al. [50].

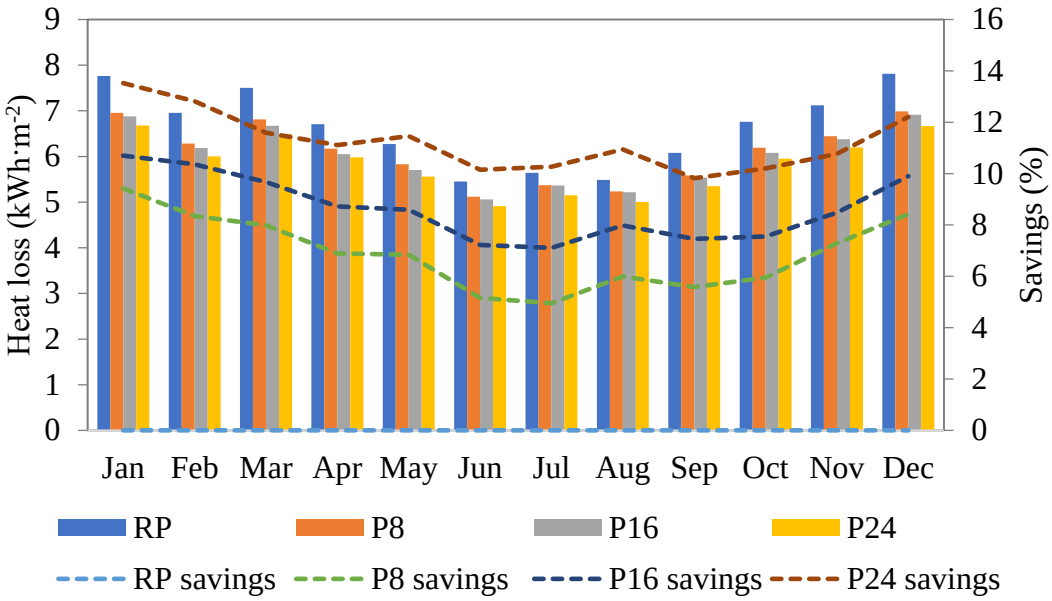


Figure 6. Monthly heat losses and energy savings in Šerák.

Table 4. Annual heat energy savings produced by FSPCM plaster.

Location	Plaster	Heat Transmission per Unit Area of the Wall ($kWh \cdot m^{-2} \cdot a^{-1}$)	Savings on Heating (%)
Šerák	RP	79.55	-
	P8	72.98	8.26
	P16	72.04	9.45
	P24	69.94	12.08
Prague	RP	71.27	-
	P8	66.22	7.09
	P16	65	8.8
	P24	63.13	11.36

The increased thermal storage capacity of studied plasters induces an important feature that consists of temporary storing of the heat and releasing it back to the interior (further referred to as recuperation heat), especially when the indoor temperature drops during nights. The maximum monthly recuperation flux densities were achieved during hot months when the temperature gradient in the wall assembly is lowest, thus, more heat can be stored. The higher temperature gradient in cold months reduces the ability of the plaster to recuperate the heat flow from the interior to the exterior. The monthly results of recuperation heat analysis are depicted in Figures 7 and 8, the annual summary is given in Table 5. The monthly recuperation heat flux densities for P24 in Prague ranged from 4.9 to 5.6 $kWh \cdot m^{-2}$. However, the improvements were significantly lower compared to Liu et al. [51] due to increased thermal conductivity of the ceramic brick allowing more significant heat transmission from the plaster to the load-bearing structure. Therefore, the interior surface performance was significantly worsened thus, the detected improvements ranged between 8.61%–13.2% during particular months (P24, Prague). More significant improvements in recuperation ability were observed for winter periods when the values reached 13.3% to 19.09% depending on the PCM dosages in Šerák. In summary, the monthly recuperation heat flux densities in Šerák were more convincing compared to Prague, specifically, the improvements exceeded the data obtained for Prague by about 5%, due to lower

performance of the reference plaster in this region. The dynamic of outdoor conditions changes poses a substantial factor for the performance of the PCM systems since the increased thermal inertia of outdoor air limits the occurrence of the phase change. As proved by Wu et al. [52] who compared the energy savings achieved by novel PCM composite, energy savings reached values of around 20% in Paris and Atlanta, while in Beijing they dropped about 10%. On the contrary, the application of gypsum-cement boards with PCM did not result in any beneficial outcomes when used in Chicago [22].

