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Proceeding Paper

Development of High Added Value Products from Industrial Minerals for Hybrid Energy Storage †

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Abstract: Industrial minerals are at the forefront of innovation and play an essential role in many innovative applications. Their functionalities and properties make them very versatile materials which are essential to many industries. A combination of properties such as heat capacity, density, price, availability, and eco-friendliness are exceptional and crucially advantageous of industrial minerals utilisation as thermal energy storage (TES) systems. This technology stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. In this context, the utilisation of industrial minerals as carriers for impregnating phase change materials (PCM) can deliver new innovative products acting as short-term energy storage systems for construction applications to the market. TES is a technology that can solve the existing mismatch of energy supply and demand and improve buildings' system performance by smoothing temperature fluctuations, as well as improving the reliability of the heating and/or cooling source. However, the most recent publications in this area are focused on PCM-enhanced building components thermal and kinetics analysis rather than focusing on the building component scale. This study is focused on the industrial minerals-PCM application as part of the building's envelope, aiming to determine the benefits for buildings in terms of thermal energy performance and renewable energy penetration based on real data, harvested by an intelligent monitored building in Lavrion Technological and Cultural Park operated solely for research activities.

Keywords: thermal energy storage; energy efficiency; industrial minerals applications

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1. Introduction

Energy and fuel crisis together with environmental pollution due to the significant waste generation poses major constraints to sustainable development. The sector of industrial minerals takes initiative in researching high added-value products to meet the demands of society and the European Union targets for increasing their penetration in the market. In this framework, new products from industrial materials are being engineered daily and their utilisation changes respectively. Industrial minerals are characterised by properties such as (i) high heat capacity, (ii) abundant availability, (iii) no flammability and (iv) eco-friendliness, which are exceptional and crucially advantageous in TES applications. Specifically, latent heat TES (LHTES) stock thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation [1].

According to recent studies, industrial minerals depict a great potential for being used also in LHTES applications in conjunction to buildings construction materials and with the incorporation of PCM into these materials for the overall building thermal performance [2–5]. Specifically, impregnating suitable PCMs into industrial materials and applying them on the building envelope (i.e., walls) has been researched for the last decades to reduce fluctuations of the interior temperature, improve human comfort, and offer energy savings for the building [4,6]. The LHTES stores thermal energy obtained by heating or cooling a storage medium in order to use the stored energy at a later time for heating and cooling applications. In this context, the development of a mortar able to store thermal energy by substituting industrial minerals with varying amounts of PCM composite deems prospects for improving building's thermal performance and provides potential for renewable energy sources (RES) penetration increase compared with ordinary cement mortars as it increases the TES capacity of the building elements.

The main objective of this study is to investigate the potential of using industrial minerals-PCM as fillers in mortars of the building's envelop in terms of thermal energy performance and RES penetration for buildings. The analysis is performed in a simulation environment (i.e., EnergyPlus, MATLAB) using calibrated models, based on real data harvested by an intelligent monitored building in Lavrion Technological and Cultural Park (LTCP) operated solely for research activities.

1.1. Thermal Mass in Buildings

Thermal mass depicts the ability of a medium to absorb, store, and release thermal energy. In view of building design, it comprises buildings' elements, such as the building's walls, roof and ceiling, and floor, and provides a quantification of how the building's "inertia" against indoor temperature fluctuations [7]. It is evident that the thermal mass of a building affects the thermal balance between internal and external conditions and can even-out and delay extremes in thermal conditions by absorbing heat as temperatures rise and releasing it as they fall. This function stabilises the internal environment and provides thermal comfort to the occupants. In parallel, this characteristic contributes in reducing the electric demand for heating and cooling services systems [8], especially when operating in conjunction with RES systems. The concept of exploiting buildings thermal mass for increasing RES penetration is investigated thoroughly and the great potential to maximise the RES penetration is demonstrated [9,10]. Thus, the selection of materials for enhancing the thermal mass is believed of high importance.

1.2. Materials for TES

The application of PCMs is advocated as advantageous, especially for extremely hot and cold climates, which significantly affect both the interior temperature and the energy consumption of the building. The PCMs considered suitable for building applications are mainly those with phase transformation from solid to liquid. The solid-liquid PCMs provide an exceptional storage capacity within narrow variations of the temperature as well as negligible volume changes resulting in large buildings' energy savings. The effectiveness of PCM based LHTES applications in buildings highly depends on the selection of the proper incorporation method. There are several ways for incorporating PCMs in construction materials including (i) direct incorporation, (ii) immersion, (iii) encapsulation, (iv) shape stabilization, or (v) form-stable composite PCMs [11]. The majority of the methods present application obstacles associated with PCM leakage, heat transfer performance, and volume changes during the phase change process as well as adverse effects on the physical and mechanical properties of the building materials/components, which led to limited use of them in buildings [12].

