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EVALUATION OF THERMAL AND MECHANICAL PROPERTIES OF DEMONSTRATION WALL UTILIZING PHASE CHANGE CEMENTITIOUS MATERIALS

Jan Červenka[a,*], Michaela Herzfeldt[a], Antonio Caggiano[b], Eduardus Koenders[b]

[a] *Červenka Consulting s.r.o., Na Hřebenkách 55, 150 00 Prague 5, Czech Republic*
[b] *Technische Universität Darmstadt, Franziska-Braun-Straße 3, 642 87 Darmstadt, Germany*
[*] corresponding author: `jan.cervenka@cervenka.cz`

Abstract. International project PoroPCM involves partners from Germany, Czech Republic, Spain and Japan with the objective to develop new multifunctional Phase Change Materials modified porous cementitious nanocomposite (PoroPCM). Such material can be utilized for storing heat energy in the insulation layer of buildings compared to commonly used insulation materials since the phase change increases heat capacity. This enhanced feature reduces the amount of energy necessary for running the heating/cooling system. For the testing of the newly developed phase change cementitious composite a demonstration wall will be developed and tested for its thermal as well as mechanical performance. The topic of the paper is the description of the properties of the new phase change cementitious nanocomposite. The main emphasis of the paper is the description of the demonstration wall behaviour under typical environmental conditions. The wall design is supported by numerical simulation of the wall physical parameters. The numerical modelling involves the definition of suitable numerical models for the simulation of the thermal properties of the new phase change nanocomposite. The numerical model is then used to demonstrate the performance of the wall layer design. The presented pilot results show efficiency increase of the insulation material in the range 15–70 %. Also modelling of wind resistance of the layered structure is included. The developed wall design and PoroPCM material will be tested and verified by a large scale test in the final year of the project.

Keywords: Phase change material, cementitious nanocomposite, insulation performance, thermal analysis.

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1. Introduction

The energy demand for heating and cooling of the global building stock represents a massive part of the total energy consumption around the world (≈ 40 %). In the EU, it accounts for about half its energy consumption [1]. To attenuate demand, thermal insulation of construction and building elements, like walls, roofs and floors, has become the most important measure to enhance energy savings of the new and existing building stock.

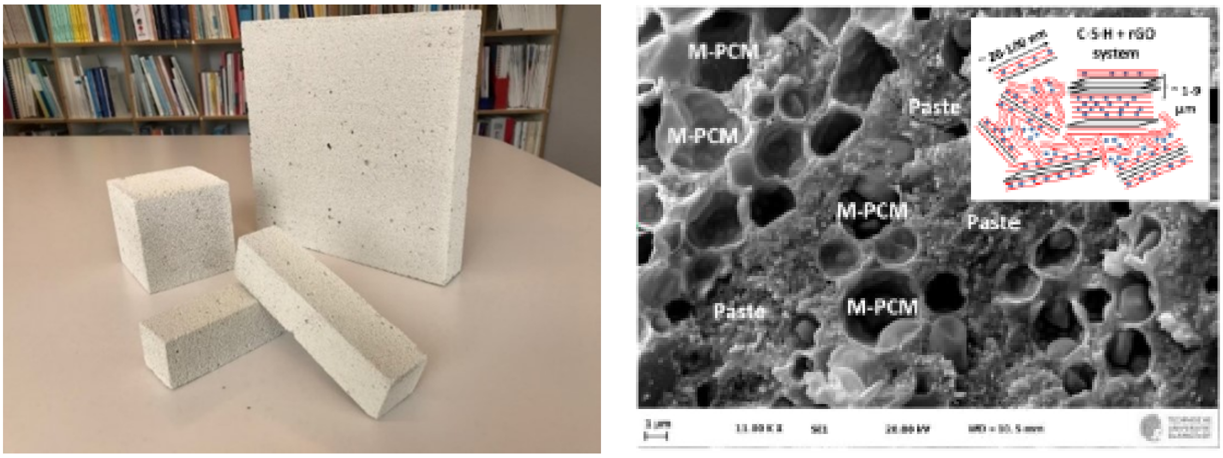
In order to comply with the European targets on energy savings, the German federal government will merge the rules that currently apply in parallel:

(i) the Energy Saving Act (EnEG),
(ii) the Energy Saving Regulation (EnEV), and
(iii) the Renewable Energy Heat Act (EEWärmeG),

into a new Building Energy Act (GEG) [2]. These stricter regulations have led to extreme thicknesses (even up to 40 cm) of the standard insulation layers, mostly attached to the outer surface of the building envelope.

