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Thermal performance of an office cubicle integrated with a bio-based PCM: Experimental analyses

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Abstract

Phase change materials (PCM) have the potential to enhance the energy performance and thermal comfort of buildings. The main purpose of this work is to investigate the thermal performance and indoor climate benefits of bio-PCM integrated in an office cubicle. The study is based on experimental work, where air temperature of the 15 m^2 test room, as well as the surface temperature of the PCM and the walls, floor and ceiling were recorded. Different scenarios were considered, including PCM used as a suspended ceiling without supporting ceiling plates, as well as PCM covered with ceiling plates. The preliminary result shows that a significant cooling effect could be achieved when using 17 m^2 of uncovered PCM directly exposed to the occupied zone. The PCM could therefore, to a certain extent, reduce the need of mechanical cooling and thus save costs for installation, energy use and maintenance.

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Keywords: Bio-PCM; experiment, office cubicle; thermal comfort, energy performance

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1. Introduction

In office buildings it is often difficult to expose thermal mass in partition walls, floor and ceiling, due to the requirements of building layout flexibility and the need for acoustic absorption material. Thus, they tend to experience rapid thermal energy load changes. This causes fluctuation in indoor temperature, that can reduce the thermal comfort of the occupants. One preventive measure to solve this problem is to incorporate phase change materials (PCM) in building elements and thus increase the thermal mass of the building.

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PCMs are materials that undergo a phase transition between liquid and solid when heated or cooled. At the temperature in which the phase change occurs, PCMs store thermal energy in the form of latent heat (melting) and reject it when being cooled (solidifying).

PCMs can be integrated into building elements by immersion, direct incorporation and encapsulation [1, 2]. Immersion involves immersing the building material into melted PCM, where the building material absorbs the PCM by capillary action. In the case of direct incorporation, the PCM is added directly into the construction material during the production process, such as mixing PCM powder with gypsum powder during the manufacturing of the gypsum board. Encapsulation techniques can be either microencapsulation where particles or droplets of PCM are surrounded or coated with a continuous film of polymeric material to produce capsules or macro encapsulation in which the PCM is contained in larger containers (bags, tubes) before integration into the building.

PCMs of inorganic salt hydrates, organic paraffin waxes, and mixtures of these are the most common for building integration. One of the central criteria for the selection of PCMs for buildings application is that the PCM should undergo phase change near the operating temperature of the building space [3, 4]. PCMs should also have good thermal conductivity and high latent heat per volume unit, and should not pose a risk to health or the environment. PCMs should be able to exploit diurnal swings in outdoor temperature, whereby absorbed heat during the daytime is released at night when the outdoor and indoor air is cooler.

Several studies and reviews have been conducted on the performance of PCMs at different components of buildings [5-10]. Kuznik et al. [5] and Liu et al. [6] studies showed that PCM applied in the internal wallboards of a room improved the thermal comfort of occupants due to the thermal stoarge of the PCM and radiative effect of the walls. The PCM boards on a wall reduced the interior wall surface temperature when it absorbed the excess heat (charging process). An experimental study by Cabeza et al. [7] revealed that a PCM enhanced concrete wall leads to an improved thermal inertia as well as lower inner temperatures, in comparison with conventional concrete. An experimental study by Koschenz and Lehmann [8] about microencapsulated PCM, having a phase transition range of 20–24°C and integrated into ceiling panels, showed that the PCM stored enough thermal energy to compensate for the typical daily heat gains in office buildings with high internal heat loads and large glazing areas.

However, most of currently available PCMs are derived from petroleum products, and they affect the fire and environmental performances of buildings. In this regards, bio-based PCMs are one of the most promising candidates owning to their better fire resistance [11, 12], and environmental performance, as well as acquiring basic properties for PCMs used in buildings. Bio-based PCMs are organic in nature and can be manufactured with a range of different melting points.

The objective of this paper is to evaluate the thermal performance of a bio-based PCM with a transition range of 18.5-23°C, integrated in an office cubicle designed according to passive house standard.

