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Research paper

PCM enhanced concrete panels allow to reduce overheating in lightweight buildings

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Abstract: The article presents the results of research on the thermal and mechanical properties of concrete slabs with pumice aggregate soaked with dodecanol (duodecyl alcohol), i.e. an organic material that changes its phase at a temperature +24°C. It is possible to implement this type of integration of phase-change material with a typical building material in any precast concrete plant without additional expenditure on equipment and without technically difficult vacuum impregnation. The use of concrete panels with a 4% mass content of PCM as the internal cladding of building components allows for a significant change in the internal heat capacity of the building and, consequently, a change in the thermal properties of the buildings. In a very simple modeled object with a light wooden structure, intensively cooled during the night, the influence of the type of internal cladding on the internal thermal comfort in the summer was analyzed. It has been shown that the cladding in the form of a concrete PCM panels with a thickness of 3.5 cm, compared to a standard gypsum board, effectively limits the temperature increase and significantly shortens the duration of discomfort conditions. The maximum daily fluctuation of operative temperature during summer, which was approximately 15 K in a lightweight building, has been limited to approximately 8 K thanks to PCM concrete panels. The difference in the average values for the entire simulation period, equal to 1.76 K, does not fully illustrate the improvement of thermal conditions during periods of high heat load. Reduction of the plate thickness to 2 cm only slightly worsened the conditions in the analyzed facility and can be treated as a reasonable compromise solution for lightweight construction technologies. In the case of an unreasonably large window area, regardless of the actual space thermal capacity, it is not possible to obtain the acceptable conditions inside only by means of the passive methods.

Keywords: space overheating, thermal capacity, phase change, PCM, oversized glazing area

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1. Introduction

Modern buildings are characterized by increasingly better thermal insulation of external enclosure and other solutions aimed at minimizing energy demand. A frequently used technology for constructing buildings is a technology based on durable structural elements forming a frame and filled with thermal insulation. Heat transfer through such partitions is low, but the disadvantage of this technology is the low thermal mass of the objects. Additionally, oversized glazing area may create a disproportion between the large amount of energy reaching the interior and the limited storage capacity of the building. The thermal capacity of a building is determined primarily by the thermal capacity of its enclosure. The ability to store excess thermal energy and release it when the room cools down results in more efficient use of solar radiation in winter and reduces the risk of overheating in winter and summer [1, 2]. The occurrence of too high internal temperature is particularly harmful because of people's feelings and because of the energy use and cost of running air conditioning devices. In low energy construction, where the basic aim is to achieve the lowest possible energy demand, the aspect of heat capacity becomes particularly important [3, 4].

One of the effective ways of passive accumulation of thermal energy in buildings is the use of phase changing materials, usually abbreviated as PCM. In this case, the latent heat of phase change is used to accumulate energy. During melting or solidification stage, a large amount of heat is accumulated or released [5]. The properties of these materials can help keep temperature changes within a comfortable range or at least reduce the peak electrical power demand for space cooling. They also allow for more uniform operation of the air conditioning system, reducing the need for heating at night.

In terms of application in construction, the main parameters of phase-change materials are: appropriate range of transition temperature [6, 7], effective heat capacity and stability of the material during cyclical transformations, long-term strength and fire resistance [7, 8]. The melting and solidification temperature of PCM construction products offered on the market is usually in the range of 21–28°C.

Phase change materials offered by manufacturers for use in construction can be applied by:

– adding microcapsules containing PCM to plaster mortars, concrete screeds or plasterboards,
– filling cavities in flexible mats or aluminum plates with big portions of PCM,
– placing capsules containing PCM in fibrous insulation [9],
– directly incorporating fluid PCM by immersion and direct impregnation methods [10, 11],
– vacuum impregnation of aggregates (which uses pressure pump to mechanically remove entrapped air from porous materials (e.g. lightweight aggregates, LWAs), after which the PCM is allowed into the vacuum chamber and is forced into the pore spaces of the LWAs [10].

The method of direct integration of PCM with building materials is very popular. Already in the 1980s, attempts were made to directly mix PCM with a material such as gypsum or cement or to saturate porous materials with a phase change material [12–14]. Later, encapsulated forms of PCM in the form of microgranules were used [15–17]. Ready-made products have also been created, such as plasterboards made of PCM [18], flexible mats or aluminum plates filled with concentrated PCM [19].

Due to the technical and economic limitations of existing PCM applications, the authors attempted to create a new product in the form of simple-to-make concrete wall panels containing dodecanol as a phase-change material. This organic substance is quite often used as PCM in building construction. The results presented in publication [20] indicate, among others, the use of pumice as a highly porous material that absorbs dodecanol well in immersion process. The selection and use of a specific phase-change material has environmental impact that cannot be ignored [21]. Regardless of the positive reduction in carbon dioxide emissions as a result of PCM application in a building, the production of this material itself may be harmful for the environment. Dodecanol is a fatty alcohol which can be produced through the hydrogenation of the fatty acids present in palm and coconut oils [20]. Metal catalysts such as nickel, platinum and palladium are used in this process. Dodecanol's reagents are naturally occurring and commonly available, and the hydrogenation process is relatively simple using metal catalysts. Therefore the production of dodecanol as a PCM is unlikely to have negative environmental effects [20].

