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In situ thermal and acoustic performance and environmental impact of the introduction of a shape-stabilized PCM layer for building applications

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ABSTRACT

Energy consumption in buildings accounts for up to 34% of total energy demand in developed countries. Thermal energy storage (TES) through phase change materials (PCM) is considered as a promising solution for this energetic problem in buildings. The material used in this paper is an own-developed shape stabilized PCM with a polymeric matrix and 12% paraffin PCM, and it includes a waste from the recycling steel process known as electrical arc furnace dust (EAFD), which provides acoustic insulation performance capability. This dense sheet material was installed and experimentally tested. Ambient temperature, humidity, and wall temperatures were measured and the thermal behaviour and acoustic properties were registered. Finally, because of the nature of the waste used, a leaching test was also carried out. The thermal profiles show that the inclusion of PCM decreases the indoor ambient temperature up to 3 °C; the acoustic measurements performed *in situ* demonstrate that the new dense sheet material is able to acoustically insulate up to 4 dB more than the reference cubicle; and the leaching test results show that the material developed incorporating PCM and EAFD must be considered a non-hazardous material.

1. Introduction

Energy consumption in buildings represents 34% of total energy demand in developed countries [1] and this trend is remaining constant or increasing regardless of the new directives and legislation that have taken effect recently to increase the energy efficiency and reduce the energetic consumption in this sector [2,3].

In this scenario, worldwide there is considerable research effort to develop more sustainable and energy-efficient systems for implementing in the building sector [4]. Within this situation, thermal energy storage (TES) is considered as a promising solution for this energetic problem in buildings [2]. A TES system can store energy following three different mechanisms: using sensible heat (SHTES) when a temperature gradient is applied to a medium [5]; using latent heat (LHTES) when a phase change of state occurs [5]; and using heat released during a thermochemical reaction (TCTES) [6]. Moreover, TES materials can be introduced in several parts of the building in order to increase the energy efficiency of the HVAC system or to reduce the energy demand of the building: TES materials can be included in the structure of the building [7], in the internal coatings of the walls [7], or in the façades of the building [8], all these three are examples of TES passive system, and finally they can be implemented in the heat pump to regulate the indoor part of the building as active TES system [9]. The study presented in this paper is focused on phase change materials (PCM) included in the internal layer of an intermediate wall of the building and it acts as a TES passive system.

Several researchers have developed their own equipment in order to measure the thermal behaviour of the constructive system simulated using a water bath or heating/cooling systems real ambient conditions [10–13]. On the other hand, there are several research groups that have implemented and tested the thermal

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performance of passive system in building walls. For example, Farid et al. [14] analysed the thermal behaviour of implementing PCM in timber construction (this type of construction is common in climatic zones like New Zealand). However, that study consisted of a single room cubicle and the experimental set-up presented in this paper consists of a double room cubicle with all the wall temperatures controlled as well as the internal and external ambient temperature and relative humidity. Moreover, Castellón et al. [15] demonstrated experimentally that it is possible to improve the thermal comfort and reduce the energy consumption of a building with the inclusion of PCM in several constructive systems using concrete, conventional brick and alveolar brick and recently, de Gracia et al. [9,16] tested experimentally the thermal performance of a ventilated double skin façade (DSF) with phase change material (PCM) in its air channel, during the heating and cooling season in the Mediterranean climate.

The experiments presented in this paper were carried out in the experimental set-up of the University of Lleida, which is located in Puigverd de Lleida, Spain (see Fig. 1).

The PCM implemented in a building wall as a layer was developed and characterized by Barreneche et al. [17,18]. This material is a shape stabilized PCM with a polymeric matrix with 12% paraffin PCM, and it includes a waste from the recycling steel process known as electrical arc furnace dust (EAFD). The composition of this waste consists of heavy metal oxides that will provide high density to the shape stabilised PCM as well as it will increase the acoustic insulation of the final constructive system.