2. Materials and methods

In this work, the impact of bio-based PCM on the operative temperature and cooling power demand of an office cubicle is investigated in a full-scale test room. The test room is located inside the indoor climate laboratory at HiOA. The test room is separated from the laboratory room by roof, floor and walls. On one of the walls, there is a door and a window towards the laboratory room. The floor area of the test room is 15 m^2 and the room height below the suspended ceiling is 2.30 m. The room height of an office cubicle is normally higher than in the test room, very often around 2.7 m. It was assumed that the measured air temperatures in the occupied zone were slightly higher than what would have been in a room with a higher ceiling. A suspended ceiling, covering an area of 8.64 m^2 (3.6 m x 2.4 m) of the ceiling surface, is mounted about 150 mm below the ceiling of the test room. Fig. 1 shows sketches and a photo of the test room and the test setup.

The experimental work was performed without PCM as well as with PCM, in two different amounts and building elements. The general overview of the different scenarios investigated in the experimental work is presented in Table 1.

Table 1. Scenarios considered during the experimental work.

Scenario	Description
1	No PCM. No suspended ceiling. No gypsum board on wall.
2	9 m^2 uncovered PCM as suspended ceiling. 8 m^2 PCM uncovered in one wall
3	No PCM. Suspended ceiling of aluminium plates. Gypsum boards on one wall
4	9 m^2 PCM in suspended ceiling covered with aluminium plates below. 8 m^2 PCM covered with gypsum boards in one wall
5	9 m^2 PCM in suspended ceiling covered with aluminium plates below. Gypsum boards on one wall, but no PCM in wall