A significant barrier to the dissemination of this technology is still the high cost of materials containing PCM. It is related both to the still limited scale of their production and application in construction, but also to the cost of the PCM itself and the technology of incorporation.

A barrier of a completely different nature is a kind of contradiction that appears when trying to combine lightweight construction technology with massive storage elements. However, it seems that the operational advantages of such a mixed solution, analyzed within the technical life cycle of the building, will outweigh the disadvantages related to the increased energy consumption of production or the transport of massive housing elements. Concrete panels, which are not elements of the building structure, can be added at any stage of construction or life cycle of a light building if the conventional methods of microclimate protection fail or become too energy-intensive and expensive.

The subject of the article is the presentation of a new material, whose production should be technically easy and economically profitable. The preliminary results of research on its thermal and mechanical properties have been shown. Based on the obtained results, a number of simulations were performed, the results of which are included in the paper. The subject of the computer simulation was a lightweight office building with various variants of internal wall cladding.

2. Material characteristics

2.1. Integration procedure

The design of the concrete mixture used to create the panels was made in accordance with the guidelines for class M20. The ingredients of the mixture are: cement, coarse aggregate with a diameter of up to 20 mm (of which 25% is gravel and 75% pumice), fine aggregate with a diameter of up to 10 mm (pumice) and sand. The pumice aggregate was saturated with phase change material. Dodecanol 98% (duodecyl alcohol), an organic compound with the chemical formula $C_{12}H_{26O}$, was used as the PCM. The phase transition temperature of dodecanol starts at 24°C and the heat of phase change is 180 kJ/kg, boiling point equal to 259°C, while its flash point temperature is 127°C [22].

An opportunity to overcome the previously mentioned technological and economic barrier is a simple method of integration of PCM with concrete by natural soaking of porous pumice aggregate. Vacuum soaking, which is commonly used for this purpose, allows for more effective filling of small pores, but also makes the production process more expensive and technically complicated, thus eliminating small and poorly equipped plants. Natural soaking of porous aggregate is possible in any plant. In case of the tested material integration was carried out by soaking the pumice in dodecanol solution for 24 hours at 40°C and draining it for 2.5 hours. Then, the samples were seasoned in laboratory conditions until a mass difference of less than 0.1% was obtained between subsequent measurements. As a result of the impregnation, a 4% mass content of dodecanol in the final product was achieved. Produced in this way PCM material samples (Fig. 1), were then subjected to strength, fire and thermal tests.

Fig. 1. Cross-section of the exemplary PCM concrete sample

2.2. Results of the initial material tests

Material density is equal to 1911.24 kg/m^3. Material samples with dimensions of 150 × 150 × 150 mm (matured for 28 days) were tested for their compressive strength. It was found to be equal to 15.78 MPa (class C20/25). The obtained value allows the use of this material for the production of low-load structural elements.

The samples were then subjected to a flammability test. The test result was positive, thanks to the good protection of the organic substance by the pumice aggregate and the cement matrix, the material is non-flammable.

The thermal conductivity coefficient of the new material was measured in a FOX 314 plate apparatus. The tests were carried out at an average temperature of +10°C (+20°C and 0°C), i.e. in conditions below the phase change temperature. The value of the thermal conductivity coefficient obtained from measurement in these conditions was 0.776 W/(m·K). The thermal conductivity test was also performed under conditions of complete melting of the phase material, i.e. at an average temperature of +30°C, obtained by heating the lower plate of the apparatus to +25°C and the upper plate to 35°C. The value of the thermal conductivity coefficient of PCM concrete did not change. The heat capacity of the concrete sample was measured by means of the non-stationary method, obtained value of heat capacity was equal to 0.737 kJ/(kg·K).

3. Simulation model

A simplified test model of an office building was created in Design Builder software (Fig. 2). The dimensions of the modeled building are $6 \times 8 \times 2.7$ m. Designed window area meets the traditional requirement for the minimum area of windows in spaces intended for people presence, i.e. 1/8 of the floor area. The windows are located only in the southern wall. This is related to the possibility of obtaining significant energy gains in the winter, and at the same time allows for a rational reduction of the thermal load in the summer. The area of the two windows constitutes a total of 27% of the area of the southern wall. The whole facility consists of the two identical rooms (Fig. 2).

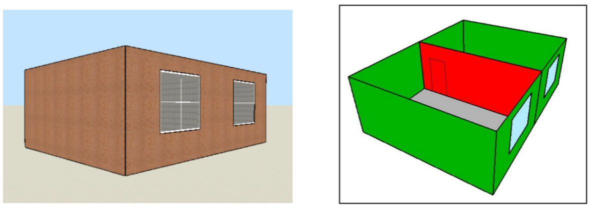

Fig. 2. Design Builder model

The building is characterized by a light wooden structure of walls, roof and suspended floor. Wooden wall frame is covered outside with impregnated boards and inside filled with a 24 cm layer of expanded polystyrene (EPS). In the initial variant, the internal finishing layer is 1.25 cm thick plasterboard (gypsum panels). In the variant in which the effect of using PCM is analyzed, the plasterboards on the inner surface of the walls and the flat roof were replaced with 3.5 cm thick PCM concrete panels. Mounting method of the panels should be adapted to various construction substrates. Due to the lack of external loads, this should not pose a design challenge. However, it is also possible to strengthen light panels with micro synthetic fibers, according to the method shown in [23]. Detailed information on the structure and arrangement of the layers and material properties adopted for the simulation are summarized in Table 1.

