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Dynamic heat storage and cooling capacity of a concrete deck with PCM and thermally activated building system

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ABSTRACT

This paper presents a heat storage and cooling concept that utilizes a phase change material (PCM) and a thermally activated building system (TABS) implemented in a hollow core concrete deck. Numerical calculations of the dynamic heat storage capacity of the hollow core concrete deck element with and without microencapsulated PCM are presented. The new concrete deck with microencapsulated PCM is the standard deck on which an additional layer of the PCM concrete was added and, at the same time, the latent heat storage was introduced to the construction. The challenge of numerically simulating the performance of the new deck with PCM concrete is the thermal properties of such a new material, as the PCM concrete is yet to be well defined. The results presented in the paper include models in which the PCM concrete material properties, such as thermal conductivity, and specific heat capacity were first calculated theoretically and subsequently the models were updated with the experimentally determined thermal properties of the PCM concrete. Then, the heat storage of the decks with theoretically and experimentally determined thermal properties were compared with each other.

Finally, the results presented in the article highlight the potential of using TABS and PCM in a prefabricated concrete deck element.

1. Introduction

The concept developed in this article presents the dynamic heat storage potential of combined high latent heat storage, due to the phase change material (PCM) and the thermally activated building system (TABS). The two technologies are combined in a prefabricated concrete deck element, see Figs. 1 and 6, in order to investigate their potential to: decrease energy use for cooling in the building, shift the high indoor temperature peaks to the hours when the building is not occupied, improve indoor thermal comfort by flattering the diurnal temperature variations and determine limitations and challenges, if any.

The advantage of PCM is its very high latent heat storage capacity. On the other hand, PCM has very low thermal conductivity and not that high density. The combination of such material with a concrete material of high density and a rather high thermal conductivity might result in a new technology for energy storage in buildings. TABS is a system that can provide heat and cold to a room and, at the same time, activate the thermal mass of the building. The advantage of the system is its low operation temperature close to indoor temperatures. The disadvantage is its slow response to the cooling or heating need.

The combination of the two technologies might result in an increase of the heat storage capacity of the building interior and, at the same time, in a possibility to actively respond to increased heating or cooling needs that cannot be covered solely by the passive heat storage.

The TABS concept started in the 1990s in Switzerland and involved an idea of activating the thermal mass of concrete slabs located between each storey of the building. As a consequence, when circulating hot or cold water in the slabs, the building can be respectively heated or cooled. TABS was investigated in many theoretical studies and was implemented in a number of full scale projects, presented for example in [1]. Additionally, laboratory tests and theoretical studies have indicated that this technology can be energy efficient and has a significant potential to reduce operational costs for the cooling/heating of buildings and provide an appreciated indoor thermal comfort [2].

There is also a substantial amount of research focused on PCM application in the refurbished light weight buildings and light weight constructions in order to increase thermal mass of the building [3,4]. There are also numerous publications on thermal properties of various PCMs, but in the pure state [5–7].

The development of the microencapsulation technique of paraffin, which allows its direct integration into the building materials,

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Nomenclature

Symbols

VHC	volumetric heat capacity [J/(m^3 K)]
ρ	density of material [kg/m^3]
Cp	specific heat capacity [J/(kg K)]
I	thermal inertia [J/(m^3 K)]
Cp(T)	specific heat capacity in function of temperature [J/(kg K)]
X	weight ratio (0–1)
λ	thermal conductivity [W/mK]

Abbreviations

PCM	phase change material
TABS	thermally activated building system
DSC	differential scanning calorimetry
DTA	differential thermal analysis

e.g. such as concrete or plaster, is a relatively new technology that has not received much attention yet. Therefore, few research studies on mixtures of concrete and microencapsulated PCMs are available. On the other hand, well developed numerical models that can calculate construction elements with PCM [8,9] are already available.

Although an extensive amount of publications on TABS and PCM can be found, these two technologies are usually investigated as separate technologies. The exceptional development of the prototype for the thermally activated plaster ceiling panel with PCM was proposed by [10]. The developed panels are a composite of microencapsulated PCM mixed with gypsum. In these panels, the capillary tubes are integrated to circulate water and by that activate the deck/discharge heat stored by the deck. The paper starts with the conceptual design, continues with the numerical optimization of the model and finishes with the initial numerical and experimental investigation of the developed panel performance. The investigation highlights that the panels need to integrate highly conductive aluminium fins in order to overcome the discovered low thermal conductivity of the new PCM gypsum composite and to be able to store sufficient amount of heat. Moreover, although the paper presents the effective specific heat capacity in function of temperature of the new composite of the PCM gypsum, it does not explain how that property was determined. The outcome of the simulation indicated that, in a typical summer week, the developed panel can maintain an indoor temperature within comfort range of a standard office room. The experimental investigation indicated that the panel was able to store 290 Wh/m^2 during the 7.5 h of the melting process which was less than the expected 320 Wh/m^2. The lower heat storage was explained by a lower quantity of incorporated paraffin than initially designed and by a lack of complete control of the new composite density during the mixing and filling in the panel process. The research presented in [11] takes into account the challenge of measuring the specific heat capacity of self-compacting concrete with microencapsulating PCM, but the proposed calculation methodology simplifies the problem and the experimental set-up disregards the influence of the surrounding temperature on the heat transfer within the sample. This subject is further discussed in [12].

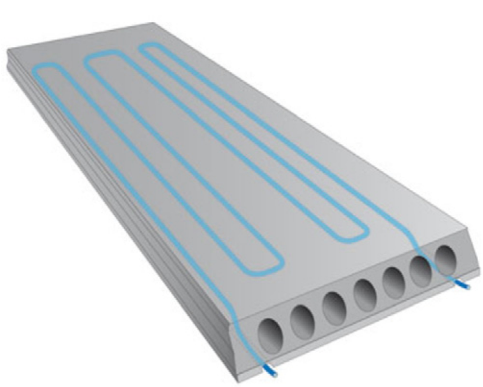

Fig. 1. ThermoMax – Spæncom: prefabricated concrete ceiling deck element with integrated water pipes.

The study presented by [13] investigates the use of PCM in concrete floors. Four chambers of the same size are constructed; two with PCM concrete floor and two with ordinary concrete floor. The only heat source in each chamber is the solar irradiation through the windows. In the study, the PCM in the floor is activated by direct sun irradiation, however in practice, it would be very unusual to find concrete floor without any kind of covering such as wood, polyvinyl or tiles that would protect the PCM from thermal activation. Therefore, although the research indicates that this technology could save some energy and decrease the temperature fluctuations in the houses, it would be very difficult to implement it on a broader scale in practice. Similar research to the one presented in [13] can be found in [14]. The proposed experimental set-up consists of two identical cubicles made of concrete where one is built of conventional concrete and one of the new concrete with admixed 5 wt% of microencapsulated PCM. The results obtained revealed a decrease in temperature fluctuation in the room with PCM concrete and a shift of the temperature peak in the wall of 2 h. On the other hand, neither [13] nor [14] clearly distinguished how much of the decrease of temperature fluctuation is due to the reduced thermal conductivity and how much is due to the increase of the heat storage capacity of the concrete with PCM. What is more, the diurnal indoor temperature fluctuates from very low to very high temperatures in both cases, which would not be acceptable by any means in a real building, and therefore the energy accumulation would be lower in practice than in the presented experimental set-ups.