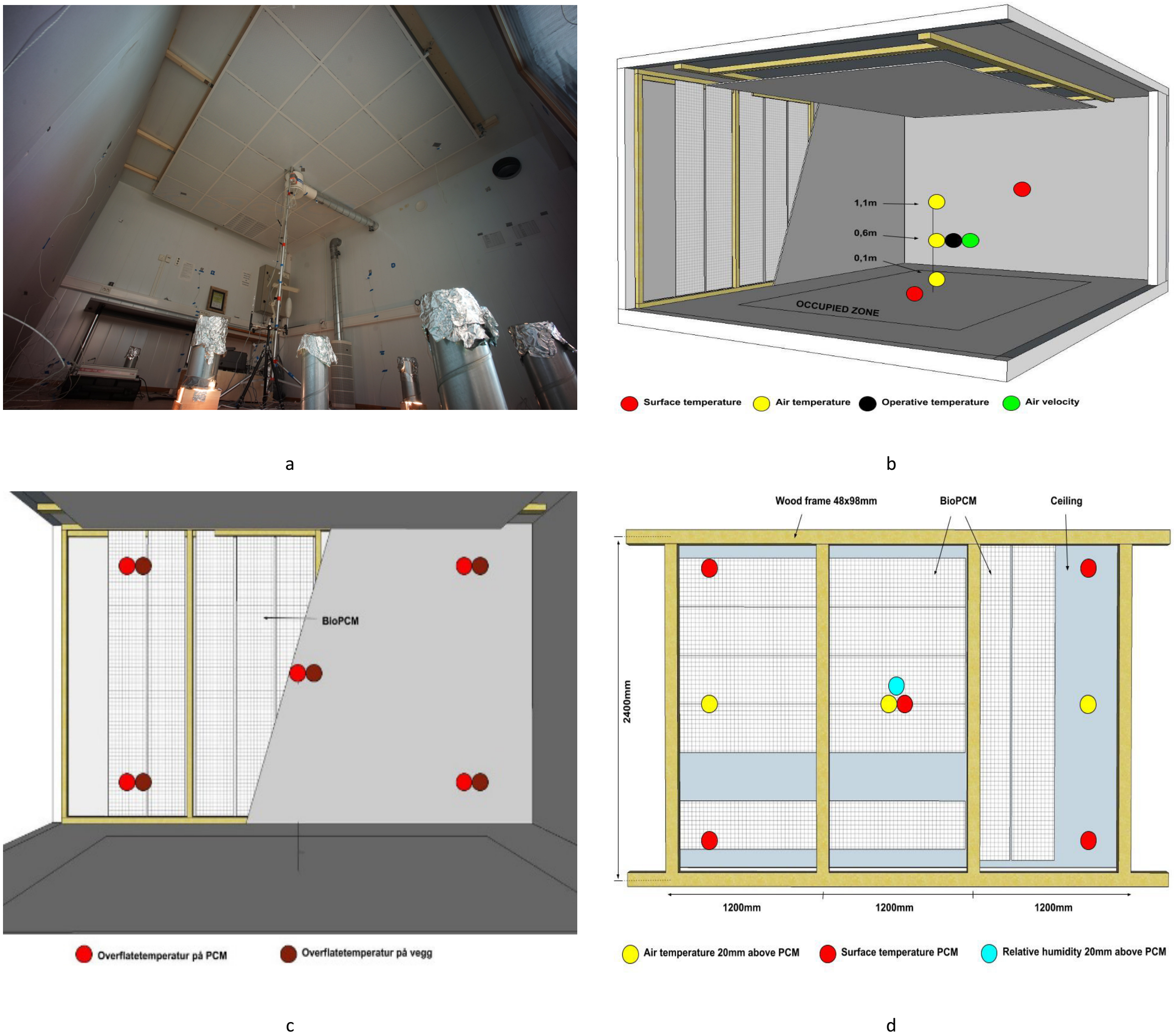

Fig. 1. (a) photo of test room interior; (b-d) sketches of the test room showing measurment points; (b) three-dimensional view; (c) elevation of wall with PCM; (d) plan view of suspended ceiling.

The first scenario (Scenario 1) was a control case without suspended ceiling, only with the support structure for suspended ceiling consisting of 40 mm high steel profiles making a 0.6 by 0.6 m horizontal grid. In Scenario 2, 4 and 5 the PCM was put on top of the suspended ceiling support structure. In Scenarios 3, 4 and 5, thin 0.6 x 0.6 m aluminum plates with 20% perforation, covered on the back side with a thin textile fabric, were mounted in the suspended ceiling grid (below the PCM in Scenario 4 and 5). The suspended ceiling structure was hung by steel braces in a 48 mm thick wood frame attached to the roof of the test room. To achieve good heat exchange between the air above the PCM and the air volume of the room, an air gap of 60 mm was left between the wood frame in the roof and the suspended ceiling grid.

In Scenarios 2 and 4, PCM was mounted in one of the long walls in the room; directly exposed to the occupied zone in Scenario 2 and covered with 13 mm thick gypsum boards in Scenario 4. The wall was also covered with gypsum boards during Scenarios 3 and 5.

Heat load from occupants, lighting and electric equipment during working hours (08:00-16:00) was set to 135 W, 60 W and 83 W respectively, e.g. 278 W altogether. The heat load from occupants was assumed considering a typical case of an office cubicle with 10 m^2 floor area per person. The floor area of the test room is slightly larger than a typical office cubicle for a single person (ca 10 m^2). It has been compensated for this difference by increasing the internal heat load from persons and computers so that it corresponds with the load from 1.5 persons and 1.5 computers. Solar heat gain was considered an average constant gain of 240 W to the office cubicle between 05.00 and 22.00. In reality, this will of course vary through the day. This simplification will underestimate the operative temperature in the middle of the day, and overestimate it in mornings and evenings. The solar heat gain from the window was simulated using Simien [13], a tool used for energy and indoor climate simulation within the Norwegian construction industry. For the simulation, a south facing 1.5 x 1.5 m window with frame factor 0.2, g-value 0.45, U-value of 0.8 W/(m^2K) and summer design climate in Oslo was considered. Simien is able to simulate e.g. solar heat gain, indoor air temperature and operative temperature for each hour throughout 24 hours with hourly based summer design climate data for e.g. outdoor temperature and solar radiation.

The total heat load in the test room was supplied by a combination of electric heaters and light bulbs, and was controlled by a time switch. Moreover, the test room was ventilated by a small air-handling unit, called a Flexit Spirit Uni 2. The airflow rate from the air handling unit can be controlled manually in three levels: 70 m^3/h, 185 m^3/h and 250 m^3/h. According to the Norwegian building code [14], the minimum fresh air required for an office cubicle during working hours is 76.6 m^3/h. Therefore, in order to avoid damping of the air handling unit capacity, the minimum airflow rate of 70 m^3/h was applied at working hours for all scenarios. During the night hours, the airflow rate was increased to maximum level to make the PCM release the heat absorbed during daytime. The supply air temperature setpoint, both within and outside the working hours, was set to 16 ^{o}C. This is a commonly used supply air temperature in Norwegian office buildings during periods with high cooling demand, in order to achieve as much cooling as possible and at the same time to avoid draught and condensation problems.