It was assumed that the modeled facility is used as an office and operated from 8:00 a.m. to 6:00 p.m. The building is not equipped with a mechanical cooling system, the temperature inside is a function of the climate, internal gains and thermal properties of the building enclosure. The only way to cool the interior during the hot season is intensive night ventilation. The amount of ventilation air required during office work was adopted in accordance with the EN 16798-1 standard [24] as for category II of a building with low levels of pollutant emissions and equal to 2.3 h^{-1}. During the night the number of air changes was assumed to be 6.6 h^{-1}. The model includes the option of protecting the interior against excessive cooling during the night by automatically turning off the mechanical ventilation when the internal air temperature drops below 18°C. The amount of infiltration air results from the local requirements for the tightness of the building envelope with mechanical ventilation, i.e. the value of the coefficient $n_{50} = 1.5$ h^{-1}.

Internal energy gains were calculated assuming the use of the facility by 5 people from 8:00 a.m. to 6:00 p.m. and the operation of computer equipment (5 laptops) and a photocopier during this period. In total, it was assumed that the operational thermal load is equal to 20 W/m^2 and the radiant fraction is 0.2.

Table 1. Characteristics of the structure and material data of building components

External wall					
d [mm]	layer	λ [W/(m·K)]	ρ[kg/m^3]	c [J/(kg·K)]	comments
24	impregnated facade board	0.13	700	1400	
70	wooden grate				
15	OSB panel	0.13	650	2100	
240	EPS (within wooden frame)	0.035	15	1500	
	finishing layer according to variant:				
12.5	fire-resistant plasterboard	0.3	900	1000	plasterboard variant
35	PCM concrete panel	0.78	1911	620	PCM variant
U = 0.134 W/(m^2·K)					
Suspended floor					
d [mm]	layer	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]	comments
10	ceramic tiles	1	2500	840	
22	OSB panel	0.13	650	2100	
200	EPS (within wooden frame)	0.033	15	1470	
15	OSB panel	0.13	650	2100	
U = 0.163 W/(m^2·K)					
Flat roof					
d [mm]	layer	λ [W/(m·K)]	ρ [kg/m^3]	c [J/(kg·K)]	comments
1	water membranę	60	7850	460	
70	wooden grate				
15	OSB panel	0.13	650	2100	
260	EPS (within wooden frame)	0.035	15	1500	
	finishing layer according to variant:				
12.5	fire-resistant plasterboard	0.3	900	1000	plasterboard variant
35	PCM concrete panel	0.78	1911	620	PCM variant
U = 0.128 W/(m^2·K)					
Internal wall					
d [mm]	layer	λ [W/(m·K)]	ρ[kg/m^3]	c [J/(kg·K)]	comments
12,5	fire-resistant plasterboard	0.3	900	1000	plasterboard variant
70	mineral wool (within wooden frame)				
12.5	fire-resistant plasterboard	0.3	900	1000	
70	PCM concrete panel	0.78	1911	620	PCM variant

For the calculation of thermal comfort indicators, it was assumed that employees in the morning (until 11:00 a.m.) may be additionally dressed in light outerwear with long sleeves (thermal resistance of their clothing is 1 clo). After 11 a.m., their clothing is typical summer clothing with 0.5 clo. Employees perform light office work, which corresponds to a metabolic activity of 120 W/person according to the Design Builder library.

Only the warmest months of the summer period, i.e. June and August, were used for simulations. It was assumed that the building is located in Krakow, Poland.

4. Simulation results

4.1. IU

Figure 3, shows the air temperature values in the modeled office facility throughout the simulation period for two basic analysis variants: internal gypsum cladding and concrete panels with the addition of phase-change material. Additionally, the graph shows the outside air temperature values (dashed line).

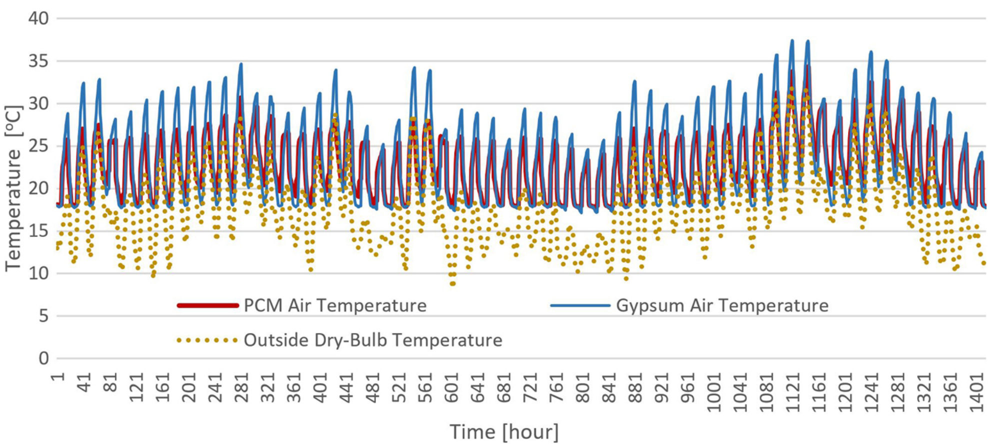

Fig. 3. Summer courses of internal and external air temperature (dashed orange line)