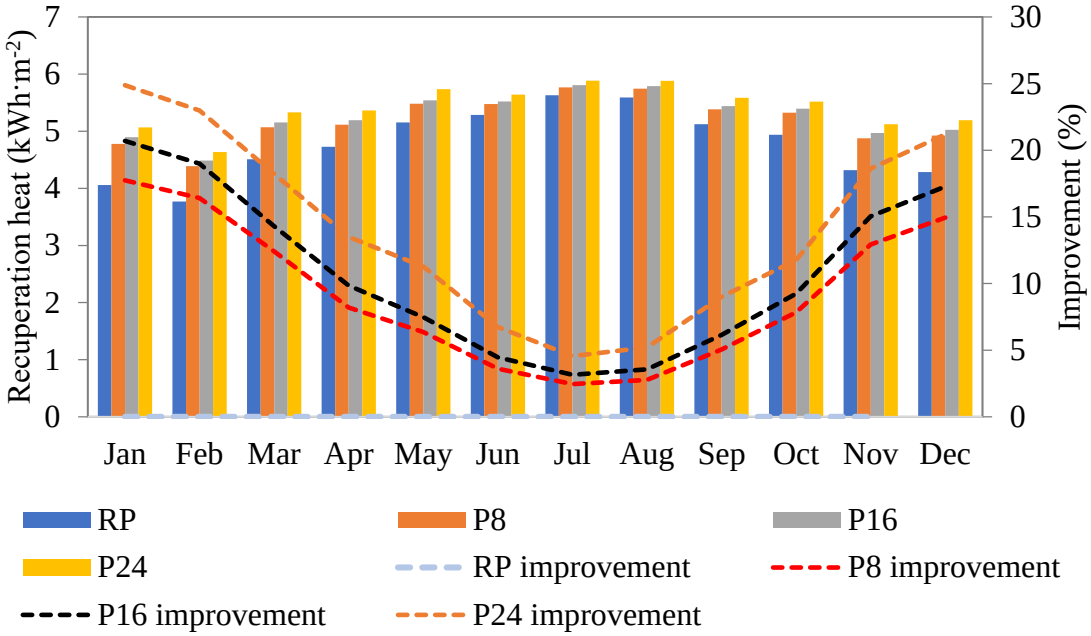


Figure 7. Monthly benefits associated with the utilization of recuperation heat in Prague.

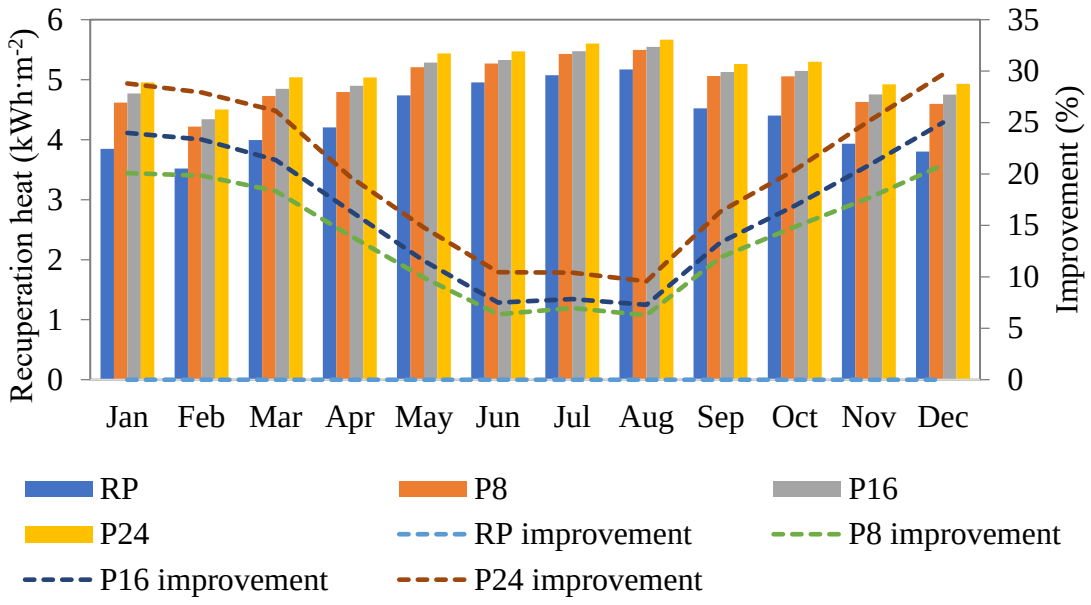


Figure 8. Monthly benefits associated with the utilization of recuperation heat in Šerák.