The present paper will present the experimental measurements which test the thermal performance of the new shape stabilized PCM used as a dense sheet when it is implemented as a layer of a building wall and will compare the results with a commercial constructive system. The acoustic behaviour will be measured *in situ*. Moreover, a leaching test was used to evaluate the potential environmental impact after its use, at the disposal step.

2. Experimental set-up and methodology

The experimental set-up located in Puigverd de Lleida (Spain) consists of two identical cubicles with double cabins as is shown in Fig. 2. The constructive system under study is located in the intermediate wall.

In one of the cubicles the new shape stabilized PCM was installed and the other one was used as a reference where a commercial dense sheet was used.

2.1. Thermal measurements in situ

The temperature is measured inside both rooms on each wall as well as on the roof and floor. Furthermore, the indoor and outdoor ambient temperature and ambient humidity are measured over time. Moreover, the temperature in the intermediate wall is measured at five locations (up south, up north, down south, down north and centre) and the temperature is also controlled on the dense sheet and on the other walls (north, west and east).

Two flux sensors are located in each intermediate wall in order to measure the heat crossing this wall. The control-sensors distribution is shown in Fig. 3. The sensor presented in green colour are temperature sensors, the one presented in red colour is heat-flux sensor and the grey ones are temperature sensors but across the wall.

Moreover, each cubicle has a heat pump and an electrical oil radiator in order to control the indoor temperature. The external walls of the room where the dense sheet is implemented were completely insulated with 8 cm PUR foam in order to minimize the external influence on the temperature fluctuation inside this room.

The constructive system installed in the intermediate walls is shown in Fig. 4 and it is composed by the dense sheet between two gypsum boards and mineral wool on one side (see Fig. 4). The side with mineral wool should be installed next to the non-controlled temperature room (i.e. garage).

The constructive system described in Fig. 4 can be implemented as the wall that separates an indoor room with a garage, the building stairways and the flat indoors, etc. Then, one of the rooms has control-temperature and the other one is left at free floating conditions.

The thermal experiment performed with the experimental set-up follows the temperature profile shown in Fig. 5, where the temperature remains controlled and constant at 18 °C during the cold part of the day simulating night and at 28 °C during the warm part of the day until the temperature is stabilized.

2.2. Acoustic measurements in situ

The acoustic experimentation *in situ* was performed using a sound-level meter and analyser type 1 (CESVA – SC310) which was calibrated by a sound calibrator Brüer&Kjaer – 4230 (94bB-1000 Hz). 1/3 octave between 20 and 10,000 Hz was measured in all cases as it is shown in Fig. 6. These measurements followed the Spanish Regulation requirements presented in UNE–EN ISO 140-4 standard.

The pink noise source is located in the left chamber where the dense sheet developed is placed becoming the emitter chamber. The microphone to register the difference between levels is place on the chamber named receptor chamber. The location of the pink noise source is always in the emitter.

In addition, three different measurement of each cubicle were performed as well as three measurement of background noise. The reverberation time will depend on the materials used to build the walls chamber which will increase the noise measured inside it. For that reason both parameters are included in the equation used to calculated the difference between levels. The difference between normalized levels (D) is calculated for each measurement following the Eq. (1) where L_1 is the sound level on the emitter chamber, L_2 is the sound level on the receptor chamber, t_r is the reverberation time and t_0 is the reference time of reverberation (0.5 s).

Fig. 1. General view of experimental set-up of Puigverd de Lleida (Spain).

Fig. 2. General view of the cubicles used to performed thermal and acoustic measurements *in situ*.