As expected, on every day during the entire simulated period of the year, the maximum air temperature in the lightweight version of the building with gypsum cladding is much higher than in the case of the massive PCM cladding. The positive effect of increased internal heat capacity is visible also in the case of the minimum daily temperature. Intensive night ventilation of the building interior causes the air temperature drop to as much as 18°C in the morning. In the case of a PCM concrete panel version of the modeled object, early morning temperature is higher than in the light variant. The observed differences are standard effects of the increased thermal capacity of the building envelope.

4.2. Operative temperature

The beneficial effects of increased heat capacity can be reasonably analyzed by taking into account the values of the operative temperature in both analyzed variants of the modeled object (Fig. 4). The operative temperature, combining air and radiant temperature, much better approximates human thermal feelings than the air temperature itself.

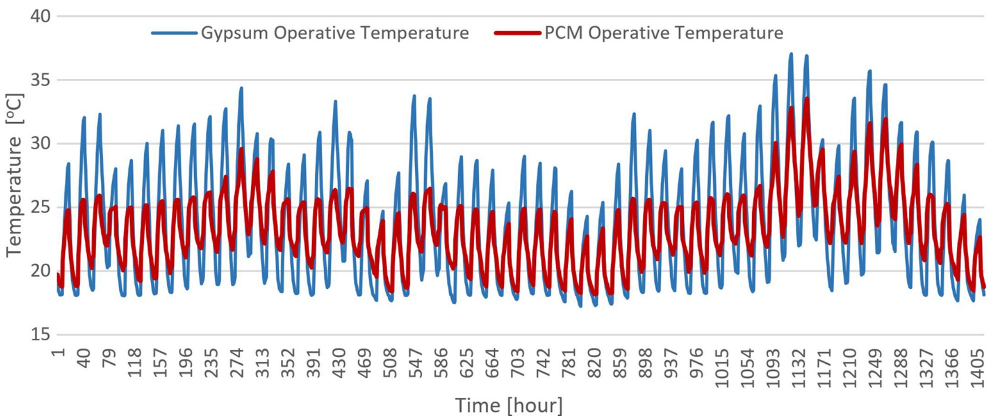

Fig. 4. Summer course of operative temperature in case of gypsum internal cladding and PCM concrete panel upon walls and ceiling

In the case of light gypsum cladding, the maximum daily fluctuations in operative temperature reach up to 15 K, while in a room with PCM concrete panels they do not exceed 8 K. The significantly reduced amplitude applies not only to maximum values but also to minimum values, related to intensive night cooling. The computational model imposed a condition regarding the minimum air temperature in the building during the night (18°C) and hence such conditions occur in the simulated space almost every day (Fig. 4). Intensive night cooling of the interior is desirable in the perspective of another hot day, but may cause discomfort during morning hours. A compromise solution in this situation is to adjust the clothing resistance to changing conditions. For this purpose, the model assumed an increased level of clothing resistance during the first hours of office work. Increased energy storage is beneficial in this situation, significantly shortening or even eliminating the morning subcooling of the building space below 20°C.

More detailed analysis of the thermal conditions in the modeled room is possible based on the graphs presented in Fig. 5. External air temperature and window solar gains, as well as the operative temperature for the two analyzed variants have been shown. In both cases internal discomfort is observed, but due to the increased thermal capacity of PCM panels, milder conditions (or lower cooling load) can be achieved. Importantly, in the variant with PCM plates, night cooling does not lead to discomfort in the morning. In the graphs shown in Fig. 5 the characteristic time shift between the maximum of solar gains, the external air temperature and the maximum of the operational temperature inside can be observed.