Industrial minerals (i.e., silica-based material, perlite, diatomite) are considered suitable for the development of a form-stable PCM and can be used as supporting materials due to their highly porous structure and very high surface area. In this case, the composite can be fabricated by impregnating PCM into porous supporting materials through either natural immersion or vacuum impregnation [4]. Natural immersion is performed by mixing the porous supporting material directly with the melted PCM at atmospheric pressure conditions in order to for the PCM to be absorbed naturally. Furthermore, the vacuum impregnation method is performed by impregnating the liquid PCM into the porous carrier under very low-pressure conditions in order to evacuate the air and moisture and enable a larger absorption the PCM [13]. Hence, this study aims to investigate the potential of incorporating PCMs into industrial minerals to develop LHTES for building renovation applications and determine the benefits for buildings in terms of thermal energy performance and RES penetration.

1.3. Applications of Incorporating PCM into Industrial Minerals

Incorporating PCMs with industrial minerals as carriers into buildings (i.e., walls, slabs, ceilings etc.) has been researched extensively for the last decades in order to reduce fluctuations of the interior temperature, improve human comfort, and offer energy savings [4,6,14–16].

According to Zhang, et al. [14], a form stable polyethylene glycol/expanded perlite/carbon (PEPC) composite was obtained. The PEPC was fabricated by vacuum impregnation into the expanded perlite/carbon (EPC) and 70.14 wt.% and 66.38 wt.% polyethylene glycol (PEG) could be retained in EP and EPC without leakage, respectively. The analysis indicated that the melting latent heat was 134.93 J/g and the melting temperature was 55.19 °C, while during freezing the values were 129.27 J/g and 46.71 °C, respectively. In addition, the thermal conductivity of PEPC composite was 0.479 W/(mK), being 2.975 times that of PEP composite. Therefore, the PEPC depicted enhanced thermal properties including ideal thermal conductivity, good thermal reliability and chemical stability, which indicate PEPC to be a promising candidate for buildings TES applications.

Another study from Lv et al. [16] tried to employ Octadecanol (OC) to compound with EP. OC/EP composites were prepared via vacuum impregnation. It was observed that the leakage phenomena were weakened by adding expanded graphite with mass fractions of 5%, 10% and 15%. The results indicated a latent heat capacity of 60% OC/EP/15EG to be 140.2 kJ/kg, and phase transition temperature to 59.0 °C. The thermal performance was evaluated and the efficiency of heat storage and release was improved significantly. To conclude, incorporating PCMs into industrial minerals is still in research level, however the findings show promising results for developing hybrid composites suitable for building LHTES applications.

2. Form-Stable Industrial Mineral-PCM Mortar

2.1. Selection of Industrial Mineral

Industrial minerals comprise materials such as Bentonite, Diatomite, Graphite, Gypsum and Anhydrite, Kaolin, Magnesite, and Perlite [2,17]. In particular, expanded perlite (EP) has been investigated extensively as the supporting material because of its advantageous properties for the fabrication of form-stable PCM composites and TES cementitious mortars. EP is a glassy amorphous volcanic rock that offers high porosity and a morphology suitable for impregnating PCM into its porous, while it provides numerous advantages including (i) excellent thermal insulation, (ii) very low density, (iii) very little impact on the environment, (iv) non-toxic, (v) non-flammable, (vi) chemical resistant, and (vii) abundant availability.

2.2. Selection of PCM

There are plenty PCM candidates which offer potential for being applied in LTES systems in buildings. In this regard, the selection of the most appropriate PCM for any given application can be obtained by taking into consideration the properties of the materials. It is worth mentioning that only PCMs with a phase transition close to human comfort temperature (20–28 °C) are suitable. In Table 1 some commercial PCMs with melting temperature suitable for building applications are presented [18]. In the present study, the PCM used is the commercial grade paraffin RT21 from RubithermÒ, consisting of saturated hydrocarbons.

Table 1. Properties of typical commercial PCMs [18–20].