Possible innovative solutions could include the potential of materials to embody large amounts of thermal energy, which would stabilize the inner thermal comfort and leads to a strong reduction of the insulation thickness, like a thin layer [3]. A maximization of the synergetic interplay between thermal conductivity and the potential to store/release large amounts of solar and environmental heating/cooling energy into components of the building envelope can be achieved by an effective use of Phase Change Materials (PCMs), which minimizes the additional need of primary energy for heating/cooling [4, 5].

Nowadays, numerous articles on PCMs have been reported in literature, in several fields of applications, and most of them of scientific nature. The experimental-based research is predominantly addressing the thermo-hydro-chemo-mechanical properties of cementitious materials with PCMs [6–8]. In those works, the investigated PCMs are characterized by a melting temperature that varies between 19 °C and 26 °C, which corresponds to a standard temperature range for comfortable living [9]. According to their chemical compositions, PCMs can be categorized as Organic- (O) (paraffin and non-paraffin), Inorganic (I) compounds (salt hydrate and metallic) and eutectics (O-O, I-I, I-O) [10]. PCMs can also be identified by their mode of phase transition: liquid-gas, solid-gas, solid-liquid and solid-solid. Solid-liquid is the pre-



(A). Samples of the PoroPCM material.

(B). Structure in the electronic microscope.

FIGURE 1. PoroPCM material samples and detail of the structure.

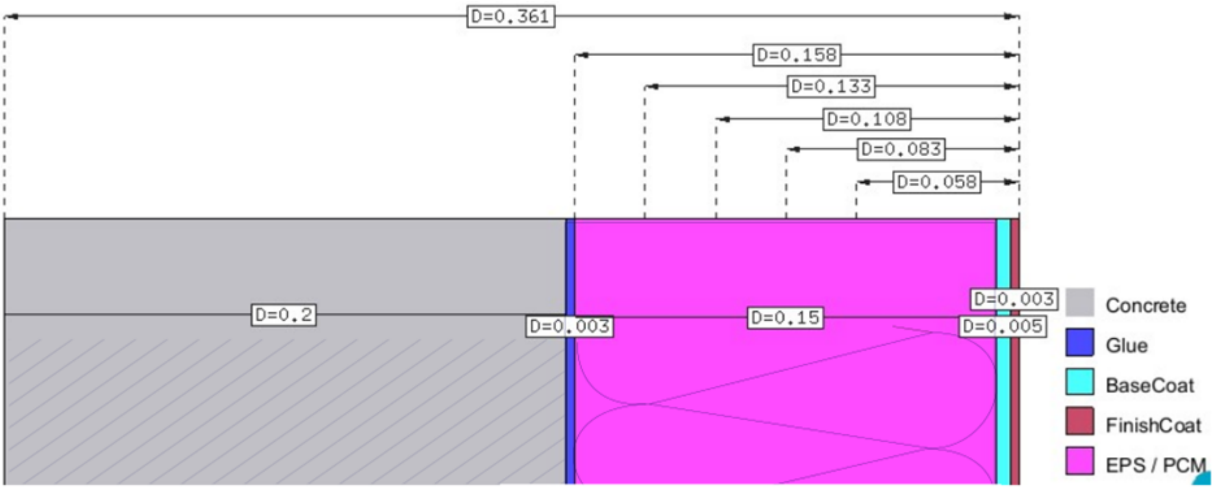


FIGURE 2. Individual layers of demonstration wall with the locations of temperature monitoring points (dimensions in meters).