According to Energy Management & Storage Solutions [15], which represents Bio-PCM in Europe, Bio-PCM is a non-toxic nutritionally inert chemical known as a "fatty ester" that is derived from rapidly renewable plants. The PCM is wrapped into small pockets in a thick plastic foil, forming 0.42 x 2.4 m^2 blankets. Basic data of the bio-PCM is presented in Table 2.

During the test, air temperature was measured in the supply air duct, and in the middle of the test room at 0.6 m above the floor. The test room's internal wall surface temperatures, as well as the top surface of the PCM in the suspended ceiling and the surface of the PCM in the wall were also measured. Both the air and surface temperatures were measured by K-type thermocouples, having +- 1.5 ^{o}C uncertainty. The thermocouples were logged by an Intab PC-logger 3100i which is operated by Intab EasyView software version 5.6.

Table 2: Basic data of the Bio-PCM [11]

Parameter	Value
Manufacturer	Phase Change Energy Solutions Inc., USA
Material name	BioPCM Q23 M51
Melting point	23.0°C
Solidification point	18.5°C
Thickness	20.8 mm
Thermal conductivity	0.2 W/(m K)
Specific heat capacity	1970 J/(Kg K)
Density	235 kg/m3

It is assumed that the air velocity during the measurements is lower than 0.2 m/s. Thus, the operative temperature can be calculated as an average of the calculated mean radiation temperature and the measured values of air temperature at 0.6 m above floor level. The mean radiation temperature is calculated from measured surface temperatures and view factors of the surfaces exposed to a person sitting in the middle of the room:

$$\overline{T_r^4} = T_1^4 F_{p-1} + T_2^4 F_{p-2} + \cdots T_N^4 F_{p-N}$$

Where $\overline{T_r}$ is the mean radiation temperature in kelvins, T_N is the surface temperature of surface N in kelvins, and $F_{p\text{-}N}$ is the angle factor between a person and surface N [16].

3. Results and discussion

3.1. Operative temperature of scenario 1 and 2

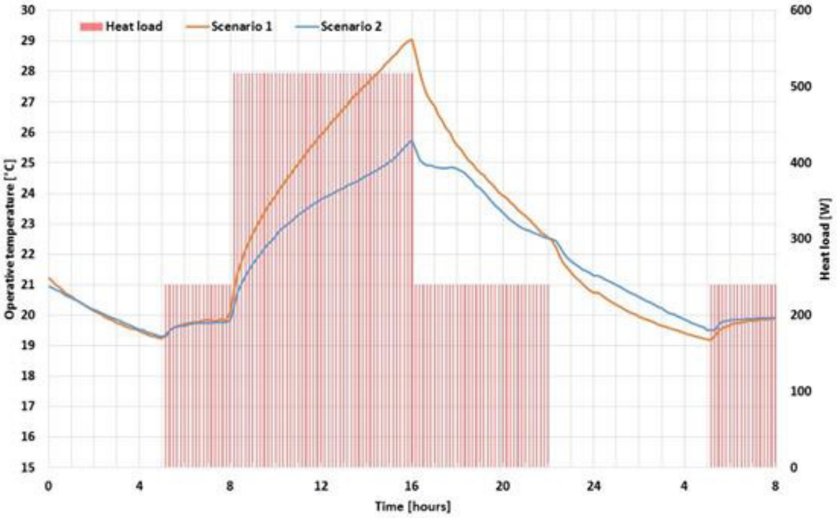

Fig. 3: Operative temperature of the test room at 0.6 m above floor level together with heat load: scenario 1 and 2.