Name	Type	Melting Temperature [°C]	Heat of Fusion [kJ/kg]
Astorstat HA17	Paraffin and Waxes	21.7–22.8	-
RT21	Paraffin	20–23	190
RT26	Paraffin	24–26	232
Climsel C23	Salt Hydrate	23	148
E23	Plus ICE (Mixture of Non-Toxic Eutectic Solution)	23	155

2.3. Form-Stable Industrial Mineral-PCM Composite

The development of form-stable composites by impregnating paraffins into EP shows that not only the thermal but also the mechanical properties, such as the compressive strength are increased when compared to EP-based mortars. It is evident that the combination of EP with paraffin results in a composite with outstanding properties because of the low surface tension of paraffin and good adhesion between expanded perlite and paraffin. As it is reproduced in Figure 1 by SEM images, the EP is characterised by high porosity, enabling the paraffin to be absorbed and after absorption, only a few failure surfaces of EP-PCM can be observed. For this reason, the impregnation of PCMs into EP has been researched thoroughly as shown in Table 2 which outlines the thermal and mechanical characteristics of paraffin-EP mortars [17].

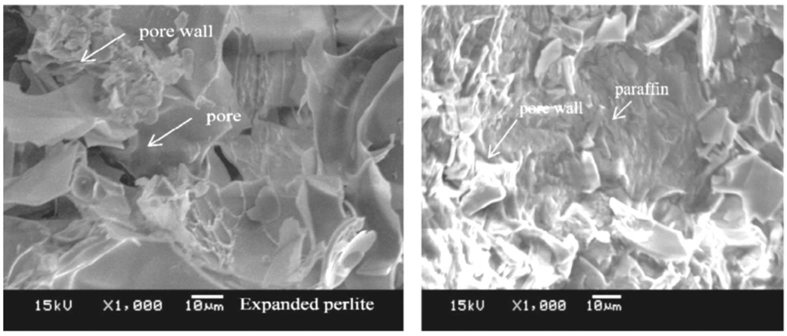


Figure 1. SEM images of expanded perlite (**left**) and paraffin-expanded perlite (**right**) [17].

Table 2. Properties of typical commercial PCMs.

PCM-Mortar	Heat of Fusion of PCM [J/g]	Heat of Fusion of Product [J/g]	Phase Transition Temp. of PCM [°C]	Phase Transition Temp. of Product [°C]	Compressive Strength of Product [MPa]	Ref.
Polyethylene glycol/EP/carbon	Melting-190.1 Freezing-176.4	Melting-134.9 Freezing-129.3	Melting-56.9 Freezing-42.0	Melting-55.3 Freezing-46.7	-	[14]
Paraffin/Hydrophobic EP/cement	Melting-133.3 Freezing-132.1	Melting-12.15 Freezing 12.28	Melting-19.2 Freezing-25.5	Melting-16.3 Freezing-24.6	With 43% PCM-7.53 at 28 days	[19]
Paraffin/EP/clay geopolymer	135.46	96.77 (55.47% PCM)	38.21	35.59 (55.47% PCM)	8.0	[21]
Paraffin/EP/cement	122.05	128.46	46–48, 5–6	19.45 (PCM composite)	9.27–23.88 for 28 days	[22]

For the purpose of this study, the Paraffin/Hydrophobic EP/cement mortar solution is selected. According to Ramakrishnan et al. [19], a novel form-stable PCM was developed by using hydrophobic EP in order to study the possibility of direct application into cementitious composites without the requirement of protective surface layers. The work showed no liquid PCM leakage and was considered suitable to be directly applied in cementitious materials.

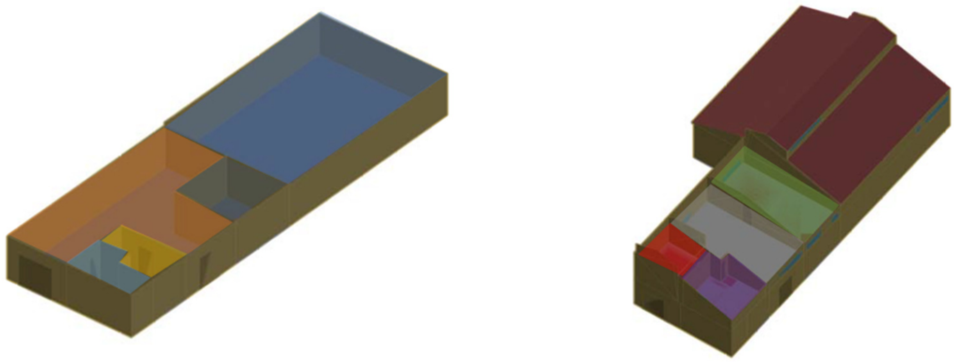
3. Performance Assessment of EP-PCM Mortar