Table 5. Annual recuperation heat produced by FSPCM plaster on ceramic brick wall with mineral wool insulation.

Location	Plaster	Recuperation Heat per Unit Area of the Wall ($kWh \cdot m^{-2} \cdot a^{-1}$)	Improvement (%)
Šerák	RP	52.16	-
	P8	59.1	13.3
	P16	60.27	15.53
	P24	62.13	19.09
Prague	RP	57.39	-
	P8	62.33	8.61
	P16	63.22	10.15
	P24	64.97	13.2

3.2. Diurnal Surface Temperature Fluctuation

The computational simulation of the interior surface temperature distribution of the studied plasters with FSPCM admixture was performed in order to assess the discrepancy between particular seasons in detail. The effect of the increased thermal storage capacity was studied on the idealized interior temperature regime with the temperature oscillation between 18 and 26 °C in the course of the selected day cycle (24 h). Disparities obtained between the thermal performance of ceramic brick masonry with mineral wool insulation layer are displayed in detail during summer and winter periods in Prague (see Figures 9 and 10). According to the energy savings differences obtained for a particular season, the daily temperature fluctuations during the summer and winter are clearly distinguished in the tested case envelope with or without FSPCM. The presence of FSPCM in the plaster mixture determined the temperature distribution and the apparent shift in temperature increase/decrease, caused by the consumption/release of latent heat during the phase change can be observed. Here, dependence on the amount of the incorporated FSPCM on deceleration was distinct, therefore the most promising results belong to the highest FSPCM admixture. The surface temperatures of plasters with FSPCM addition during computer simulations proved the ability of the enhanced plasters to reduce the diurnal temperature fluctuation and keep the interior temperature at the desired level. To be more specific, the down-peak winter temperature was increased about 2.5 °C for P24 plaster thanks to released heat, and thus substantial energy savings and thermal comfort were gained. A beneficial effect of the FSPCM plaster application was reached also during the summer peak temperatures when the maximal temperature dropped by about 1.5 °C. Hourly temperature profiles obtained corresponded to calculated annual energy savings described in the previous section and similar results were achieved also for performed simulation in Šerák. The employment of the finite element method was found also by other researchers as an effective tool for the assessment of PCM composite performance since the study of Kheradmand et al. [53] proved the adequate predictive capacity of such models with sufficient accuracy.

Considering the peak temperature stabilization, the results obtained indicated more satisfactory outputs compared to Sari et al. [54], who achieved only 0.78 °C reduction during the heating period. The crucial role plays in this sense the placement, thickness, and heat conductivity of supporting material [55]. As investigated by Li et al. [56], a proper correlation between the climatic conditions and phase change temperature poses an important factor for the effectiveness of latent heat-storage systems.

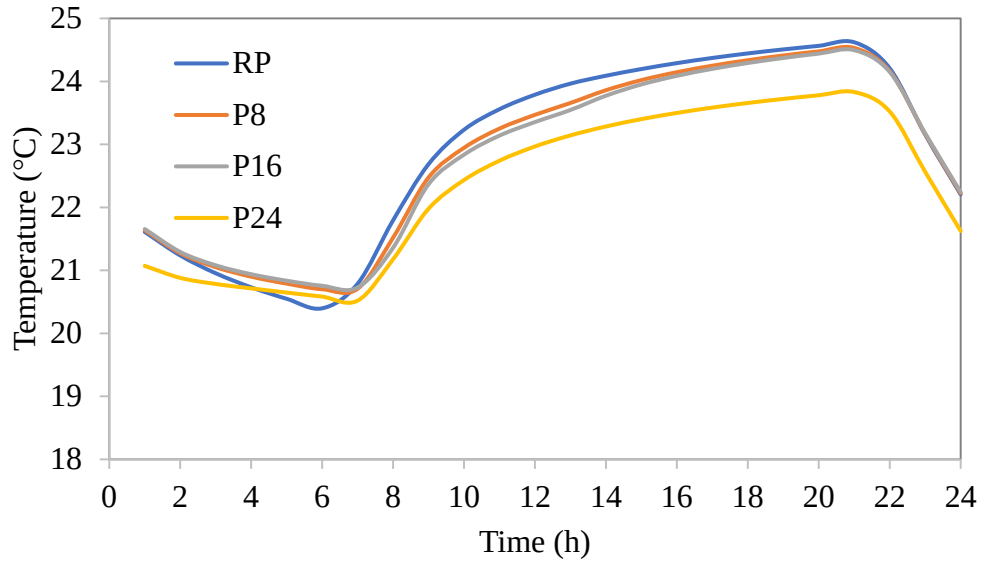


Figure 9. Distribution of interior surface temperatures of studied plasters during summer in Prague.