Due to the fact that the extensive initial work to the study presented in this paper has been done in [12,15–17], the paper includes many cross-references to these four studies. However, to make this article understandable and reader-friendly, some of the critical assumptions and methodologies will be repeated and presented yet again.

In the presented investigation, the numerical model of the hollow core concrete deck element initially developed and presented in [15] is updated with the new, measured thermal properties of the new concrete composite mixed with microencapsulated PCM. The experimental investigation of the thermal conductivity of the PCM concrete samples, by use of the standard hot plate apparatus, was proposed in [16]. The methodology of measuring the thermal conductivity of the PCM concrete is summarized and shortly presented in Section 2.3 and the key results are presented in Section 2.5. The results of the experimental investigation revealed that the theoretical calculation of the thermal conductivity based on weight average method gives much higher results than the ones obtained from the experiments. The experimental procedure to determine so-called “effective heat capacity” of PCM concrete in function of temperature was proposed and investigated in [12]. The developed methodology from [12] to experimentally determine Cp(T) is shortly presented and summarized in Section 2.4. In [12], various methods to calculate Cp(T) were also found to give various results. Based on the conclusion made in [12], it seems that the “inverse method” should provide the most accurate results, but on the other hand, the “numerical simple method” is still accurate and provides results that could be implemented more easily and give better stability of the numerical models developed in the study presented in this paper. Therefore, in the research presented in this paper, the results obtained from the "numerical simple method" will be used. Moreover, findings from the numerical study on the heat transfer in the inhomogeneous hollow core concrete deck elements presented in [17] were taken into consideration when the models presented in this study were developed. Presented in [17] is the numerical investigation of the four various assumptions to the heat transfer within the air hollow in the air hollow core and how they influence the total thermal conductivity of such an inhomogeneous construction. In [17], the air void is modelled as:

- adiabatic boundary;
- air in the void is given thermal properties, however air is standing still and neither convection nor radiation is considered;
- air cavity is given surface to surface radiation boundary;
- air in the void is given equivalent thermal conductivity calculated based on [18] which considers heat transfer by convection and radiation in closed voids.

Concurrently, the experimental measurement of the thermal conductivity of the concrete hollow core deck was performed in the guarded hot box apparatus. The investigation indicated that the air void simulated with equivalent thermal conductivity that includes convection and radiation gives the closest results of total thermal conductivity determined experimentally with use of hot box apparatus. Therefore, in this investigation this approach to simulate heat transfer within air void was implemented in the models.

Firstly, this paper presents the concept development of the integrated PCM and TABS in the prefabricated hollow core slab element. Secondly, the developed concept is transferred to the COMSOL Multiphysics program. The initial findings regarding the best location of the PCM concrete presented in [15] will be elaborated. The boundary assumptions to calculate the models will be illustrated and elucidated. Consequently, the theoretically and experimentally determined thermal properties of concrete with various amounts of PCM will be compared with each other. What is more, the diurnal dynamic heat storage capacities are compared for the passive approach for the theoretically and experimentally determined thermal properties of PCM concrete. After this, the same passive models are thermally activated for 24 h/day with use of embedded water pipes. The cooling power of the thermally activated approach is compared between the reference deck without PCM and the deck with the theoretically and experimentally determined thermal properties of the PCM concrete material.

2. Methodology

2.1. Development of specification of PCM and TABS deck element

If PCM is directly incorporated in the construction material such as concrete, it can be located either in floors, walls, ceilings or in various combinations of these in the building. As stated in the previous section, the floor would most likely give the best results since this is the construction element that has the most direct solar irradiation exposure. However, floors are usually obscured with a miscellaneous covering that would protect PCM concrete from the direct solar irradiation. Walls cover a relatively large area and are also a strong candidate for incorporating PCM. However, they are often hidden behind furniture, and therefore the final effect of PCM would be limited and difficult to predict. If PCM is located in the ceiling, then the risk of having the element be hidden is minimized. On the other hand, this solution would require more cautious architectural design since a suspended ceiling would not be recommended in that case.

In this study, the development and design of the combined PCM and TABS concrete deck element was based on the existing and commercially introduced product called ThermoMax, see Fig. 1. Yet, ThermoMax is produced as deck made solely of concrete – without PCM.

The advantage of using the prefabricated elements is that the quality is repeatable and the thermal properties of PCM concrete in these elements can be accurately predefined. As a consequence, the performance of these elements can be simulated in a building simulation program where the indoor climate and the energy use can be calculated and predesigned.

2.2. Sensitivity analysis of location and percentage of integrated PCM

As presented in [15], the best exploitation of the latent heat storage is when the layer of the PCM concrete material is located on the very bottom surface of the deck. The initial investigation also revealed that the PCM concrete layer should not be thicker than approximately 3 cm otherwise the PCM in the deeper layers is not sufficiently activated and cannot contribute to the heat storage of the concrete deck element. This thickness, however, will have to be revised in this article since the theoretically determined thermal properties vary significantly from the experimentally determined.

The advantage of only casting a PCM concrete in the thin layer on the bottom of the deck is that the strength and other physical properties of the deck will be kept unchanged since all reinforcement and bearing properties would not be affected by the PCM presence in the concrete.

2.3. Thermal conductivity measurement of PCM concrete

Measurements of thermal conductivity of PCM concrete were conducted with use of a hot plate apparatus type EP500 fabricated by Lambda Messtechnik. The apparatus was upgraded to the version which allows measurements of concrete samples of thermal conductivity up to 2 W/mK.

The samples are inserted between a hot (upper) plate and a cold (lower) plate with dimensions 50 cm × 50 cm. The upper plate is lowered with the given pressure until the pressure set point is reached. The measuring area is the innermost square of dimensions 15 cm × 15 cm, and the rest is a frame which should be made of a highly insulating material. In the experiments with concrete samples, it was discovered that the frame made of elastic foam gives the best result repeatability. Additionally, the apparatus is equipped with perimeter zones which surround the measured sample and which control the temperature according to an embedded algorithm. Finally, a 1D heat flow is achieved, from the hot to the cold plate, within the measured sample. One set of experiments includes three measurements at three various mean temperatures. In this investigation, mean temperatures of 10, 20 and 40 °C were chosen for measurements. Moreover, the temperature difference between the hot and the cold plate is set to be 15 °C in all series of measurements. In that manner, one measurement (10 °C) is done for the temperatures across the sample below PCM melting point, one measurement (20 °C) is done for the temperatures across the sample within PCM melting point and one measurement (40 °C) is done for the temperatures across the sample above PCM melting point. However, measurements revealed that thermal conductivity of PCM concrete material is almost independent of the temperature within the investigated temperature range.

In order to ensure a good attachment between the apparatus plates and the measured samples, a thin layer of ultrasound gel should be applied on the sample surfaces attached to the plates of the hot plate apparatus. The complete methodology and results of measured thermal conductivity of PCM concrete samples are presented in [16].