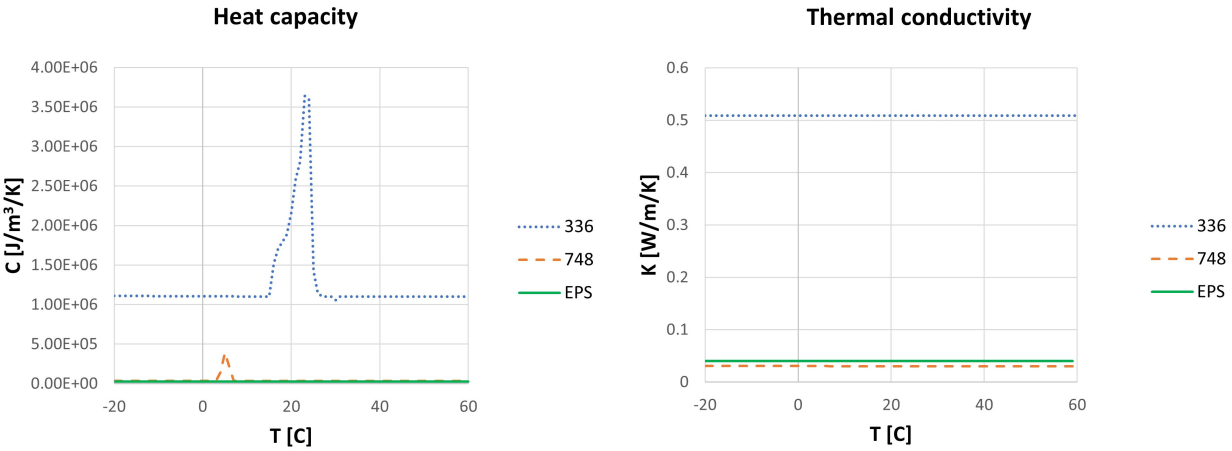
ferred mode for building applications with Thermal Energy Storage (TES) [11].

The PoroPCM system is proposing a highly innovative insulation system for energy savings of new and/or existing buildings. It is made of ultra-light porous cementitious foam blended with PCM, see Figure 1. It is sustainable, non-flammable and fully recyclable. The major difference, with the current practice, is that the proposed insulation system combines the benefits of a minimum thermal conductivity (λ-value [12–14]) with the capability to embody large amounts of thermal energy that will stabilize the inner climate of buildings. By doing this, a very thin insulation layer can be achieved having similar thermal insulation properties as a regular layer, made of EPS, XPS, or similar. This innovative system has an extremely low CO_2 footprint, a very low raw materials use, is non-toxics, acoustic absorbing, dimensionally stable, and not affecting the indoor air quality [15, 16].

2. PHASE CHANGE CEMENTITIOUS MATERIAL

Since the development of porous PCM insulator is basically new concept the simulation of insulation performance is a useful tool for developing a suitable wall design.

The investigated wall design represents typical system with heavyweight load-bearing part of the wall made of reinforced concrete (Figure 2). In a preliminary study, mainly numerical tests of the insulation performance have been carried out on lightweight and heavyweight structures in different locations all over the world. More details on this initial study are available in [17]. Those preliminary results helped to distinguish different porous PCM materials and optimal performance at different conditions. The condition that varied were mainly location, internal air-conditioning, heavy or lightweight system and heating or cooling season or the combination throughout whole year. Based on the result of this internal study the porous PCM materials with specific thermal properties have been



(A). Heat capacity of materials 748, 336 and EPS.

(B). Thermal conductivity of materials 748, 336 and EPS.

FIGURE 3. Thermal properties of studied materials.

Material	Melting point [°C]	Heat storage capacity [J/g]	Liquid density [g/ml]
RT24	24	160	0.77
PT4	5	187	0.88

TABLE 1. Pure PCM thermal properties.

chosen. For the analyses presented in this paper, the two materials with large differences in their thermal properties have been chosen, specifically, materials with ids 336 and 748. These materials are part of numerically conceived database developed by CIMEC containing two types of PCM, PureTemp® (PT) and Rubitherm® (RT). The id 336 refers to material with zero porosity containing air but 40 % of microencapsulated PCM fraction in cement paste (RT24). Contrary to that, the id 748 describes very porous material with porosity 96.6 % and 40 % of microencapsulated PCM fraction (PT4), see Table 1.

In contrast to the usual structural materials that have constant thermal properties, in the new porous PCM materials the thermal properties vary with the temperature.

In the following calculations, the porous PCM materials are going to be compared to standard expanded polystyrene (EPS) insulation material. The time dependent thermal properties of PCM materials are depicted in Figure 3.

Regarding the mechanical testing of PoroPCM, preliminary tests have been carried out using cube samples of size 10 × 10 × 10 cm. The initial portion of PCM within cementitious foam samples is 20 % of volume. Bulk density of samples is 200 kg/m^3 and the testing shows compressive strength of samples of about 0.2 MPa.