To investigate the cooling potential of the bioPCM directly exposed to the indoor air, experimental work was conducted when the PCM was mounted as a suspended ceiling and in one of the test room's walls (scenario 1 and scenario 2). The result is depicted in fig. 3. The result revealed that adding 17 m^2 of PCM to the test room (9 m^2 in ceiling and 8 m^2 in one of the walls) yielded a significant drop in the operative temperature of the room, with maximum temperature drop of 3.3˚C (from 29.1 to 25.8 ˚C), around 16:00 o'clock. It was also discovered that the PCM ensured the operative temperature to be below 26 ˚C throughout the operating hours. The guide to the Norwegian building code [14] recommends that the operative temperature in an office cubicle should not be greater than 26 ˚C for more than 50 hours during a normal year. This revealed the potential of the PCM with the possibility to avoid installing local mechanical cooling and thus save costs for installation, energy use and maintenance.

3.2. Operative temperature of scenario 3, 4 and 5

In these scenarios, the effect of the PCM when it was covered by aluminum ceiling plates and gypsum wallboards were investigated, and the result is shown in fig. 4. Comparing scenario 3 and 4, the operative temperature of the test room reduced moderately with a maximum temperature drop of 1.0 ˚C (from 27.5 to 26.5 ˚C).

It was also observed that when the PCM was removed from the wall, and only the PCM mounted on aluminum ceiling was considered (scenario 5), the PCM could bring only a small change in the operative temperature (from 27.5 to 27.2 ˚C). This shows that the amount of PCM used in the office cubicle has a significant impact on the cooling effect. However, this poor performance could also be attributed to the rise in the temperature of the supplied air. It was observed that the temperature of the supplied air during working hours was higher for scenario 5 than scenario 3, which could be one uncertainty for this experimental work.

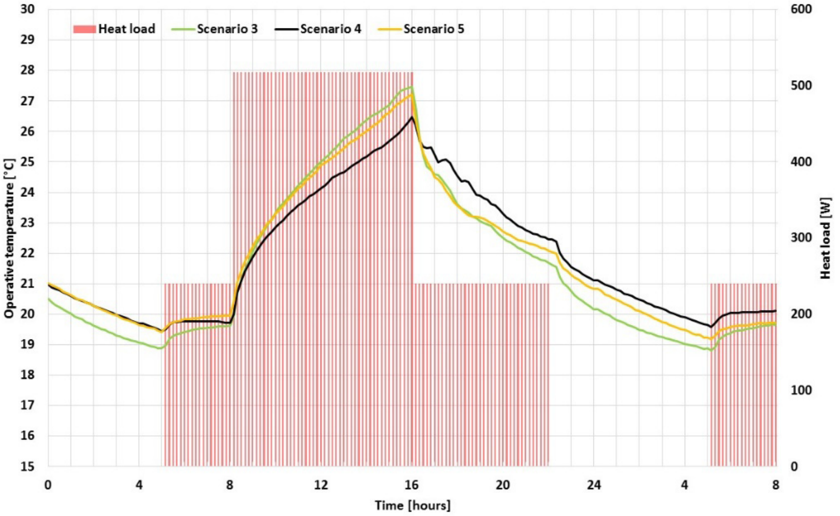

Fig. 4: Operative temperature of the test room at 0.6 m above floor level together with heat load: scenario 3, 4 and 5.

3.3. Operative temperature of scenario 2, and 4

In this experimental work, the impact of covering the PCM with common surface materials was studied. In the case of scenario 2, the PCM was covered by aluminum ceiling plates and gypsum wallboard. As shown in fig. 5, the covering elements, to a certain extent, degrade the performance of the PCM (maximum temperature drop of 0.7 ˚C, from 26.5 to 25.8 ˚C). This is mainly due to the high heat resistance of the gypsum board. Moreover, the limited perforated area of the aluminum ceiling (20 %) also contributed to limit the heat transfer area for convection heat transfer (i.e. a higher perforation rate would have increased the convection heat transfer).