2.4. Experimental methodology to determine specific heat capacity of PCM concrete

As stated in [7,11,19], the PCM samples or samples with PCM have to be of a substantial size in order to represent the bulk material used in practice. The PCM concrete samples can have aggregate particles up to 8 mm in size. This means that in the case of concrete materials, it is the aggregate size that determines whether or not a sample is representative. Concrete samples of only few milligrams have to be considered as inhomogeneous materials and secondly, as not representative samples, and therefore neither Differential Thermal Analysis (DTA) DTA nor Differential Scanning Calorimetry (DSC) methodology, cannot be used. Even the T-history method that allows measurements of bigger cylindrical samples is not applicable. First of all, in order to treat concrete samples as semi-homogeneous, the diameter of that cylindrical sample would have to be a couple of centimetres at least, and second of all, in order to fulfil the criteria of Bi < 0.1 (the temperature distribution can be considered as uniform), the sample would have to be very long. This would make the experimental set-up unfeasible. Nevertheless, if a sample is measured by a DSC method or other method in order to define material specific heat capacity, the focus has to be put on accurate temperature and heat flow measurements. For the sake of good reliable results, it is also crucial to prepare correct samples of representative dimensions in order to overcome the challenge with inhomogeneity. Moreover, the measured samples have to be under dynamic temperature load and both heat flux provided to the sample and the temperature of the sample have to be registered in time.

In [12] is a complete description of the novel proposed experimental methodology to determine specific heat capacity, and in this section only the essential summary of activities done in [12] will be presented.

The experimental set-up to determine Cp(T) of the PCM concrete consists of a modified hot plate apparatus and specially prepared concrete samples with PCM. For the purpose of the experiments, the standard hot plate apparatus was modified in order to be able to conduct dynamic thermal experiments. The control system of the hot plate apparatus was upgraded with the new mode enabling definition of a dynamic temperature load. A steady temperature at 18 °C on upper and lower plate is defined in the dynamic mode first. This steady state is maintained for at least 5 h in order to ensure that the whole sample reaches the same temperature. Afterwards, the sample is heated symmetrically by both the upper and lower plate from 18 °C to 32 °C over 10 h, and then the temperature is stabilized at 32 °C. For the designed temperature range and heating time, the temperature change within dynamic mode is only 0.023 °C/min.

In each measured sample, 9 thin thermocouples measuring the vertical temperature profile in the sample are evenly distributed. A very thin, square-shaped heat flux film of dimensions 8 cm x 8 cm manufactured by Captec is then positioned in the middle of the top surface of the sample. The prepared sample is surrounded with an elastic insulating frame and an upper "hot" plate is lowered until it reaches the top of the concrete sample. The dynamic test is triggered after the last visual inspection is performed to verify if the sample is attached properly to the lower and upper plate of the apparatus. At the same time, logging process of signals from the thermocouples and heat flux sensor film is started with the use of Helios Data logger type 2287A.

The measured temperature and heat flux results are used to develop four various methods to calculate specific heat capacity of PCM concrete in function of temperature ("simple method", "numerical simple method" and "inverse method"). The calculation methodologies of all three proposed methods are presented fully in [12]. As stated in [12], "simple method" has its shortcomings and is therefore not suggested for present investigation. The "numerical simple method" and "inverse method" give very similar results and are considered as more reliable than the "simple method". However, although the "inverse methodology" should provide the most accurate results the results of the "numerical simple method" are still very accurate, are much easier to implement in the present study and give better stability of numerical model than the results of the "inverse method". Therefore the results from "numerical simple methodology" were chosen to be implemented in the models developed in this investigation.

2.5. Thermal properties of combined PCM and concrete material: theoretical vs experimental

In order to be able to calculate the dynamic heat storage capacity of any material, three parameters have to be known: density-ρ, thermal conductivity – λ and specific heat capacity – Cp.

The initial theoretical calculation of the thermal properties (thermal conductivity and specific heat capacity) of the new composite of the PCM concrete presented in [15] are based on weight average calculation of the concrete and PCM. The initial theoretical calculations utilizing weight average method, see Eqs. (1) and (2), have been used due to lack of experimental data of PCM concrete material.

$$\mathrm{Cp}_{\mathrm{PCM\text{-}concrete}}(T) = \mathrm{Cp}_{\mathrm{PCM}}(T)_{\mathrm{DSC}} \times X + \mathrm{Cp}_{\mathrm{concrete}} \times (1 - X) \quad (1)$$

$$\lambda_{\mathrm{PCM\text{-}concrete}} = \lambda_{\mathrm{PCM}} \times X + \lambda_{\mathrm{concrete}} \times (1 - X) \quad (2)$$

The results of the theoretical calculation are depicted respectively in Figs. 3–5. The calculation of the theoretical specific heat capacity for combined concrete and PCM is based on the results of Cp(T) obtained from Differential Scanning Calorimetry (DSC) of pure microencapsulated PCM type DS 5040X from BASF. Due to the fact that PCM specific heat capacity varies with its temperature, the same was assumed analogically for the combined concrete and PCM material.

To experimentally determine the thermal properties of the PCM concrete material, special samples with 0 wt%, 1 wt%, 4 wt% and 6 wt% (by weight) of microencapsulated PCM type DS 5040X from BASF have been cast. The procedure and design of the casts and as well the experimental methodology to determine thermal conductivity and specific heat capacity can be found in [12,16] respectively and a short summary of the measurements methodology was presented in paragraphs 2.3 and 2.4 of this paper. The results of the experimentally determined thermal conductivity are presented in Fig. 3 and experimentally determined specific heat capacity results (by the numerical simple method) are presented in Figs. 4 and 5.

The density of the samples is determined by the direct measurements of the cast samples and is depicted in Fig. 2.

The effective specific heat capacity of the reference sample that does not contain PCM, which also means that it only reflects sensible heat storage properties, was measured at approximately 785 J/(kg K). The results for the 1 wt% PCM concrete are not presented as the measurements on this sample gave uncertain results. For that reason, further investigation presented in this article will consider only the 0 wt%, 4 wt% and 6 wt% PCM concrete material. Moreover, it was discovered that with the presently available superplasticizers the concrete samples with PCM higher than 6 wt% showed bad workability and therefore will not be taken into consideration for further investigation.