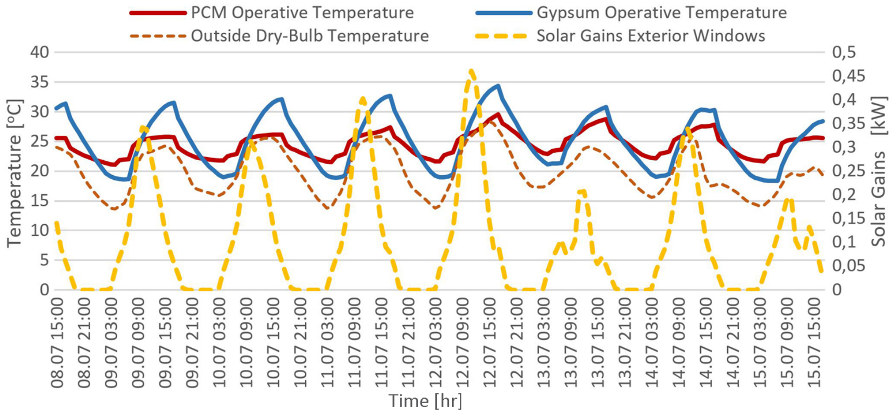

Fig. 5. Operative temperature course during the selected hot summer period

Daily changes in conditions inside the building as a function of the internal thermal load are shown in Fig. 6. Reduced intensity of night ventilation at 5:00 a.m. prevents further operative temperature drops in the plasterboard housing and even a slight increase in the PCM variant. A sharp change in slope of the diagrams corresponds to the change in the way the room is operated since 8:00 a.m. (heat gains from people and equipment). From this moment the operative temperature is rising in the both simulated room variants. In the case of the lightweight building, this growth is intense and lasts until the end of office hours, i.e. until 6 p.m. In the case of the PCM panels the significant change of the operative temperature trend at +24°C can be observed. It is related to the intensive heat absorption during the phase of dodecanol melting. In the following hours, until the end of working time, a constant but much lower than in the lightweight building rise of operative temperature occurs. A characteristic relationship between the two analyzed graphs is that they intersect twice during the day, as a result of different ability to store energy.

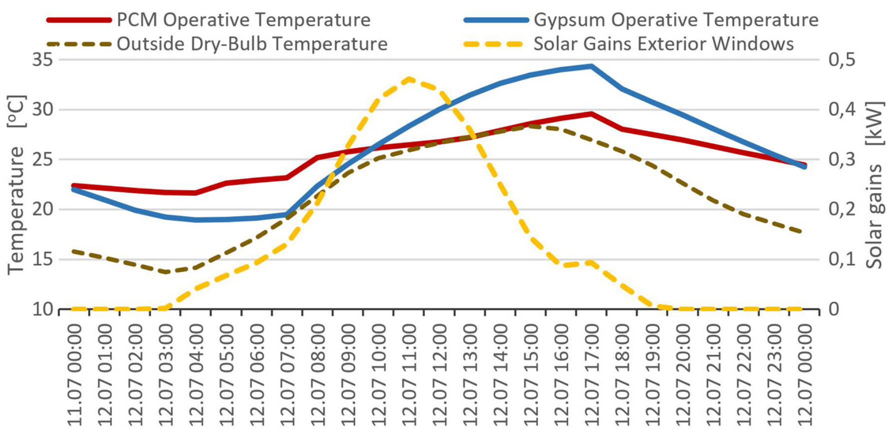

Fig. 6. Operative temperature course during one sunny day (12.07)

4.3. Thermal discomfort

Figure 7 shows the average values of air temperature, radiant temperature and operative temperature during office hours for the entire simulated summer period. The difference in average values for this long simulation period is not large and does not fully illustrate the significant change in interior conditions during hot summer hours. This is due to, among others, taking into account too low temperature in the morning, often occurring in a room with lightweight cladding. However, one can notice the difference between the air temperature and the radiant temperature of the building enclosure. Mainly convective heat gains from people and office equipment directly increase the air temperature, while the surface temperature of the building elements is clearly lower and more diverse between both variants.

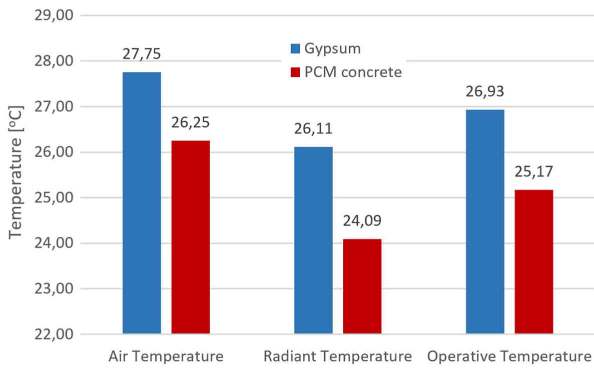

Fig. 7. Mean values of air, radiant and operative temperature during the simulation period

Fig. 8 shows the number of discomfort hours for the both analyzed variants. Adaptive thermal comfort was checked in accordance with the requirements of the EN 16798-1 standard [24] and for the previously given assumptions regarding the activity of users and the insulation of their clothing. The results given below apply only to office hours and not to the entire simulation period. The lower thermal capacity of the gypsum cladding results in a significant (over 30%) extension of the discomfort duration compared to the more massive variant.

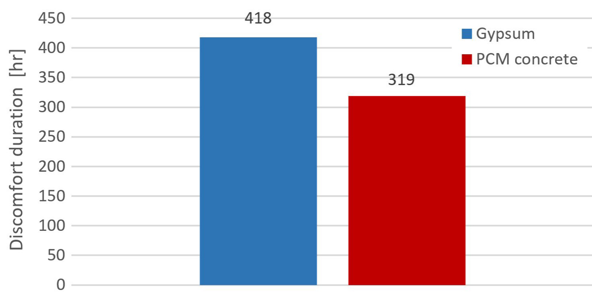

Fig. 8. Discomfort duration during the office hours

4.4. Incidence frequency

Discomfort duration should not be treated as the only information illustrating the differences between the variants. For building users, intensity of overheating is also important, i.e. the actual temperature values inside, including those that go far beyond the comfort range. Fig. 9 shows a complete summary of the incidence frequency of the operative temperature inside for the both analyzed cladding variants.