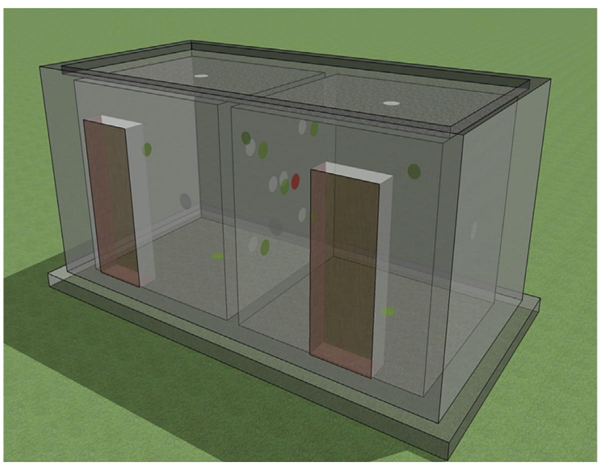

Fig. 3. Control-sensor distribution in each cubicle used in this study.

$$D_{nT} = L_1 - L_2 + 10\log\left(\frac{t_r}{t_0}\right)[\text{dB}] \quad (1)$$

The main acoustic insulation value ($D_{nt,w}(C,C_{tr})$) is calculated following the standard UNE-EN ISO 717-1 where C and C_{tr} are the correction of the acoustic spectra.

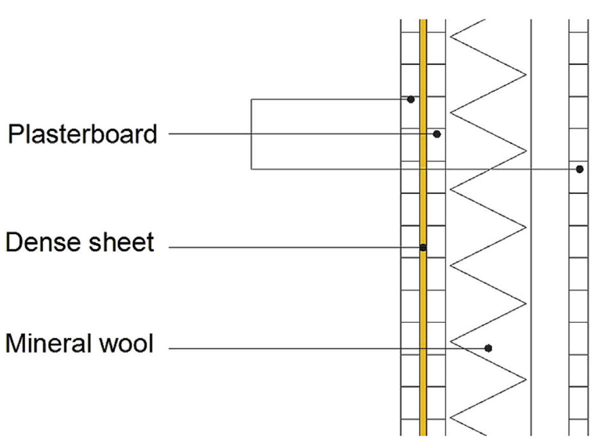

Fig. 4. Sketch of constructive system installed as intermediate walls inside the cubicles.

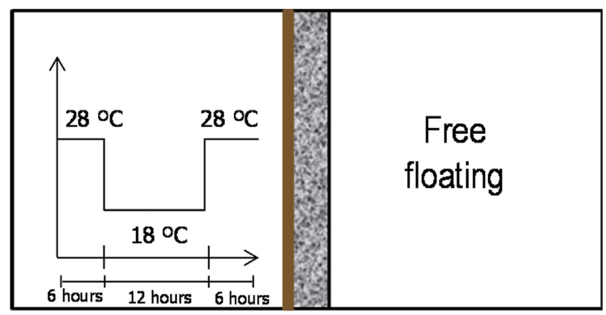

Fig. 5. Thermal experiments performed inside the cubicles.

2.3. Environmental impact: leaching test

Finally, a leaching test following the UNE-EN 12457-2 was performed to classify for the disposal of the product after its use. Moreover, the results concerning the heavy metal contents will be classified as inert, non-hazardous, or hazardous according to the European Directive.

3. Materials

The material implemented in the experimental set-up described in the above section was a dense sheet used as shape stabilised PCM. This shape was manufactured in a Banbury mixer and shaped in a hot-roll lamination and 500 kg were obtained [18].

This material is composed by 12% wt. paraffin PCM (RT-21 commercialized by Rubitherm, $T_m = 21$ °C, $\Delta H_m = 160$ kJ kg^{-1}), 71% wt. of Electrical arc furnace dust (EAFD), which was characterized and described by Barreneche et al. [17], and 17% of polymeric matrix – EPDM. EAFD is considered as hazardous substance which

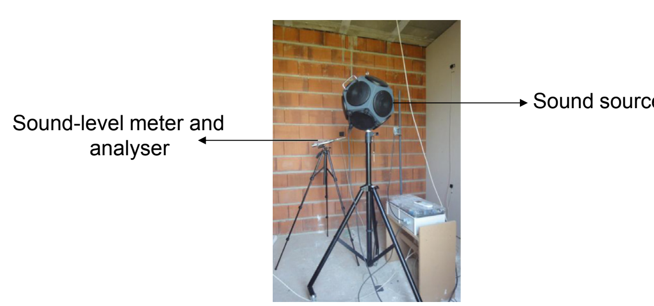

Fig. 6. Equipment used to perform the acoustic measurements *in situ*.