Finally, there is significant drop of density and thermal conductivity between the reference sample and the sample with 1 wt% of

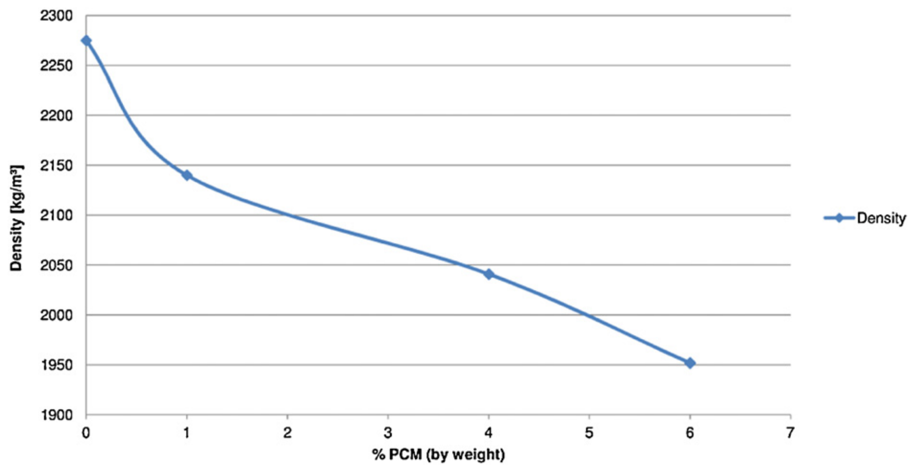

Fig. 2. Density of the PCM concrete samples.

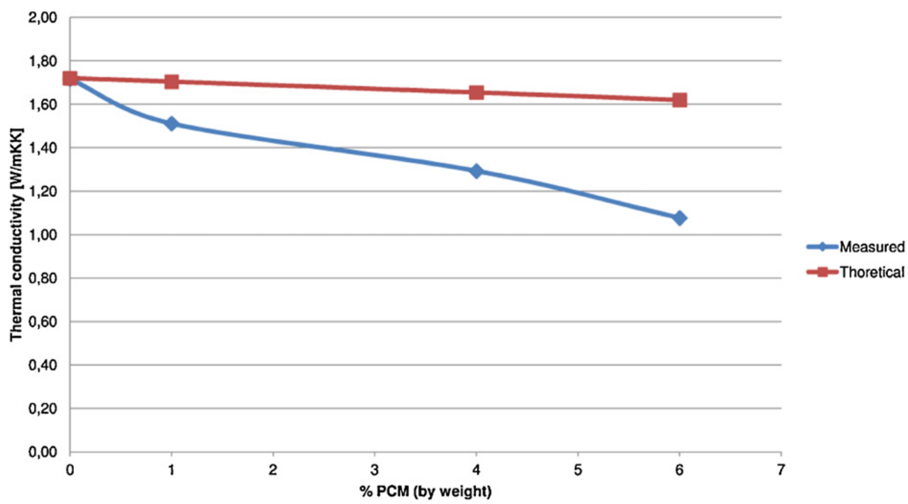

Fig. 3. Thermal conductivity of PCM concrete samples.

PCM. This drop is due to a higher air content in the samples with PCM than the one without PCM. For 0 wt%, 1 wt%, 4 wt% and 6 wt% PCM, the air content was measured at 1.4%, 4.9%, 4.6% and 3.8% respectively.

2.6. Boundary condition

For the purposes of this study, the hollow core deck simulated in the COMSOL Multiphysics is simplified to 2D model and a section

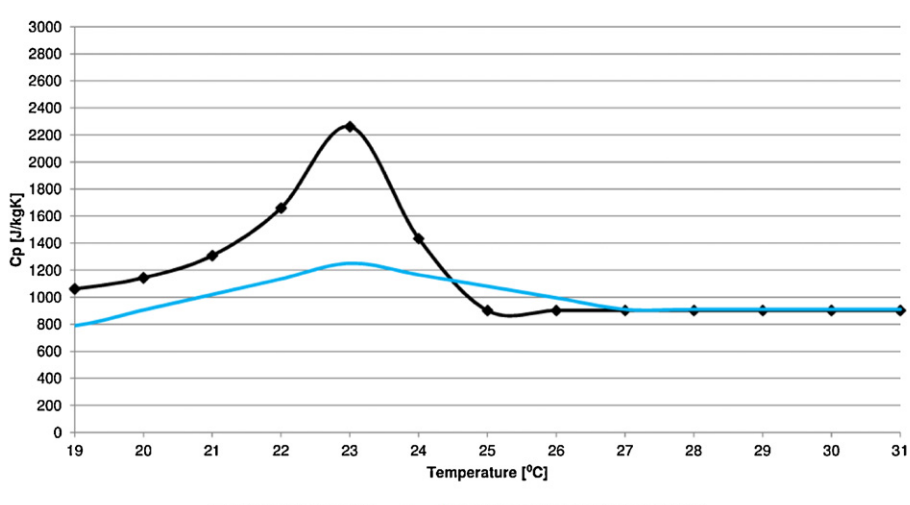

Fig. 4. Theoretically and experimentally determined effective specific heat capacity in function of temperature for 4 wt% PCM concrete sample.

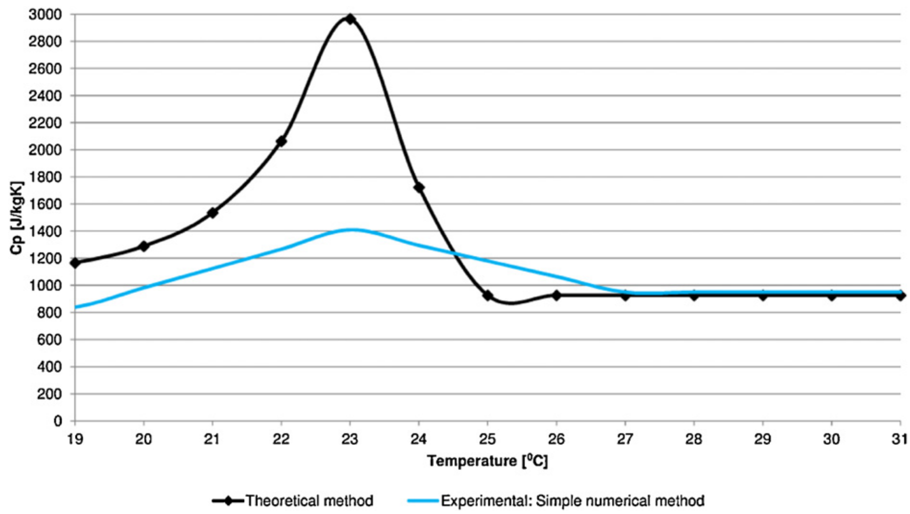

Fig. 5. Theoretically and experimentally determined effective specific heat capacity in function of temperature for 6 wt% PCM concrete samples.

with a pipe and a hollow air core, see Fig. 6. Due to the fact that in the real deck, vertical boundaries of such model are facing almost the same sections, these boundaries are defined as symmetric (adiabatic). Furthermore, it is assumed that the temperature on the upper and lower surface fluctuates with a diurnal sinusoidal pattern between 20 °C and 26 °C in order to imitate indoor temperature condition in the building. Moreover, combined heat transfer coefficient for convection and radiation, which in this study is varied between 4 and 30 W/(m^2 K), is applied on the upper and lower surface. Also, when the diurnal dynamic heat storage capacity is calculated, which means that the deck is passive, water in the pipe is only defined as a material and no boundary is applied. However, when the deck is simulated as thermally activated, the pipe perimeter is defined as heat flux boundary condition, and the heat transfer coefficient on the internal surface of the pipe is defined at 15,000 W/(m^2 K). That high heat transfer coefficient was chosen to imitate the temperature boundary condition and to obtain the same heat flux effect as from temperature boundary type. There are two purposes of choosing the heat flux boundary condition instead of simply applying a temperature boundary. First, is to be able to switch TABS on and off in selected time segments, which is not possible in a temperature boundary condition. Although in this paper the TABS is modelled as constantly active in the scope of future activities, it is expected to model decks with various activation schedules. And to be able to compare models, the compatibility of model boundary condition has to be preserved. Second reason is to always simulate maximum TABS cooling performance at defined water temperature, and this is done for a high heat transfer coefficient that result in the same cooling capacity as would be obtained if temperature boundary were applied to represent water pipe.