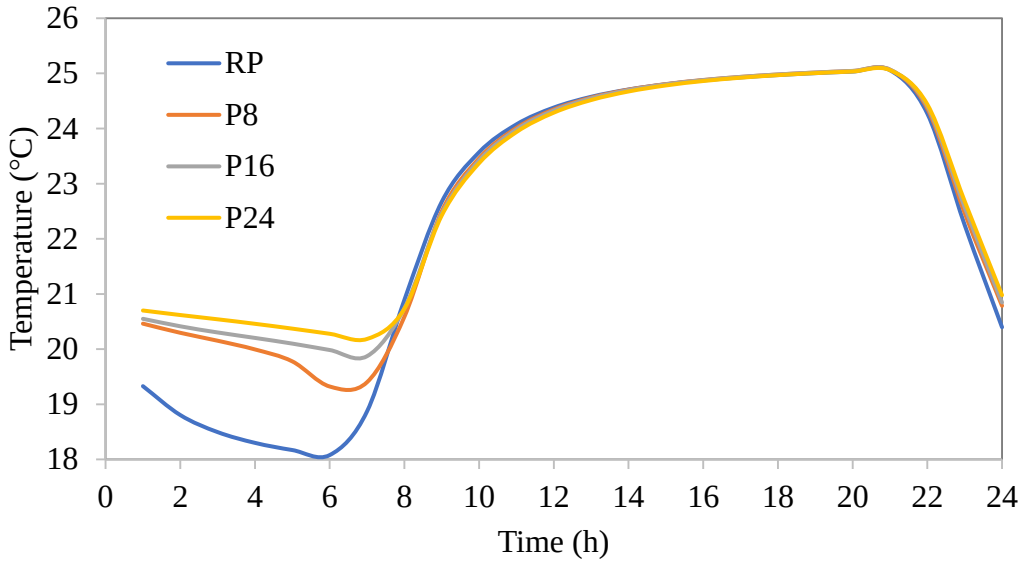


Figure 10. Distribution of interior surface temperatures of studied plasters applied during winter in Prague.

4. Discussion

Calculated energy savings, based on the evaluation of the entire year heat flux densities, proved a considerable potential for PCM application in the field of energy conservation in the building sector. The plaster mix with laboratory-developed FSPCM based on dodecanol and diatomite [40] reached promising values of the possible annual savings which provide at least similar results compared to the commercially produced PCMs [20,39,41]. The significant influence of PCMs on the possible energy savings was proved by many studies. For example, the interesting work of Parameshwaran and Kalaiselvam [57] used silver nano-based PCM for improvement of the heat transfer during the charging and discharging cycles. Here, appreciable savings in the range from 7.5% to 50% were achieved. However, advanced systems of heat recuperation, storage and distribution were used. A much better and closer comparison of PCMs benefits for potential energy savings can be found in the study published by Biswas et al. [58], where the annual heat gains for different wallboards and orientations were investigated. The annual vs. peak summer behavior of the PCM wallboard was

dictated by the interior cooling set point relative to the phase change temperature range of the PCMs. Therefore, the substantial effect of the PCM on the energy savings was confirmed as well as divergent results for particular seasons.

In the light of obtained results, studied modified plasters documented the positive effect of FSPCM admixture on the indoor thermal comfort maintenance. The obtained benefits inevitably associated with considerable energy savings thanks to FSPCMs utilization during peak periods promote the employment of passive thermal moderation techniques. As is described in several studies [59,60], the location of building equipped by PCM elements need to be considered for optimal and efficient design of heating/cooling solutions. Apart from the cooling demands which are typical for hot regions, the energy savings related to colder regions pose another task for PCM adjustments. As described above, even small changes in the climate can cause alterations in PCM efficiency especially when exterior relative humidity differs [61]. In other words, the experimental studies aimed at the investigation of PCM suitability must be linked with a detailed climate characterization in order to provide a useful tool for PCM utilization design. For the ideal function of the plaster improved by FSPCM admixture, substantial temperature differences between day and night are required to complete the phase transition of FSPCM. Most of the present studies focus on the application of PCMs in a hot climate [62]. However, the utilization of PCMs in mild climate regions is also associated with several benefits that need to be assessed [23].