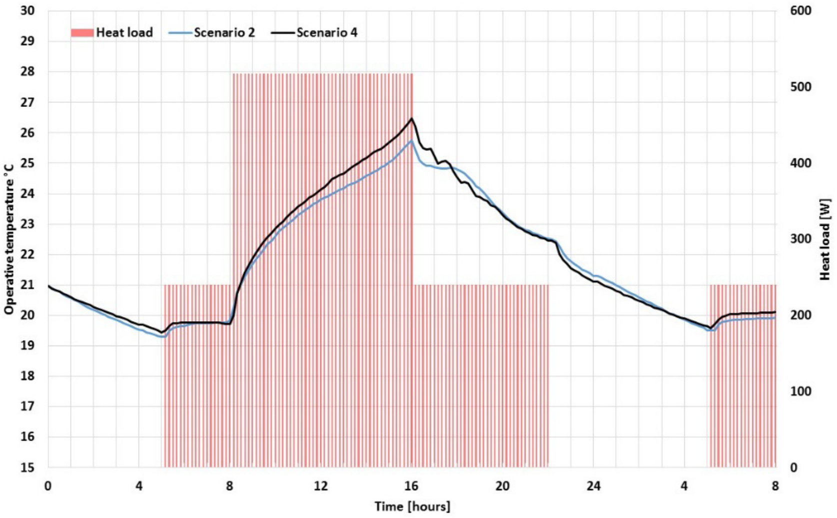

Fig. 5: Operative temperature of the test room at 0.6 m above floor level together with heat load, scenario 2 and 4.

3.4. Surface temperatures of PCM

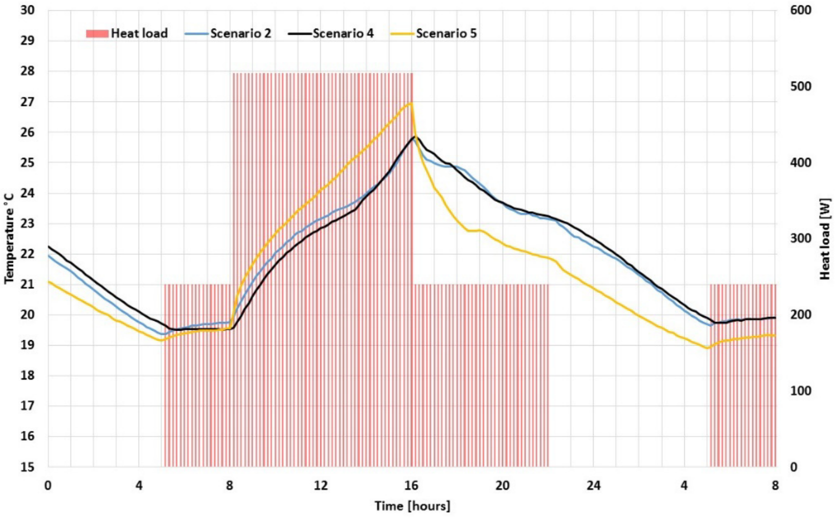

Fig. 6. Surface temperatures of PCM in ceiling in scenario 2, 4 and 5 together with heat load.

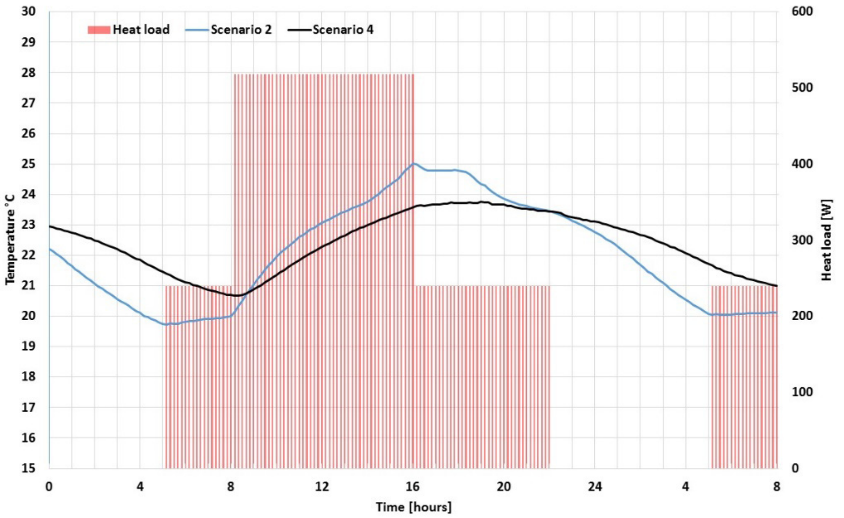

Fig. 7. Surface temperatures of PCM in wall in scenario 2 and 4 together with heat load.