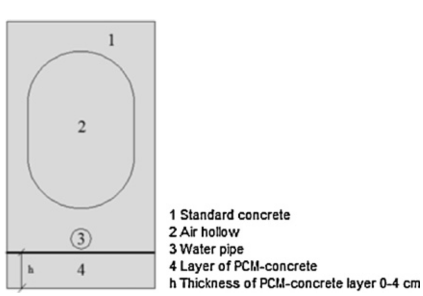

Fig. 6. Section of the hollow core concrete deck element with TABS and PCM.

In this study, the temperature of the water is defined at 16 °C. Finally, the heat transfer within the air void is given as an equivalent thermal conductivity that combines the heat transfer due to convection and radiation, and this was calculated according to [18]. The broader analysis on the heat transfer within the hollow core concrete decks was published in [17] and is shortly summarized in the introduction in this paper. The listed boundary conditions are conserved for all simulated models considered in this study. The conservation of the boundary condition allows for comparison of results between all models.

2.7. Thermal activation of the hollow core deck element

Although the TABS concept can be used for both heating and cooling, in this study focus is put solely on its cooling performance. The research on TABS presented in [20] indicated that the cooled ceiling temperatures are not an issue with respect to the normative requirements for the temperature asymmetry of the construction elements. However, the limit for cooled ceiling temperature is connected with the risk of condensation on the construction elements. The lowest permitted temperature of the cooling agent in the radiant systems depends on the relative humidity of the indoor air but it usually does not drop below 16 °C, which is the limit of surface temperature for buildings equipped with a dehumidification system. In the present study, this temperature was chosen to investigate the dependency of the cooling performance on the amount of incorporated PCM and thickness of the layer of PCM concrete.

Moreover, in this study, the centre of the pipe with water is 50 mm from the bottom surface of the hollow core slab. The diameter of the water pipe is set to 20 mm and spacing between pipes is 150 mm.

The study is carried out for full-time control mode meaning TABS are in operation constantly 24 h a day, see Fig. 7. The purpose of the present study was to investigate how the presence of PCM in the deck will affect the maximum cooling capacity of the deck which is always in operation and in which the cooling agent temperature is close to the lowest possible.

2.8. Dynamic heat storage capacity

Due to the cyclic temperature on the boundary of the deck, the model reaches periodic steady-state after a certain time. The length of this time depends on the geometry of the model, thermal properties of the model, amplitude and period of the cyclic boundary

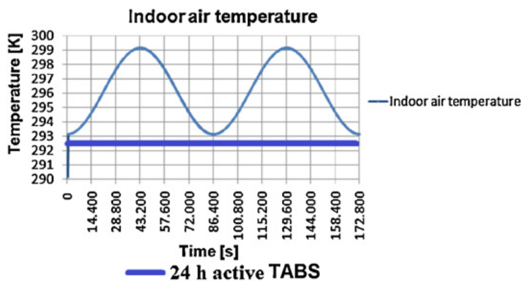

Fig. 7. TABS activation time.

condition. When the model reaches this periodic steady-state, it means that the amount of the energy transferred to the model during the charging period is equal to the amount of energy taken from the model during its discharging. The dynamic heat storage capacity is the energy/heat stored in the model during either charging or discharging period. The dynamic heat storage capacity can be also calculated on the chosen boundary of the model. Then it is calculated as the total normal heat flux transferred to or from the model during either charging or discharging period but only through that chosen boundary.

In the developed model of the concrete hollow core deck element, the cyclic temperature imitating the indoor temperature fluctuations is applied on the top and the bottom of the deck. However, it is only interesting to calculate the heat stored in the deck due to the heat transfer through the bottom surface of the deck. Firstly, the top surface of the deck would in practice be covered with various type of flooring resulting in various heat transfer to the deck on its top surface. Secondly, the construction of the deck is not changing on the top, and the layer of the various PCM concrete is applied only on the bottom of the deck. This means that the total heat storage of the deck will vary only due to the various PCM concrete layer thickness and amount of PCM in that layer.

3. Results

Firstly, the volumetric heat capacity and thermal inertia of the standard concrete material and theoretically and experimentally determined concrete with 4 wt% and 6 wt% of PCM will be presented in the function of temperature. These thermal properties shall help to better understand the results obtained for the dynamic heat storage capacity and cooling capacity of respectively passive and thermally activated decks.

Secondly, this section will present and compare the calculated diurnal heat storage capacity of the decks with theoretically and experimentally determined thermal properties of PCM concrete material, but only with the decks considered as passive elements (the water in the water pipe is not flowing). Afterwards, the increase of the heat storage capacity of the decks with various layers of the PCM concrete will be calculated with regards to the reference deck consisting only of ordinary concrete. The potential of the increase of the heat storage capacity will be parameterized with regards to the total heat transfer coefficient that represents both convective and radiative heat transfer on the surface of the deck.

Finally, the results will be presented for the calculated cooling capacity of the thermally activated deck (water in the water pipe is flowing) with and without PCM both for models calculated with theoretically and experimentally determined thermal properties of the PCM concrete. As for the passive deck, the performance of the deck with various amounts and thicknesses of the PCM concrete will afterwards be compared to the performance of the reference deck without PCM.

3.1. Volumetric heat capacity and thermal inertia

Figs. 8 and 9 respectively depict volumetric heat capacity and thermal inertia of standard (reference) concrete and the PCM concrete with 4 wt% and 6 wt% of microencapsulated PCM.

The volumetric heat capacity is calculated according to the equation:

$$\mathrm{VHC} = \rho \times \mathrm{Cp} \tag{3}$$

and describes material ability to store energy in a given volume while undergoing a given temperature change. By using volumetric heat capacity instead of directly using specific heat capacity, results take also into consideration the material's density which is decreasing for PCM concrete with increasing content of PCM.

The thermal inertia is calculated according to the equation:

$$I = \sqrt{\rho \times \mathrm{Cp} \times \lambda} \tag{4}$$

and combines volumetric heat capacity with thermal conductivity of a bulk material. The high thermal inertia describes materials that characterize high thermal mass and high thermal conductivity. The higher thermal inertia the faster material can be thermally activated and more thermal load can be stored during the dynamic thermal process.