3. Demonstration wall description

The demonstration wall design used for the initial study of the PCM material performance is shown in Figure 2. The wall composition is formed with five layers, namely concrete (200 mm), glue (3 mm), insulation (150 mm), base coat (5 mm) and finish coat (3 mm) (as it goes from inside to outside). The thickness and thermal properties of separate layers are described in Table 2 and in Figure 2.

4. Numerical modelling – thermal analysis

In the numerical modelling with ATENA software [18], the heat transport in the wall structure as shown in Figure 2 is simulated considering too scenarios of cold and warm conditions. For the cold case, the outside temperature is assumed to cycle between -5 to -11 °C. The temperature in the interior cycles between 18 to 21 °C. The heat convection coefficient for the interior surface was assumed at 7.7 W/(C m^2). For the exterior surface thermal and energy flux condition was assumed as described in Figure 4. The heat convection coefficients for the exterior surface were assumed at 20 W/(C m^2).

The results for the simulation of up to 10 temperature cycles starting from initial constant temperature of 20 °C are shown in the subsequent figures. Figure 5 shows the results for the case of cold boundary conditions. The first set of graphs at Figure 5 show the comparison of temperature evolution at various distances from the exterior surface for EPS and PCM material. Figure 6a compares the evolution of thermal flux at the interior surface, which corresponds to the energy (heating) input necessary to keep the optimal interior temperature of 18–21 °C. The similar comparison is provided at Figure 6b for the case of warm boundary conditions.

Material	**Thickness [mm]**	**Specific heat [MJ/m^3/K]**	**Thermal conductivity [W/m/K]**
Reinforced concrete	200	2.55	2.1
Glue	3	2.55	0.7
Insulation	150	varies	varies
Base coat	5	2.55	0.7
Finish coat	3	2.55	0.7

Table 2. Wall composition materials and their properties.

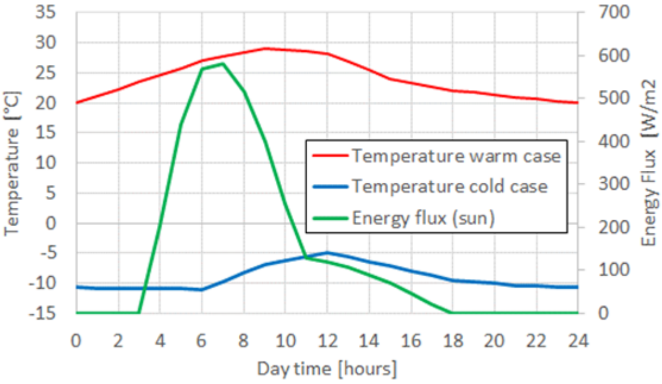
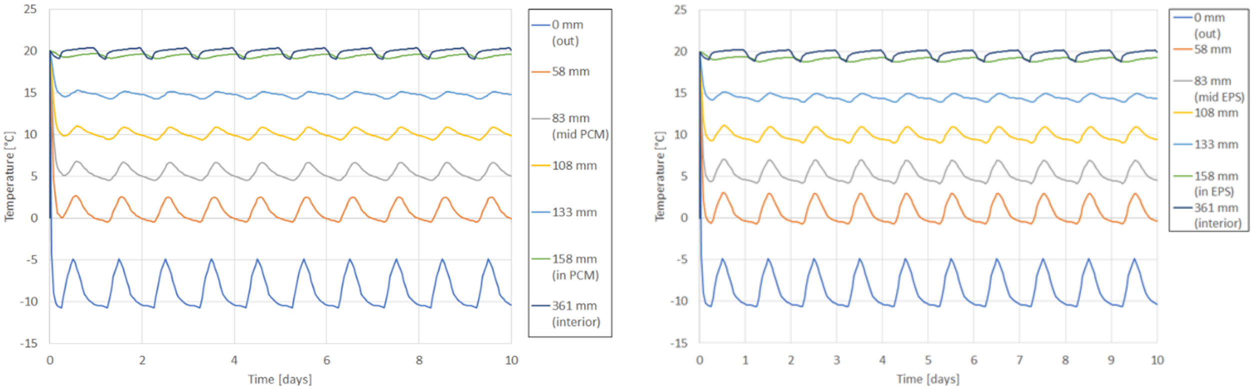
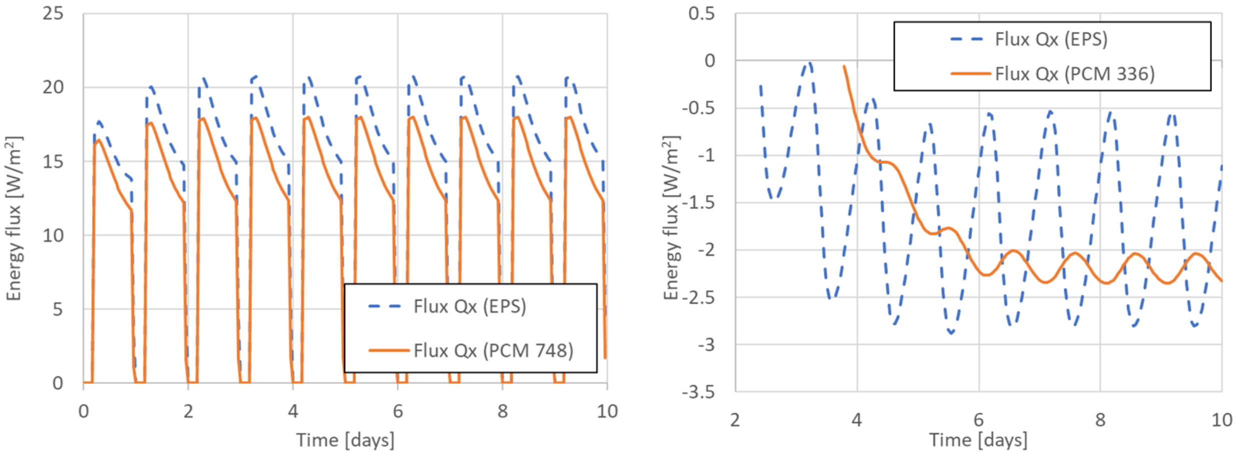