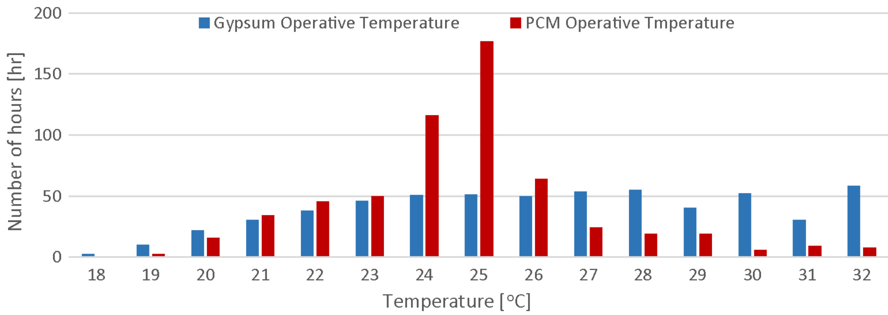

Fig. 9. Operative temperature and its duration

The summary shown in Fig. 10 well illustrates the effect of the application of the material that changes its phase at a temperature of ca. 24–25°C. The number of hours with a temperature from 24°C to 25°C is 2.3 times higher in the case of the PCM variant than in the case of the plasterboard cladding, and even 3.45 times higher for temperature range 25°C to 26°C. If it is assumed that temperature +27°C is the maximum acceptable operative temperature, the total number of hours exceeding this temperature for the PCM variant is 85, while for the gypsum variant it is 290 hours, i.e. 3.4 times more. These observations, treated as a simplified assessment of the degree of overheating, suggest huge differences in internal conditions between the analyzed variants.

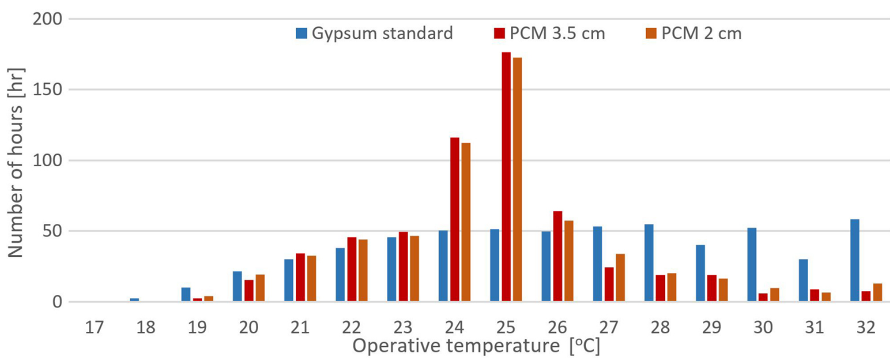

Fig. 10. Operative temperature values and their duration for gypsum panels 1.25 cm, PCM concrete 3.5 cm and PCM concrete 2 cm

4.5. 2 cm PCM concrete panels

The above-presented beneficial effects of increased thermal capacity of a lightweight building may raise reservations related to abandoning the advantages of lightweight technology, such as low energy consumption in transport, low mechanical loads and low built-in energy. Such reservations are, however, only partially true, because replacing gypsum linings with PCM concrete allows such an object to still be treated as relatively light compared to traditional masonry technologies. And the improvement in conditions inside the building achieved in this way can also be translated into potential energy savings for cooling. The adopted slab thickness of 3.5 cm results from the planned future use of this material in a combination with a masonry or reinforced concrete structure. However, additional simulations were performed to determine the impact of the PCM panel thickness on the obtained results. One of the illustrative evaluation criteria is the maximum value of operative temperature during summer period.

In the case of gypsum cladding, the maximum operative temperature value occurred on August 17 and was equal to 37.05°C. At the same time, in the room with 3.5 cm thick PCM boards, the temperature reached 32.82°C, and in the case of 2 cm thick PCM boards it was 34.15°C.

Fig. 10 shows the frequency of occurrence of operative temperature for the three variants of internal cladding: gypsum board 1.25 cm, PCM concrete panel 3.5 cm, PCM concrete panel 2 cm. A significant reduction in the thickness of the PCM panels results only in a slight change of the internal conditions. The number of hours, exceeding the subjectively set maximum temperature of 27°C in the case of 3.5 cm panels is equal to 85, and in the variant with 2 cm panels it increases to 100 hours. Therefore, a very substantial change of the thermal mass does not translate proportionally into a change of the conditions inside the buildings. So it can be assumed that 2 cm PCM concrete panels can be treated as a moderate practical variant of increasing building thermal capacity, especially in the case of very light construction technology.

4.6. Oversized window area

All the presented above results concerned a room with window area meeting the minimum lighting requirements. Contemporary architecture is still dealing with the trend of thoughtlessly designed glazing covering almost the entire wall surface. Design decisions of this type, regardless of the building thermal features, result not only in significant overheating, but also in increased demand for heating. The disastrous consequences of the oversized window design cannot be completely avoided and can only be partially mitigated by the large thermal capacity of the building components [25].