3.2. Passive approach: calculated dynamic heat storage

The results presented in Figs. 10 and 12 illustrate the diurnal dynamic heat storage of the decks with respectively 0% (reference), 4 wt% and 6 wt% PCM in the concrete. The calculated results are for the deck with the PCM concrete layer with a thickness from 1 up to 4 cm. Moreover, results are presented as function of the total heat transfer coefficient that is combining convective and radiative heat transfer, and was parameterized in the ranges from 4 up to 30 W/(m^2 K). The continuous curves represent results obtained from the models where the PCM concrete properties were calculated according to the theoretical weight average method that deploys the thermal properties determined for the separated standard concrete and pure PCM. The dashed lines represent the results obtained from the models where the PCM concrete properties were obtained from experimental investigations where measurements were conducted on the PCM and concrete combined into one material.

Figs. 11 and 13 respectively show calculated improvement of diurnal dynamic heat storage of respectively decks with 4 wt% and 6 wt% PCM in the concrete and the improvement is calculated with regards to the reference deck made of standard concrete (no PCM).

3.3. Active approach: calculated cooling capacity

The results presented in Figs. 14 and 16 illustrate the diurnal cooling capacity of the decks with respectively 0% (reference), 4 wt% and 6 wt% PCM in the concrete and water in the decks circulates 24 h/day (always). As in the passive approach, the performance of the decks is calculated with the PCM concrete layer that has a thickness from 1 up to 4 cm, and the total heat transfer coefficient on the surface is a parameter varying from 4 up to 30 W/(m^2 K).

4. Discussion

As seen in Fig. 8, volumetric heat capacity calculated based on weight average (theoretical) calculations give much higher results than the ones determined experimentally. Furthermore, the left side of the peak of the volumetric heat capacity in function of temperature has comparable width for the theoretical and experimental data where, on the other hand, the right side of the peak is

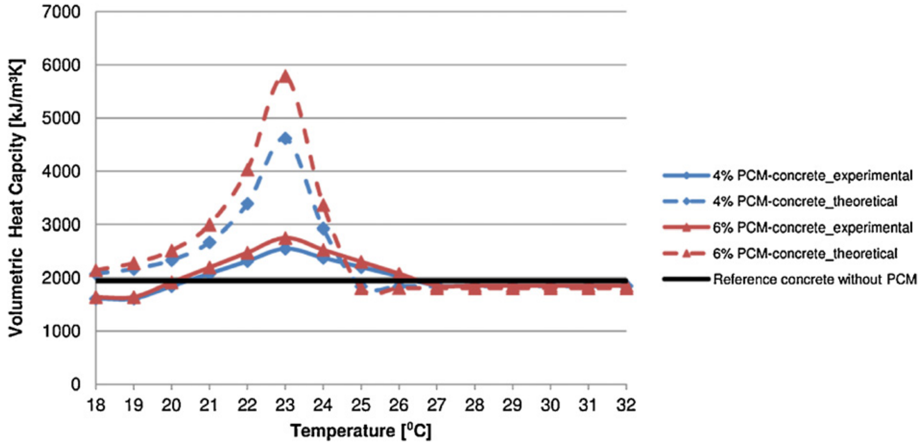

Fig. 8. Volumetric heat capacity of standard concrete and PCM concrete in function of temperature.

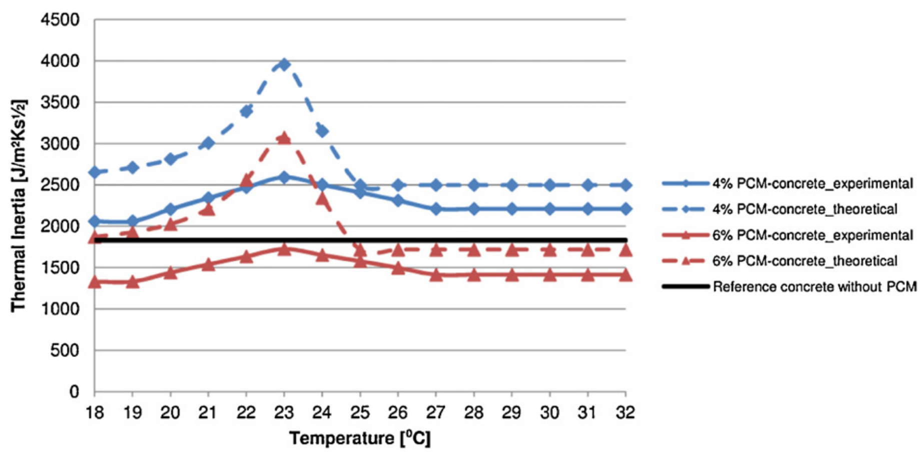

Fig. 9. Thermal inertia of standard concrete and PCM concrete in function of temperature.

much shorter for the theoretical data than for the experimentally determined results. Moreover, the difference between the volumetric heat capacity of the 4 wt% and 6 wt% PCM concrete is quite insignificant. This can be explained by the decreasing density with the increasing content of PCM in the concrete.

The results of thermal inertia presented in Fig. 9 indicate that this thermal parameter is lower for the experimentally determined 6 wt% PCM concrete than for the reference concrete. The low thermal inertia of the 6 wt% PCM concrete is the reason for the negative or almost neutral heat storage capacity improvement with regards to the reference deck presented in Fig. 13. Due to its significantly higher thermal conductivity than the experimental 6 wt% PCM concrete, the experimental 4 wt% PCM concrete has higher thermal inertia than the reference concrete and therefore the heat storage improvement is also higher with regards to the deck made only of reference concrete.

The thermal inertia for the theoretically calculated thermal properties of the 4 wt% and 6 wt% PCM concrete is significantly higher than the thermal inertia of the reference concrete but only within the melting range where the specific heat capacity is high.

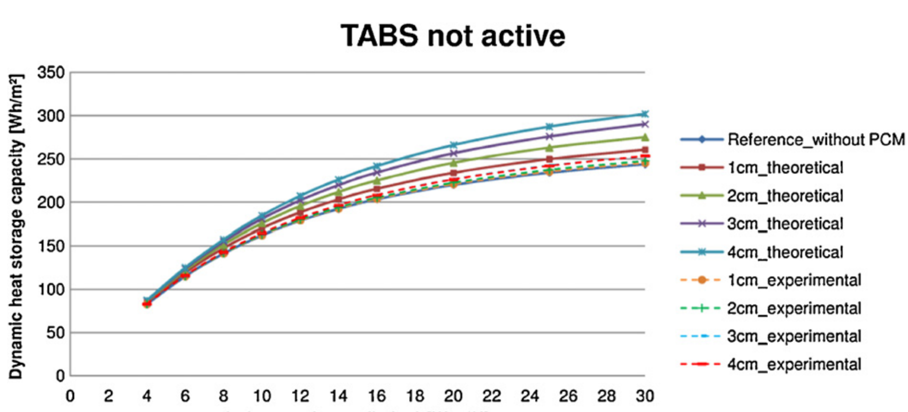

Fig. 10. Daily dynamic heat storage capacity of the deck with reference concrete and theoretically/experimentally determined 4 wt% PCM concrete.