Figure 4. Boundary conditions on the exterior wall surface.



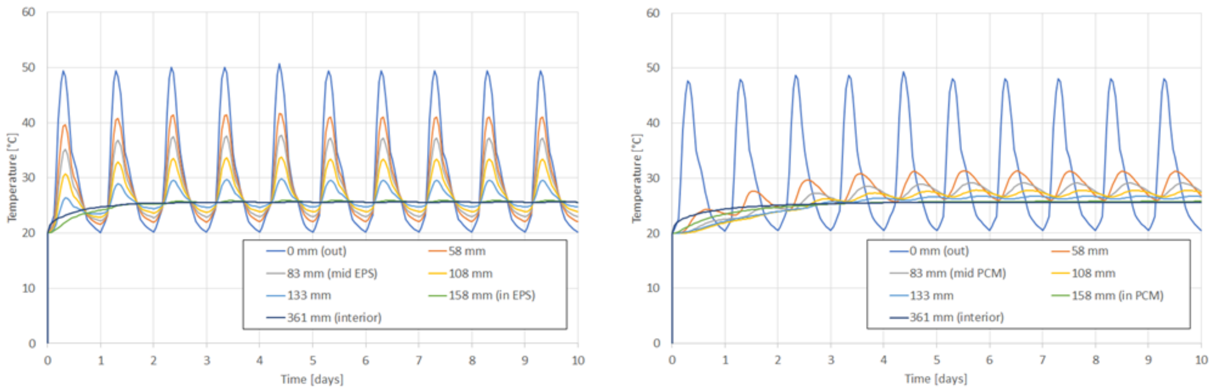
(A). (B).

Figure 5. Temperature evolution for EPS (A) and PCM-748 (B) insulation at various distances (see Figure 2) from outer surface for the heating case with the cold conditions.



(A). (B).