The surface temperatures of the PCM in the suspended ceiling are shown in Fig. 6, while the surface temperature of the PCM in the wall is shown in Fig. 7. It was observed that the cooling potential of the PCM is not fully utilized in all the cases. The minimum surface temperature of the PCM during night varies between 19.1 ˚C and 20.7 ˚C. Considering the thermal resistance of the packing material of the PCM, one can conclude that the PCM temperature was above its solidification point. This, in fact, reduces the cooling potential of the PCM during the next working day. Therefore, the ventilation rate outside working hours should be increased further to reach the solidification point.

On the other side, the maximum surface temperature of the PCM is far beyond melting point during working hours, ensuring that the PCM will melt and absorb the excess heat in the test room. In this regard, a PCM with slightly higher melting and solidification point could perform better.

In Scenario 4, both the peak surface temperature of the PCM in the wall during daytime and the minimum temperature during night, are delayed with several hours compared with the temperatures measured in the test room. Thus, it seems clear that there should be openings for air circulation between the test room and the void for the PCM behind the gypsum boards.

3.5. Limitations in the ventilation system

As the ventilation system does not have a cooling element, the temperature of the supplied air depends on the outdoor air temperature. As shown in Fig. 8 the temperature of the supplied air varied during daytime, particularly between 12:00 and 16:00 o'clock. The worst deviation occurred in Scenario 1 when the supply air temperature reached 24˚C at the end of the working hours. The impact of the variation in supply air temperature on the operative temperature (T_{op}) has been roughly analyzed by a 24 hours simulation of the test room in Simien from 24:00 to 24:00 o'clock. Thus, the measured supply air temperature was entered into Simien as the average during working hours (8:00-16:00 o'clock) and as the average outside working hours (16:00-22:00 o'clock). The operative temperature with the desired supply air temperature (16˚C) was also simulated. The results from this analysis at the T_{op} peak time (16:00 o'clock) is presented in Table 3.

Although the correction of the operative temperature due to the supply air temperature is significant, it does not alter the conclusions of this work. The difference in peak operative temperature (at 16:00 o'clock) changes from 3.3˚C to 2.2˚C between Scenario 1 and 2, from 1.0˚C to 1.2˚C between Scenario 3 and 4, from 0.3˚C to 0.4˚C between Scenario 3 and 5, and from 0.7˚C to 0.5˚C between Scenario 2 and 4.

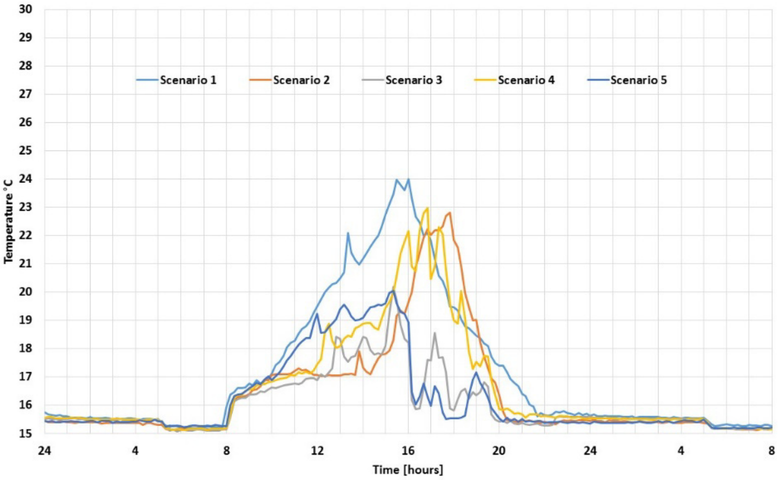

Fig. 8. Supply air temperature.