While many research papers [63,64] contemplate the influence of PCM thickness, encapsulation technique, melting temperature, clime conditions, the contexture of load-bearing material and applied PCMs is studied rarely even though PCMs was proposed as an efficient tool mainly for lightweight building envelopes which have reduced temperature peak resistance. Apparently, the effect of PCMs incorporated into the concrete [65,66] is diminished compared to other materials such as wallboards or plasters applied on load-bearing materials with low thermal inertia. Surprisingly, the consequences of PCM application on brick walls equipped by mineral wool insulation resulted in considerable savings during winter periods, when PCM plaster layer mitigated the heat fluxes between the exterior and interior sides. Notwithstanding this, this benefit can be achieved predominantly in colder climate regions. On the other hand, such constructions need to comply with the combined criteria of both cold winters and hot summers. In other words, these observations pointed out the importance of a complex analysis of PCMs application including a spectrum of important variables due to significant misrepresentation when only the selected one is chosen. In this sense, this paper substantially contributes to the understanding of the material response variation when exposed to the mild continental climate with warm summer and cold winters. Even for the Czech Republic, with relatively low differences in exterior conditions, recognizable differences in energy savings were achieved.

5. Conclusions

In this paper, the computational analysis of plaster enhanced by 8, 16 and 24 wt.% FSPCM based on diatomite and n-dodecanol on the interior side was performed. The particular importance is devoted to the relationship among temperature/relative humidity variations, material performance during the winter/summer periods, insulation, and energy consumption in two locations in the Czech Republic.

The calculated heat transmission clearly shows the positive overall effect of FSPCM on the interior climate and proved the ability of the increased thermal storage on the reduction of heat flux densities during the peak periods. Here, with the increasing amount of incorporated FSPCM in the applied plaster, the heat transmission from/to the interior is decreasing creating annual energy savings on heating. The energy savings are apparent for the smallest dosage of FSPCM, however, a linear dependence between the amount of FSPCM and energy savings cannot be considered.

Results obtained represent important data for the applicability of studied materials for the moderation of the indoor climate with respect to the temperature control within a day fluctuation or changes. The following points should be highlighted:

- Computational modeling revealed that case walls with applied modified plaster decelerated interior temperature changes during charging and discharging periods. As a result of the application of developed plaster, annual energy savings were identified in ranges from 6% to 12%, dependent on the selected location.
- Obtained results within this study clearly highlighted the contrasts between common building envelopes in terms of energy savings. Therefore, the investigation of PCMs needs to be well-specified due to a variety of influencing factors such as humidity, masonry type or applied insulation.
- Even small differences in outdoor climate conditions have a significant effect on the resulting thermal energy performance of applied PCMs. The complete overpassing of the phase change temperature poses an important criterion assessing the potential and viability of PCMs usage.
- The utilization of FSPCM plaster can significantly enhance the ability of the wall to recuperate the interior heat that would normally be lost when non-PCM plasters are applied. The amount of recuperated heat depends on the material of a load-bearing structure and can range up to 10 kWh m^{-2} a month, which presents an improvement of about 20% when compared to the non-PCM plaster.

The presented work summarizes the possible application of PCMs respecting the current trends in energy savings and sustainable development principles in the building industry. The proposed solution based on the utilization of the latent heat represents a promising way for substantial energy savings with a consequent decrease in greenhouse gas (GHG) emissions. Considering the results of this study, further experimental tests for verification of the positive effect of the shape-stabilized PCM composite should be performed. Here, especially semi-scale and full-scale experiments could be helpful to approve assumed energy savings in buildings conditioning. The detailed assessment of various factors needs to be taken into account for the provision of reliable and trustworthy results. The energy-saving potential of PCM-based materials has not been linked precisely with comprehensive cost analysis nor life-cycle assessment that could promote a broader application of the PCM technology. Taking into account the recent development of geopolymers, the economic and environmental advantages of PCM can be further improved by the utilization of various by-products and waste materials.

Author Contributions: Conceptualization, J.F. and R.Č.; methodology, J.K.; validation, J.Š.; formal analysis, R.Č.; investigation, J.F., J.Š. and J.K.; resources, J.Š. and R.Č.; data curation, J.F. and J.K.; writing—original draft preparation, J.F.; writing—review and editing, J.K.; visualization, J.F.; supervision, R.Č.; project administration, J.F.; funding acquisition, J.F. and J.Š. All authors have read and agreed to the published version of the manuscript.

Funding: This research has been supported by the Czech Science Foundation, under project No 18-03997S and specific research of the Institute of Technology and Bussiness in České Budějovice, under a project supported by internal project ID 8210-008.

Conflicts of Interest: The authors declare no conflict of interest.

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