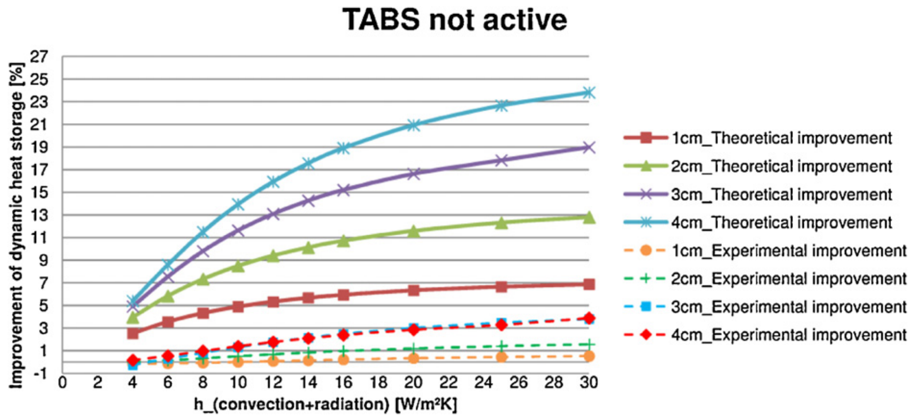

Fig. 11. Calculated improvement of the dynamic heat storage of deck with theoretically/experimentally determined 4 wt% PCM concrete with regard to the deck without PCM.

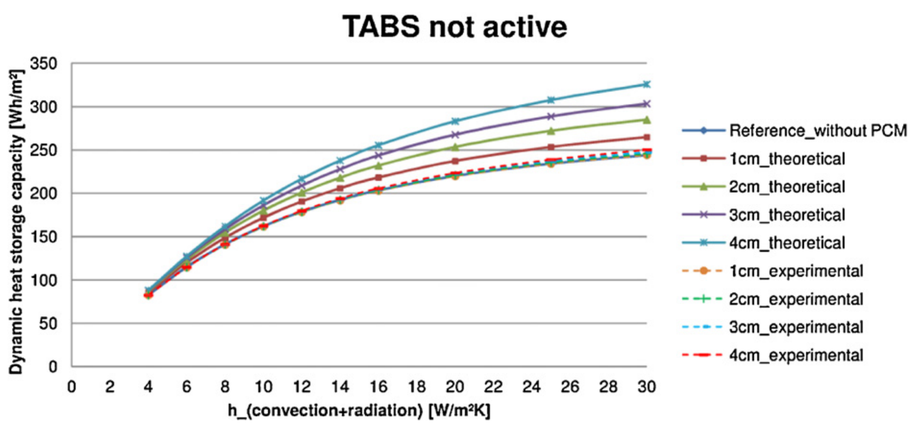

Fig. 12. Daily dynamic heat storage capacity of the deck with reference concrete and theoretically/experimentally determined 6 wt% PCM concrete.

Above the melting range the theoretical 6 wt% PCM concrete has slightly lower thermal inertia than the reference concrete.

The conclusion is therefore that when using PCM concrete in buildings, it has to be ensured that the indoor temperature swing fluctuates within the melting range of the PCM or that the used PCM has a melting range that covers expected and acceptable temperature swing in the building. In this manner, the latent heat of fusion will be utilized most efficiently. Moreover, for both theoretical and experimental parameters, the thermal inertia of the 4 wt% PCM concrete is correspondingly higher than the thermal inertia of the 6 wt% PCM concrete. This can be explained by the increasing specific heat capacity and decreasing thermal conductivity and density while the percentage of the incorporated PCM is increasing. As stated, the drop in the density and thermal conductivity of the concrete effectively counteracts the increase of the specific heat capacity due to the latent heat available within the melting range of PCM.

In Figs. 10 and 12, the increase of the dynamic heat storage in the decks with PCM with respect to the reference deck without PCM becomes more distinct the higher the heat transfer coefficient on the surface is. Also, the curves representing dynamic heat

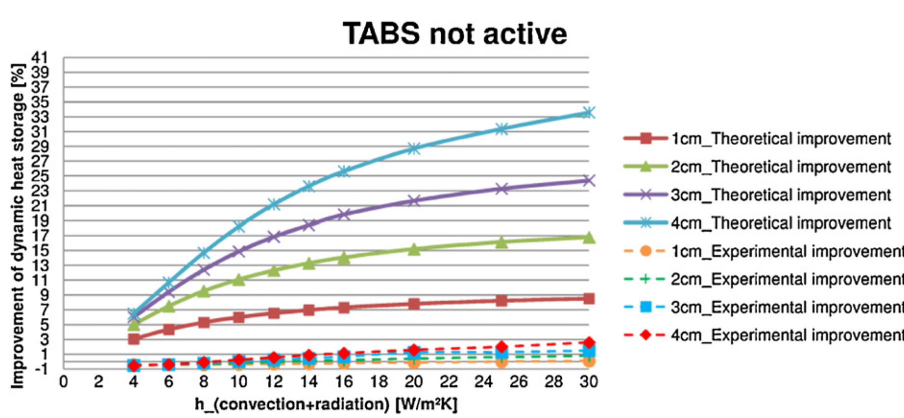

Fig. 13. Calculated improvement of the dynamic heat storage of deck with theoretically/experimentally determined 6 wt% PCM concrete with regard to the deck without PCM.

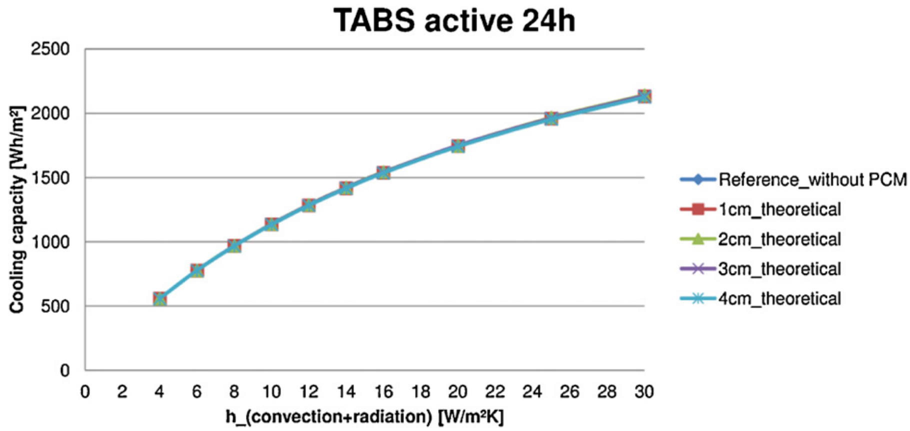

Fig. 14. Daily cooling capacity of the deck with reference concrete and theoretically determined 4 wt% PCM concrete.