must be landfilled with high caution. The main processes followed in the EAFD treatment previous landfill are the following:

- Stabilization/solidification technologies complete with Portland cement is the cheapest alternative but some problems regarding metal dissolution arise from the elevated pH in the leachate. This process is the least used [19].
- Encapsulation methods of toxic metals. These methods are not commercially interesting, as they involve important investments and there is no metal recovery.
- Pyrometallurgical processes are used to remove lead and zinc from EAFD by fuming and then condensing the metals in relatively pure form. However, with pyrometallurgical processes there is no recycling of iron to the electrical arc furnace process [20,21].
- Caustic based processes in which the leaching and dissolving steps employ simple chemistry that takes advantage of the amphoteric nature of zinc, lead, 25 tin, arsenic, selenium and aluminium can be used to treat EAFD [22].

The process of incorporating EAFD as filler into a polymer matrix, in order to obtain a composite formulation is followed in the Barreneche PhD thesis [23] to obtain the material used in this study and previously investigated for automotive industry by Niubó et al. [24,25].

However, the inclusion of this dust inside an elastomeric matrix implies the isolation of the dust as the leaching test performs will discern [26]. This rubber dense sheet has 1230 kg m^{-3} density.

On the other hand, the dense sheet installed in the other cubicle is the TECSOUND 35 commercialized by TEXSA and used as a reference in this study which has 2300 kg m^{-3} and 30 N cm^{-2} of tensile strength (UNE 104-281/6.6).

4. Results

4.1. In-situ thermal measurements

The thermal profile of the materials implemented in both cubicles were registered over several consecutive days applying the same thermal conditions by controlling the temperature inside one chamber and leaving free floating conditions inside the other chamber.

The temperature profiles of the dense sheet temperatures are presented in Fig. 7. Moreover, the temperature profiles of the south wall (top and bottom parts of the south wall) are also overlapped in Fig. 7. A period of three consecutive days during the summer season is represented in Fig. 7.

As it can be seen, the peak temperature on the wall containing PCM dense sheet was reduced up to 4 °C).

In addition, the PCM effect is shown in this figure because the sample containing PCM reach the final temperature before and it remains constant until the experiment ends. However, the temperature inside the room where the commercial sheet is installed does not achieved constant temperature on any day.

Moreover, a thermal reduction of 3 °C on the ambient temperature inside the room where the dense sheet contains PCM was achieved in the same experiments presented before as shown in Fig. 8.

Note that the indoor temperature is higher than 28 °C due to the outdoor temperature.

4.2. In-situ acoustic measurements

The difference between levels considering the emitter chamber and the receptor one for both cubicles (PCM cubicle and reference cubicle) are listed in Table 1 and the dB of acoustic insulation vs. Frequency [Hz] are shown in Fig. 9.

Acoustic measurements light up an acoustic insulation with differences of about 4 dB (difference between levels) between the PCM cubicle and the reference cubicle over almost all frequencies (see Fig. 9) and taking into account the difference between normalized levels calculated following Eq. (1). These proper acoustic insulation properties are due to the EAFD incorporation into the formula since it is composed by heavy metals. These heavy metal oxides present high densities which increase the acoustic insulation behaviour of the constructive system.