Table 3: Correction of operative temperature (T_{op}) at peak time (16:00 o'clock) together with calculated T_{op} (from measurements) and measured supply air temperature (T_{sup})

Parameter	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Measured T_{sup} average 8:00-16:00 [˚C]	19.7	17.3	17.3	18.0	18.3
Measured T_{sup} average 16:00-8:00 [˚C]	16.7	16.6	15.7	16.5	15.6
Difference in T_{op} from simulations [˚C]	1.7	0.6	0.6	0.8	0.7
Calculated T_{op} (from measurements) [˚C]	29.1	25.8	27.5	26.5	27.2
Corrected T_{op} [˚C]	27.4	25.2	26.9	25.7	26.5

4. Conclusion

Experimental investigation has been made for a 15 m^2 test room representing a south facing office cubicle with and without Bio-PCM integrated on a hot summer day in Oslo climate. The results showed that a significant passive cooling effect can be achieved by utilizing 17 m^2 of PCM. The most significant effect was achieved when the PCM was uncovered and directly exposed to the occupied zone. This could, to a certain extent, help avoid the need to install a local mechanical cooling system and thus save costs for installation, energy use and maintenance. However, further investigation should be made on the aesthetic appearance and the acoustic performance of the PCM used as an uncovered suspended ceiling. A moderate temperature drop was also observed when the PCM was covered with aluminium ceiling plates and gypsum wallboards.

4.1. Further work

As the surface temperature of the PCM does not reach the solidification point during night (cooling period), further studies with more ventilation air during night hours should be performed. A PCM with slightly higher melting and solidification point could also be considered for new tests.

It is obvious that the void for the PCM inside the wall should have been ventilated towards the room in order to increase the performance of the PCM during working hours and to reject the absorbed heat from the PCM during night. Therefore, new measurements with openings towards the room in the bottom and the top of the wall should be performed.

It could also be interesting to investigate the possibility of using exposed PCM in a suspended ceiling. Some challenges related to this would be to achieve satisfactory aesthetic and acoustic conditions in the room.

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References

[1] Memon, S.A. Phase change materials integrated in building walls: A state of the art review. Renewable and Sustainable Energy Reviews. 2014. 31. p. 870-906.
[2] Tyagi, V.V., et al. Development of phase change materials based microencapsulated technology for buildings: A review. Renewable and Sustainable Energy Reviews. 2011. 15. p. 1373-1391.
[3] Agyenim, F., et al. A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS). Renewable and Sustainable Energy Reviews. 2010. 14. p. 615-628.
[4] Tyagi, V.V. and Buddhi, D. PCM thermal storage in buildings: A state of art. Renewable and Sustainable Energy Reviews. 2007. 11. p. 1146-1166.
[5] Kuznik, F., Virgone, J., and Johannes, K. In-situ study of thermal comfort enhancement in a renovated building equipped with phase change material wallboard. Renewable Energy. 2011. 36. p. 1458-1462.
[6] Liu, H. and Awbi, H.B. Performance of phase change material boards under natural convection. Building and Environment. 2009. 44. p. 1788-1793.
[7] Cabeza, L.F., et al. Use of microencapsulated PCM in concrete walls for energy savings. Energy and Buildings. 2007. 39. p. 113-119.
[8] Koschenz, M. and Lehmann, B. Development of a thermally activated ceiling panel with PCM for application in lightweight and retrofitted buildings. Energy and Buildings. 2004. 36. p. 567-578.
[9] Madessa, H.B. A Review of the Performance of Buildings Integrated with Phase Change Material: Opportunities for Application in Cold Climate. Energy Procedia. 2014. 62. p. 318-332.
[10] Soares, N., et al. Review of passive PCM latent heat thermal energy storage systems towards buildings'energy efficiency. Energy and Buildings. 2013. 59. p. 82-103.
[11] Phasechange Energy Solutions Inc. 2016.07.10. Available from: www.phasechange.com/.
[12] Kosny, J., et al. Dynamic thermal performance analysis of fiber insulations containing bio-based phase change materials (PCMs). Energy and Buildings. 2012. 52. p. 122-131.
[13] Programbyggerne. 2016.07.10. Available from: www.programbyggerne.no/.
[14] Direktoratet for byggkvalitet. Regulations on technical requirements for building works (TEK10). 2010.
[15] Energy Management & Storage Solutions. 2016.07.10. Available from: www.pcmeurope.com/.
[16] Standard Norge. Ergonomics of the thermal environment - Instruments for measuring physical quantities. NS-EN ISO 7726:2001.