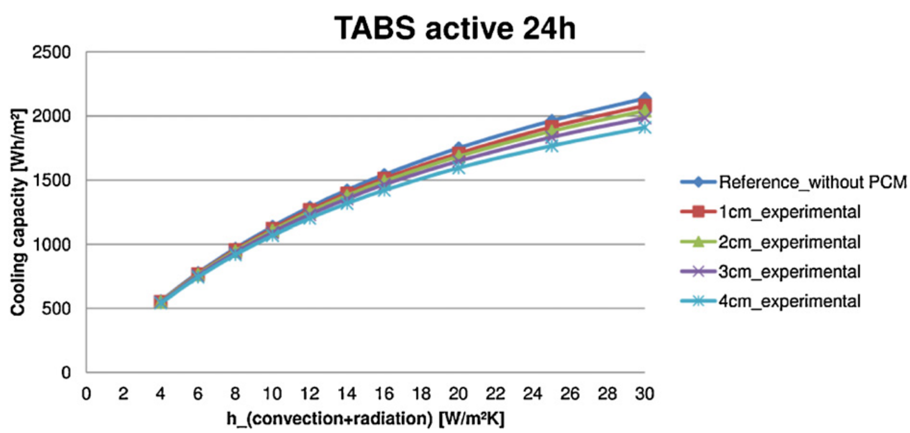

Fig. 15. Daily cooling capacity of the deck with reference concrete and experimentally determined 4 wt% PCM concrete.

storage are continuously rising with the increased heat transfer coefficients, which is the indication that the thermal mass in any decks is not fully utilized.

Moreover, presented in Figs. 11 and 13 is the improvement of the heat storage with respect to the reference deck which indicates that for the assumptions made in the theoretical calculations the improvement can be significant, but on the other hand the total heat transfer coefficient still has to be as high as possible. Contrary to the results obtained based on the theoretical assumptions for the thermal properties of the combined PCM and concrete, the improvement of the heat storage of the deck with the experimentally determined properties does not exceed 5% even for a quite high heat transfer coefficient that reaches 30 W/(m^2 K). As seen in Figs. 11 and 13, the improvement is not higher than 1% for the total heat transfer coefficient that is lower than 10 W/(m^2 K). What is more, the performance of the 4 wt% PCM concrete is surprisingly better than the performance of the 6 wt% PCM concrete. The reason is explained in Figs. 8 and 9 and at the beginning of this section.

Regarding the cooling capacity of the thermally activated decks presented in Figs. 14 and 16, the results are overlapping each other regardless of the amount of PCM and the thickness of the layer

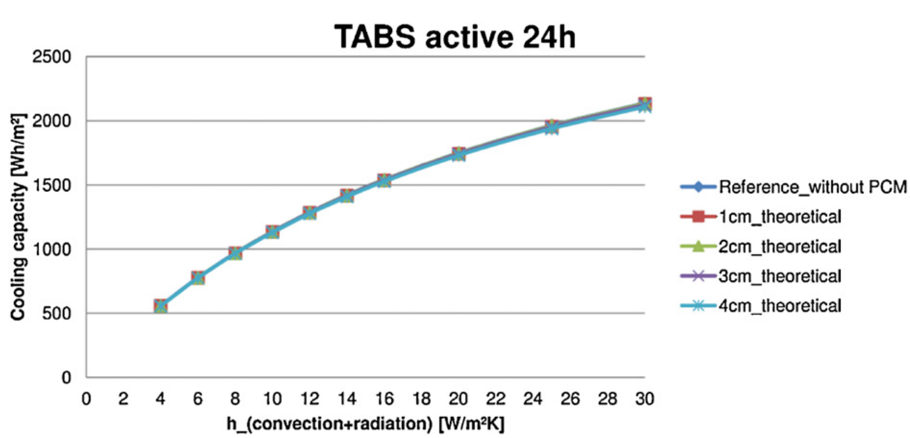

Fig. 16. Daily cooling capacity of the deck with reference concrete and theoretically determined 6 wt% PCM concrete.

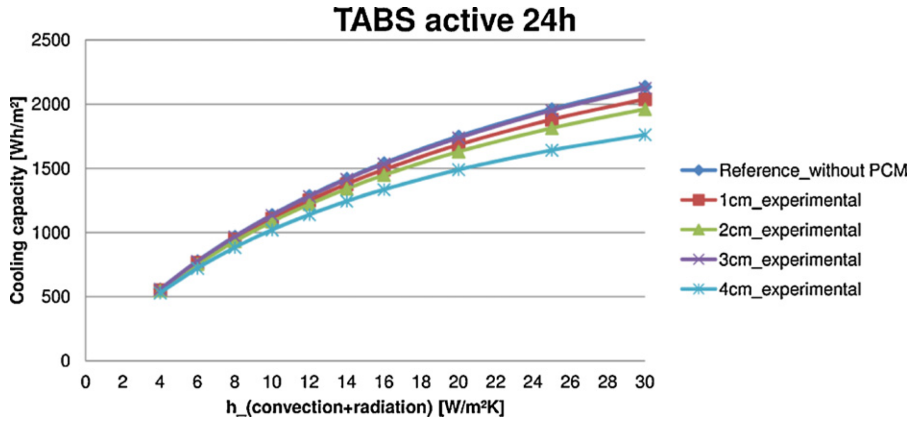

Fig. 17. Daily cooling capacity of the deck with reference concrete and experimentally determined 6 wt% PCM concrete.

with PCM for the theoretically determined thermal properties of the PCM concrete. The reason for that is the calculated insignificant drop in the thermal conductivity with the increase of the PCM amount in the concrete. Contrary to that, the cooling capacity obtained from the decks with the experimentally determined properties of the PCM concrete is considerably lower with regards to the reference deck, see Figs. 15 and 17. This is because of the drastic drop in measured thermal conductivity discovered during the investigation on the new PCM concrete material. Obtained and presented results are valid only for a 24 h/day activated deck element, where in reality TABS are usually operated in time segments. The aim of the present study was to indicate that the low thermal conductivity of PCM concrete material can decrease the efficiency of TABS. However, simulating TABS 24/day does not allow PCM to undergo the phase shift, and therefore the low thermal conductivity can have predominant influence and decrease the heat transfer. On the other hand, the investigation for passive deck highlighted that heat storage improvement due to PCM presence in concrete is very insignificant.

With respect to time, the operation of TABS in the deck with PCM concrete becomes a very complex issue. The challenge is to include all the variables that could influence the heat storage of PCM integrated in concrete, e.g. time of operation with respect to surrounding temperature, heat transfer coefficient on the surface of the deck, water temperature in the deck. Then the potential for improvement and energy savings could be analysed, for example, by comparing relevant models with and without PCM to each other. This however should be considered as standing alone study and due to the size of the task that investigation will not be included in the scope of this article.

5. Conclusions

The presented work combines numerical and experimental investigation of the new combined material that consists of standard concrete and microencapsulated PCM. The paper indicates the discrepancy between the theoretically and experimentally determined thermal properties of the PCM concrete material. Furthermore, the paper points out that the theoretical assumptions regarding the thermal properties of the PCM concrete overestimates the performance of this material with respect to the obtained experimental properties. What is more, the experimentally determined thermal properties of PCM concrete highlighted that the use PCM concrete in decks with TABS can have decreasing effect on cooling capacity of TABS. It was also concluded that further studies should be made with focus on optimization of TABS operation with respect to indoor temperature fluctuations.

Finally, further studies should be focused on experimental investigation of additional samples of various PCM and concrete mixes and full-scale measurements of the decks with the PCM concrete material.

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