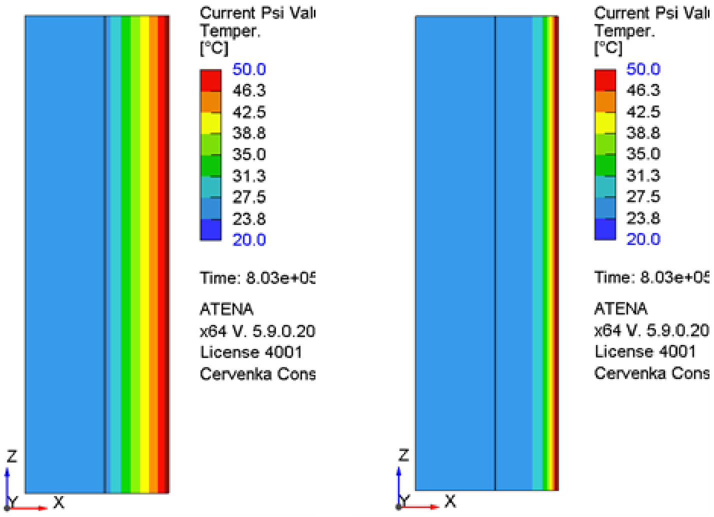
Figure 6. Comparison of energy flux on the interior heated surface for EPS and PCM-748 material for the cold case with heating and PCM-336 material for the warm case with cooling.



(A).

(B).

Figure 7. Temperature evolution for EPS (A) and PCM-336 (B) insulation at various distances from outer surface for the warm case with cooling.



(A).

(B).

Figure 8. Comparison of temperature distribution at peak outer surface temperature for EPS (A) and PCM-336 (B) material for the warm condition case with cooling during day 9 of simulation (9.29 days = 80300 s).

The comparison of cold temperature evolution (Figure 5) does not show significant differences for the two materials. The differences are more pronounced if the energy input (flux) at the interior wall is compared in Figure 6a, which clearly shows approx. 15 % lower thermal energy input for the case of PCM material.

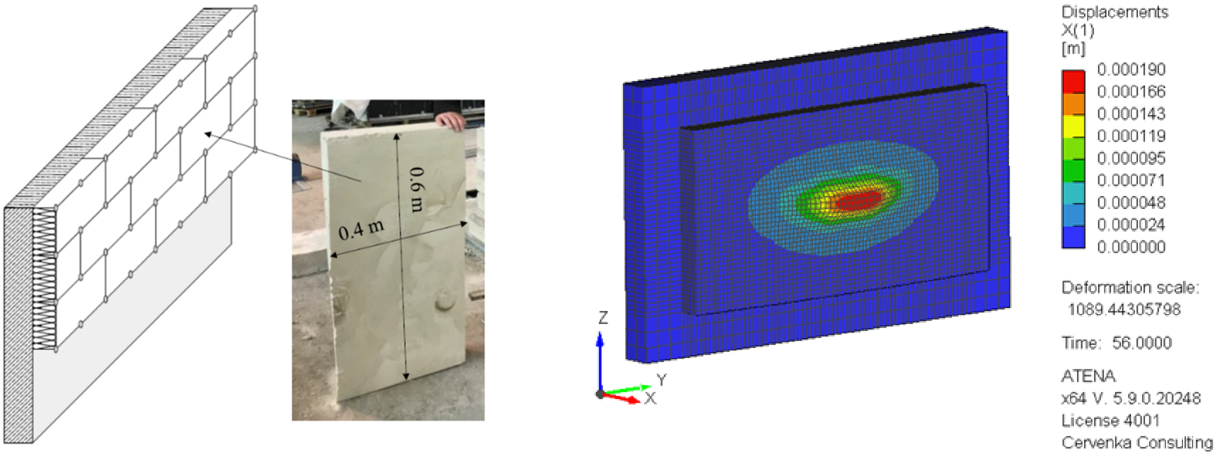
Similar results can be observed also for the case of warm boundary conditions. In this case significant differences are observed also in the graphs of temperature evolution at various distances in Figure 7b. It is possible to observe stronger inertia in the temperature evolution for the PCM material, while large temperature oscillations appear for the standard EPS material. This higher thermal inertia can be also observed in the graph of thermal flux at the interior surface namely at the first 2–4 days of the thermal cycles. It shows that in the case of PCM material it is necessary to activate cooling system after almost 4 days of warm temperatures, while in the case of EPS material the cooling needs to be activated already after two days.

This difference in thermal behaviour is also well documented in Figure 8, which compares the temperature profiles through the wall thickness at the peak exterior temperature. It clearly shows the better insulation behaviour of the PCM material.