3.1. nZEB Living Lab

For investigating the potential of an EP-PCM mortar as building's LHTES, a nearly Zero Energy Building (nZEB) Living Lab (525 m^2) is selected. nZEB is a two-storey conventional building (133 kWh/m^2 annually electrical consumption), able to harvest energy from RES and cover its demand. Its thermal mass comprises a concrete structure with double brick walls and non-insulated single-glazed windows with aluminium frames. It also has an external masonry consisting of double brick walls with EPS insulation and cement-based plaster on both sides. The building is equipped with an advanced Building Management System that monitors and controls all building's electrical loads and with diverse sensors (temperature/humidity) and facilitates the execution of different scenarios and the extraction of valuable results for sustainable solutions.

3.2. Numerical Investigation

Numerical investigation in simulation environment was performed, which allowed reducing the number of experimental trials and reaching an accurate solution. A model of the nZEB was developed in the EnergyPlus in the framework of the of European research project 'SABINA', capturing the indoor temperature as well as the building's Heating Ventilation and Air Conditioning (HVAC) electric consumption. Figure 2 depicts the thermal zones for the ground floor and the attic of the building. The model was calibrated by using real data (i.e., temperature sensors) resulting in an impressively accurate model with a normalised mean bias error (NMBE) of 1.09%, a coefficient of variation of the root mean square error (CV (RMSE)) of 3.32% and a coefficient of determination R2 of 96.5% for the heating period, while for the cooling period, the NMBE is 0.13%, the CV (RMSE) is 1.27% and the R2 is 89.48%.



(**a**) (**b**)

Figure 2. nZEB model (**a**) ground floor; (**b**) attic floor.

The next step was to readjust the model by adding a 100 mm layer of the proposed EP-PCM mortar on the interior side of the exterior walls (renovated building). The properties of the EP-PCM mortar were obtained by Ramakrishnan et al. [19] Then, two scenarios were tested in MATLAB environment for (i) the building as it is and (ii) for the renovated building. The scenarios ran for 28 days in July 2020 using real weather data from LTCP test site. The temperature set point of the building was set to 22 °C and the HVAC systems operated with a schedule from 06:00 EET to 18:00 EET. The scenarios aim to assess the potential for exploiting the generated RES power from the site by storing it in the EP-PCM mortar as thermal power. This strategy can not only reduce the imported electric consumption used for its heating and cooling demands, but also increase the penetration of the RES. It is worth mentioning that this concept of thermal mass exploitation has been successful in the framework of a European research project.

4. Results and Discussion

The proposed solution is proved to be a promising strategy for using industrial minerals into LHTES applications. It is not only applicable on new but also existing buildings targeting to renovation strategies to improve their energy performance and increase the potential of renewable integration. The scenarios targeted at converting the excess electrical energy to thermal energy and storing it in the thermal mass of the buildings. In terms of buildings energy performance, the properties of the thermal mass were improved including an increase of the thermal capacity and the thermal conductivity as well as the thickness of the walls. As a consequence, the indoor temperature fluctuations of the building were reduced by up to 18.3% when the HVAC equipment was off (night) and the average reduction was about 6.2%, while indoor temperature was quite stable when the HVAC was on (day) (see Figure 3).

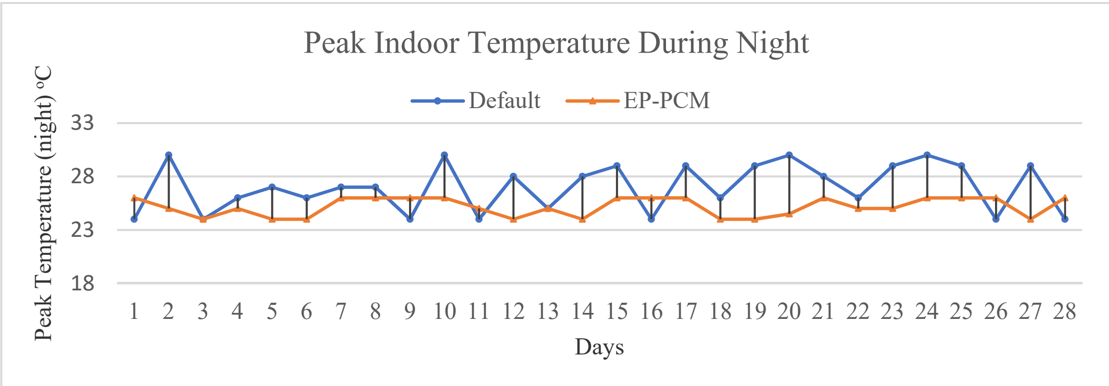


Figure 3. Daily peak indoor temperature of nZEB Living Lab in July 2020.