4.3. Leaching test

During the development stage of the PCM dense sheet, the leaching tests were considered a key issue because the raw material EAFD is a solid, classified as hazardous waste by the international

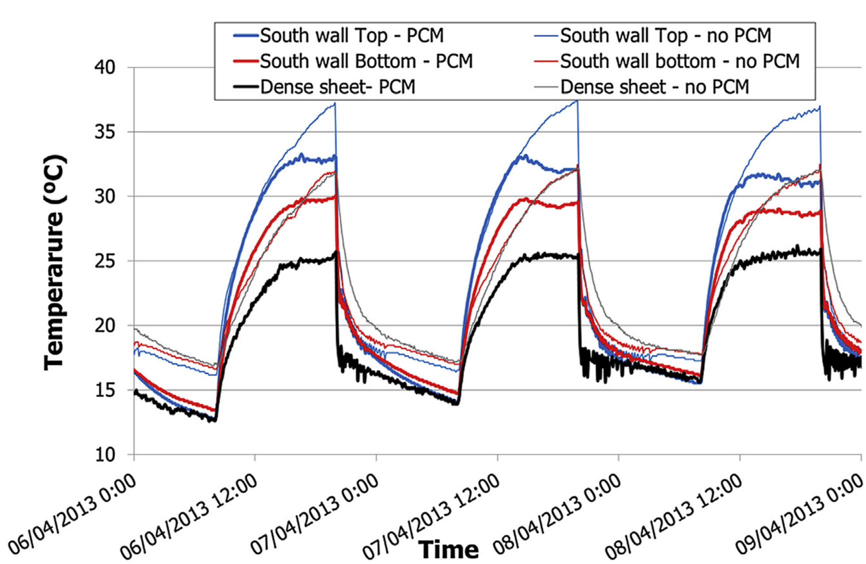

Fig. 7. Temperature profile registered on south walls inside the PCM cubicle and the reference cubicle and the directly measured temperature on dense sheets.

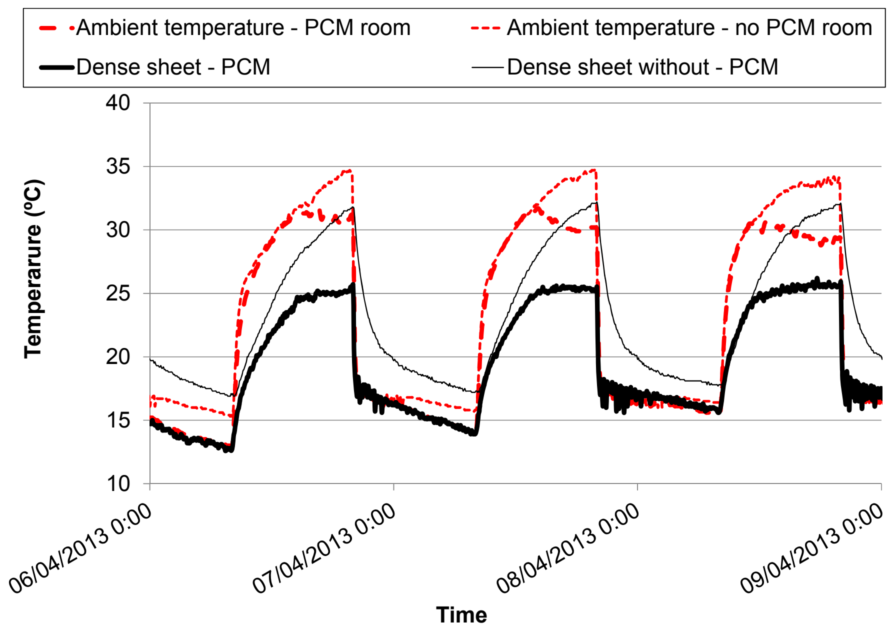

Fig. 8. Indoors ambient temperature profile registered inside the PCM cubicle and the reference cubicle and the directly measured temperature on dense sheets.

society under the European Directive 2003/33/EC [27], although when used in this dense sheet it is encapsulated. Leaching tests were performed on two samples: one is the dense sheet which contains PCM and the other one is the commercial one (TECSOUND 35). The composition of the EAFD depends on the scrap feeding of the electric arc furnace. For that reason, the results of the leaching tests may have some variation in some component like zinc or lead depending on the source.