5. Numerical modelling – wind resistance

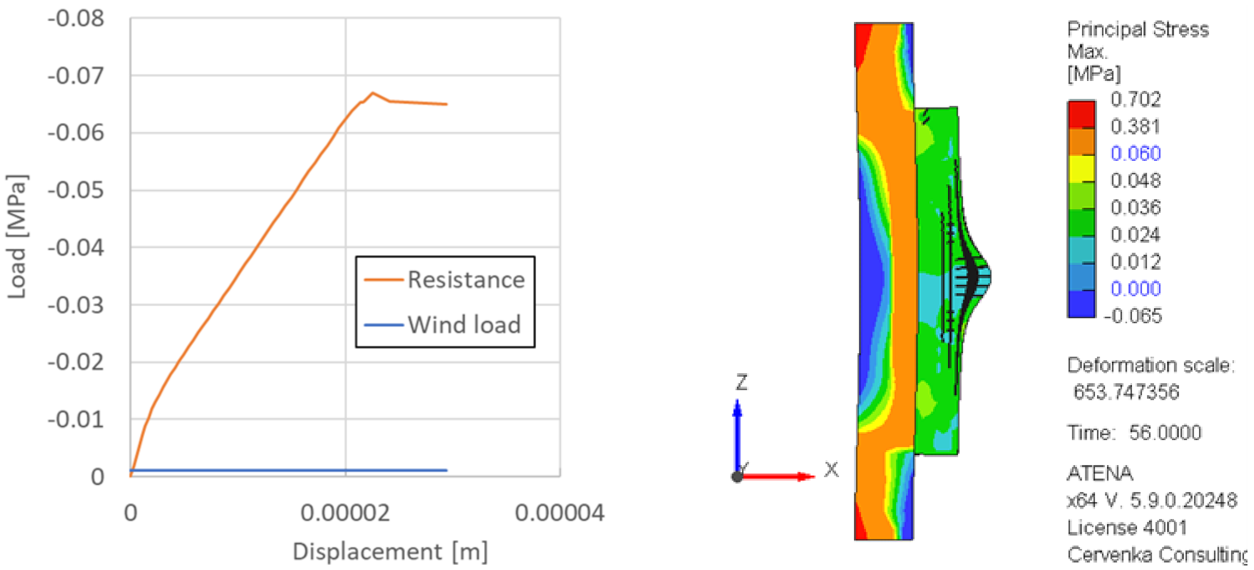
The demonstration wall is also tested on mechanical performance under the wind suction load. Due to the selected location (Sofia, Bulgaria), where future real case experiments are planned, the extreme wind suction is assumed as 1.01 kPa.

The demonstration wall is considered with mechanical anchors that are located between PoroPCM insulation boards within joints as depicted in Figure 9. There are three mechanisms that prevent the failure of the structure under wind load conditions: steel anchors, glue between reinforced concrete and PoroPCM boards and the PoroPCM material integrity. The anchor pull-out strength is assumed 1 kN and the glue



(a). Distribution of anchors. (b). Deformed structure showing displacement in the wind load direction.

Figure 9. Wall structure with attached insulation tested for wind load.



(a). Maximal principal stress with crack pattern. (b). The displacement in the wind suction direction.

Figure 10. Structure response to wind load.

tensile strength is assumed 0.3 MPa. The PoroPCM compressive strength was determined by first pilot experiments to be about 0.2 MPa, the tensile strength is assumed as tenth of the compressive strength which results in rather low value of tensile strength 0.02 MPa.

The simulation shows the failure of PCM material integrity under the wind load. The design wind load (1.01 kPa) is exceeded more than 65 times by the resistance of the wall (65.7 kPa), as shown in Figure 10.

6. Conclusions

The paper presents the first results from the international project PoroPCM (`https://poropcm.eu/`). In this project the first mix designs of optimized porous PCM materials were developed for various climatic conditions. The paper describes in more detail the thermal performance of two selected materials suitable for European conditions. The performance of the two selected materials suitable for warm and cold climates demonstrated in mainly cooling and heating conditions. These pilot results show about 15 % savings in heating energy for the cold conditions. Very good performance is observed in the warm/cooling case. The time when cooling needs to be activated when warm weather arrives is extended by about 70 % compared to standard EPS material. The performance of the PCM material is especially superior to EPS when hot periods are alternating with cooler ones or hot days with cooler nights. If hot periods extent over more than 6 days, the advantage of the PCM material is not so pronounced. Also the wind resistance of demonstration wall is tested to prove that the resistance for wind load exceeds at least 65 times the expected wind loads.

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