In the case of a very large window area, covering 90% of the southern wall area, the mean operative temperature in the analyzed building with gypsum cladding was increased to 30.82°C, and the hourly maximum value up to 46.91°C. Although a 2 cm thick PCM panels allow to reduce this value by 5 K, these conditions still correspond to dramatic overheating of the space. Figure 11 shows the frequency of operative temperature for two variants of internal cladding and a window covering 90% of the southern wall area. The last bars shown on the horizontal axis also include the hours when the operative temperature exceeded 32°C. In the case of gypsum cladding it is 2.8 times longer than in the case of PCM concrete panels. However, in both cases, too large window area clearly increases dramatically space overheating and the resulting discomfort of use. The periods of very high operative temperature are very long, and intense night cooling is not a sufficient measure to protect it against overheating.

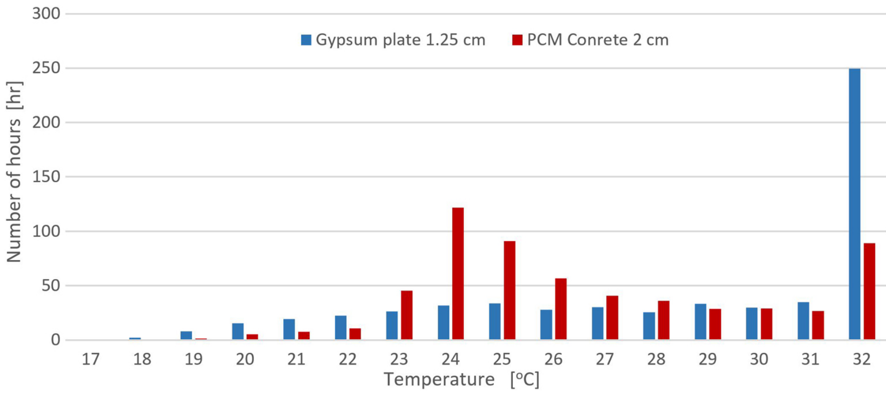

Fig. 11. Operative temperature values and their duration for gypsum and PCM panels 2 cm and oversized 90% glazing area

5. Summary and conclusions

The new PCM building material presented in the article was produced using the simplified soaking method of integrating dodecanol with the porous aggregate. This method may be easily implemented in any concrete plant, that has no advanced facilities. The PCM concrete has a density of 1911 kg/m^3, mass PCM content is 4% and a thermal conductivity of 0.776 W/(m·K). Thanks to the very high heat of dodecanol phase change, the 3.5 cm thick internal cladding board allows for obtaining large thermal capacity, and as a result, it may significantly reduce the overheating of the analyzed object.

The effects of PCM concrete panel application were analyzed by simulations of a lightweight building model in the Design Builder software. A simple passive measure of night cooling by means of the intensive night ventilation was used in the modeled building. This procedure makes sense when the thermal capacity is large enough to effectively collect excess energy throughout the day. The obtained simulation results confirm a significant reduction of daily temperature fluctuations achieved for PCM internal cladding and, as a result, a reduction in the maximum operative temperature and discomfort duration.

Due to a certain contradiction between the practical advantages of lightweight construction technology and massive 3.5 cm thick concrete cladding, the article also analyzed the application effects of 2 cm thick PCM panels. Despite a significant change in thickness, the duration of unfavorable conditions inside was extended by only 18% percent. Thinner PCM panels may constitute an easily acceptable compromise for lightweight construction technologies. The article also draws attention to the problem of rational glazing area in buildings. Excessive glazing area causes a significant deterioration of interior conditions in the summer, regardless of the interior heat capacity and night cooling of the interior.

Positive results of preliminary material tests and simulation analyzes are the basis for planned experimental tests of thermal admittance and the thermal diffusivity of concrete PCM panels in the climatic chamber and in the experimental building under construction. The planned simulation analyzes aim to determine the impact of the PCM panels on the use efficiency of passive solar gains in winter.

Acknowledgements

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References

[1] A. Waqas and Z. Ud Din, "Phase change material (PCM) storage for free cooling of buildings - A review", *Renewable and Sustainable Energy Reviews*, vol. 18, pp. 607–625, 2013, doi: 10.1016/j.rser.2012.10.034.

[2] N. Soares, J.J. Costa, A.R. Gaspar, and P. Santos, "Review of passive PCM latent heat thermal energy storage systems towards buildings' energy efficiency", *Energy and Buildings*, vol. 59, pp. 82–103, 2013, doi: 10.1016/j.enbuild.2012.12.042.

[3] L.F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, and A.I. Fernández, "Materials used as PCM in thermal energy storage in buildings: A review", *Renewable and Sustainable Energy Reviews*, vol. 15, no. 3, pp. 1675–1695, 2011, doi: 10.1016/j.rser.2010.11.018.

[4] M. Santamouris and D. Kolokotsa, "Passive cooling dissipation techniques for buildings and other structures: The state of the art", *Energy and Buildings*, vol. 57, pp. 74–94, 2013, doi: 10.1016/j.enbuild.2012.11.002.

[5] A. Zastawna-Rumin, "The analysis of the application efficiency of phase change materials in partitions in Polish low-energy buildings", Doctoral thesis, Cracow University of Technology, Cracow, Poland, 2018.

[6] K. Pielichowska and K. Pielichowski, "Phase change materials for thermal energy storage", *Progress in Materials Science*, vol. 65, pp. 67–123, 2014, doi: 10.1016/j.pmatsci.2014.03.005.