Regarding the RES exploitation, the proposed strategy achieved to increase the RES penetration during July 2020. Specifically, the utilisation of the generated power during daytime allowed an increase of RES penetration of almost 11.8%. This observation was based on the fact that during periods with excess energy, the HVAC systems were utilised in order to store thermal energy to the walls of the building. Afterwards, when lack of RES energy would occur, the HVAC system would reduce its consumption and enable the thermal energy (i.e., coolth) stored in the walls to be released back to the building.

The nZEB Living Lab is supported by a PV field and six wind turbines and it is also connected to the grid. Therefore, the set-up prioritises the RES generated power to be provided to the building, and if there is no available power, then the building is supported by the grid. In Figure 4, the energy above the *X*-axis represents the imported energy from the grid (consumption > production) and the energy below *X*-axis represents the exported energy (consumption < production). It is observed that in the first case, the building consumption is directly related to the environmental conditions, leading to increased consumption in days with less RES energy production (i.e., Day 8–10) and reduced consumption during days with higher RES energy production (i.e., Day 26–28). On the contrary, the second case utilises a strategy to charge the EP-PCM walls in the beginning of the scenario (i.e., Day 1–4) and then exploits this thermal energy in order to reduce the electric energy imported from the grid. Hence, the average energy imported during the EP-PCM case is considerably reduced compared to the default case.

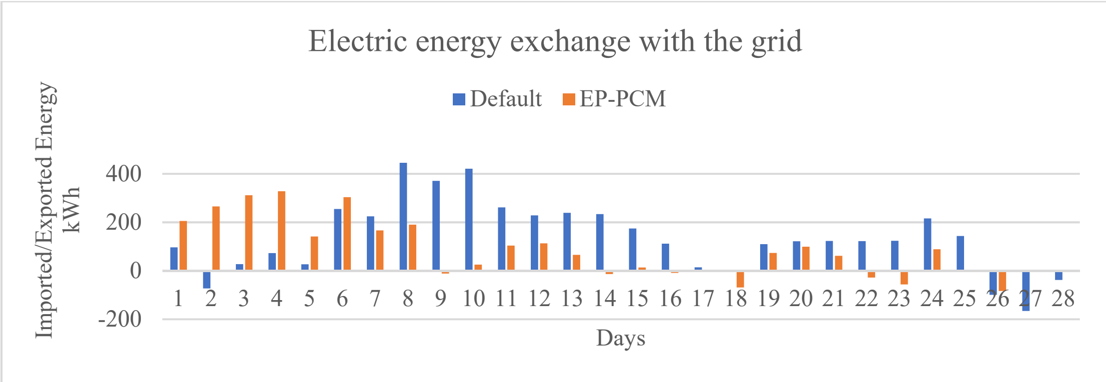


Figure 4. Daily electric energy exchange of nZEB Living Lab with the grid in July 2020.

Therefore, there is an important potential of thermal inertia storage to increase the penetration of RES to cover the electricity use and at the same time to reduce the imported electric energy from the grid.

5. Conclusions

Industrial minerals have a great potential to be used in many innovative applications. They provide versatile functionalities and properties which are valuable for enhancing buildings thermal mass and contributing to the RES penetration increase. The development of form-stable PCM composites and mortars is currently under investigation and provides promising results. Industrial minerals used as carriers can deliver to the market new innovative products acting as short-term energy storage systems for construction applications.

This study is to investigate the potential of an EP-PCM composite to increase the thermal mass of a nZEB and increase the penetration of the RES coupled to this building. In this framework, a novel Paraffin/Hydrophobic EP/cement mortar solution is selected. The scenarios take place in simulation environment and the evaluation is performed in terms of improving the energy performance of the building and increase the potential of renewable integration. The results indicate a stabilisation of the indoor temperature by decreasing the fluctuations up to 18.3% (average value 6.2%) which results in improved thermal comfort of the occupants. In parallel, the imported and exported energy of the building is analysed, resulting in a RES penetration increase of 11.8%. To conclude, the utilisation of industrial minerals in LHTES applications for buildings can lead to improved thermal performance through matching thermal availability and demand with respect to time as well as provide benefits for exploiting RES generated power.

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