[7] R. Baetens, B.P. Jelle, and A. Gustavsen, "Phase change materials for building applications: A state-of-the-art review", *Energy and Buildings*, vol. 42, no. 9, pp. 1361–1368, 2010, doi: 10.1016/j.enbuild.2010.03.026.

[8] L. Navarro, A. de Gracia, D. Niall, A. Castell, M. Browne, S.J. McCormack, P. Griffiths, and L.F. Cabeza, "Thermal energy storage in building integrated thermal systems: A review. Part 2. Integration as passive system", *Renewable Energy*, vol. 85, pp. 1334–1356, 2016, doi: 10.1016/j.renene.2015.06.064.

[9] J. Kośny, *PCM- Enhanced Building Components. An application of Phase Change Materials in Building Envelopes and Internal Structures*. Springer International Publishing Switzerland, 2015, doi: 10.1007/978-3-319-14286-9.

[10] A.K. Sani, I.O. Olawoore, and R.M. Singh, "Assessment of impregnating phase change materials into lightweight aggregates for development of thermal energy storage aggregate composites", *Construction and Building Materials*, vol. 305, art. no. 124683, 2021, doi: 10.1016/j.conbuildmat.2021.124683.

[11] D.W. Hawes, D. Banu, and D. Feldman, "Latent heat storage in concrete. II", *Solar Energy Materials*, vol. 21, no. 1, pp. 61–80, 1990, doi: 10.1016/0165-1633(90)90043-Z.

[12] P. Schossing, H. Henning, S. Gschwander, and T. Haussmann, "Micro-encapsulated phase-change materials integrated into construction materials", *Solar Energy Materials and Solar Cells*, vol. 89, no. 2–3, pp. 297–306, 2005, doi: 10.1016/j.solmat.2005.01.017.

[13] A. Eddhahak-Ouni, J. Colin, and D. Bruneau, "On an experimental innovative setup for the macro scale thermal analysis of materials : Application to the Phase Change Material (PCM) wallboards", *Energy and Buildings*, vol. 64, pp. 231–238, 2013, doi: 10.1016/j.enbuild.2013.05.008.

[14] M. Rostamizadeh, M. Khanlarkhani, and S.M. Sadrameli, "Simulation of energy storage system with phase change material (PCM)", *Energy and Buildings*, vol. 49, pp. 419–422, 2012, doi: 10.1016/j.enbuild.2012.02.037.

[15] V.V. Tyagi, S.C. Kaushik, S.K. Tyagi, and T. Akiyama, "Development of phase change materials based microencapsulated technology for buildings: A review", *Renewable and Sustainable Energy Reviews*, vol. 15, no. 2, pp. 1373–1391, 2011, doi: 10.1016/j.rser.2010.10.006.

[16] N. Shukla, A. Fallahi, and J. Kosny, "Performance characterization of PCM impregnated gypsum board for building applications", *Energy Procedia*, vol. 30, pp. 370–379, 2012, doi: 10.1016/j.egypro.2012.11.044.

[17] J. Persson and M. Westermark, "Phase change material cool storage for a Swedish Passive House", *Energy and Buildings*, vol. 54, pp. 490–495, 2012, doi: 10.1016/j.enbuild.2012.05.012.

[18] E. Rodriguez-Ubinas, B.A. Arranz, S.V. Sánchez, and F.J.N. González, "Influence of the use of PCM drywall and the fenestration in building retrofitting", *Energy and Buildings*, vol. 65, pp. 464–476, 2013, doi: 10.1016/j.enbuild.2013.06.023.

[19] K. Muruganantham, P. Phelan, P. Horwath, D. Ludlam, and T. McDonald, "Experimental Investigation of a Bio-Based Phase Change Material to Improve Building Energy Performance", in *Proceedings of the 2010, 4^{th} International Conference on Energy Sustainability*, *ASME 2010 17–22 May 2010, Phoenix, USA*. ASME, 2010, doi: 10.1115/ES2010-90035.

[20] W. Tang, Z. Wanga, E. Mohseni, and S. Wang, "A practical ranking system for evaluation of industry viable phase change materials for use in concrete", *Construction and Building Materials* vol. 177, pp. 272–286, 2018, doi: 10.1016/j.conbuildmat.2018.05.112.

[21] M. Kuta, D. Matuszewska, T.M. Wójcik, "The role of phase change materials for the sustainable energy", *E3S Web of Conferences*, vol. 10, art. no. 68, 2016, doi: 10.1051/e3sconf/20161000068.

[22] https://www.avrasynthesis.com/#/ProdDet. [Accessed: 01.12.2023]

[23] M.A.O. Mydin, "Influence of micro synthetic fibers confinement on properties of lightweight foamed concrete", *Archives of Civil Engineering*, vol. 68, no. 3, pp. 411–428, 2022, doi: 10.24425/ace.2022.141894.

[24] EN 16798-1:2019 Energy performance of buildings – Ventilation for buildings – Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.

[25] T. Kisilewicz, "Computer Simulation in Solar Architecture Design", *Architectural Engineering and Design Management*, vol. 3, no. 2, pp. 106–123, 2007, doi: 10.1080/17452007.2007.9684635.

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