Leaching test results for heavy metals are listed in Table 2. Both materials results show that the concentration limit to consider them hazardous materials is not reached in any metal. Zn and Cd concentrations are within the limits of non-hazardous materials. Finally, the other metal concentrations are within the limits of inert materials. Therefore, according to this test, both dense sheets may be classified as non-hazardous materials [28].

In addition, it is well known that the leaching behaviour of heavy metals like Zn, Cd and Pb is pH dependent, and is possible to stabilize them and reduce their leaching [28].

5. Discussion

The peak temperature reduction on the wall containing PCM of 4 °C agrees very well with those obtained previously in other in-situ studies. In them, PCM was included either microencapsulated in a concrete wall [15] or macroencapsulated (using CSP panels) in brick and alveolar brick construction systems [29]. Moreover, these results are in accordance with laboratory testing of the dense sheet [17,18].

Similarly, in-situ acoustic measurements achieved 4 dB higher value in acoustic insulation index compared to the commercial reference product considered (TECSOUND 35), showing an analogous behaviour to that measured in the laboratory [18].

All these results, plus the leaching tests presented in this paper show that the newly developed dense sheet compiles with all the necessary properties to be used in real applications and to be produced at industrial scale. Further work would be to carry out the required steps to achieve full commercialization.

Table 1
Acoustic difference between levels measured into PCM cubicle and reference cubicle.

	$D_{nT,w}$ (C:C_{tr}) [dB]
PCM cubicle	35 (−1; 0)
Reference cubicle	31 (−1; 0)

6. Conclusions

The thermal and acoustic behaviour of an intermediate wall as well as the environmental impact have been measured inside two cubicles of the experimental set-up located in Puigverd de Lleida (Spain). The first cubicle contains a PCM dense sheet that incorporates EAFD and the second one is considered the reference because a commercial dense sheet (TECSOUND 35) was installed.

The thermals profiles expound that the inclusion of PCM decreases the ambient temperature up to 3 °C and the temperature on the south part of the intermediate wall (the one exposed to solar insolation) under thermal experiments.

Moreover, the acoustic measurements performed *in situ*

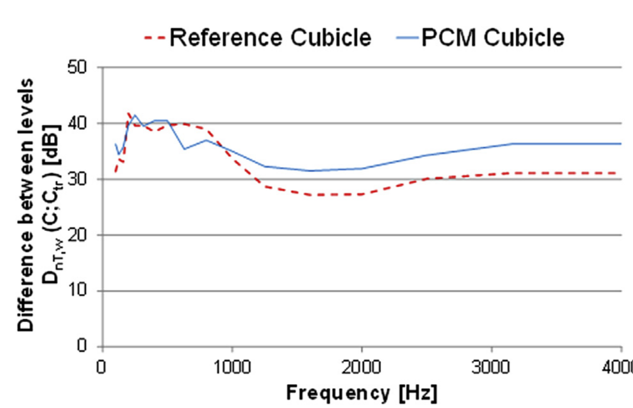

Fig. 9. Acoustic insulation measurements: Difference between levels normalized [dB] vs Frequency [Hz].

Table 2
Leaching test result of the materials installed in experimental set-up.

Element	PCM dense sheet (mg/kg)	TECSOUND 35	Classification		
			Inert	Non-hazardous	Hazardous
Pb	0.1	<0.04	0.5	10	50
Zn	8.6	17.7	4	50	200
Cd	0.21	0.19	0.04	1	5
Cr	<0.02	<0.02	0.5	10	70
Ni	0.1	0.07	0.4	10	40
As	<0.04	<0.04	0.5	2	25

illustrate that the PCM cubicle (where the PCM dense sheet is installed) is able to insulate up to 4 dB more than the reference cubicle thanks to EAFD content (due to the heavy metals).

The leaching test performed show that the material developed incorporating PCM and EAFD does not leach heavy metals with higher contents than the limits to consider the materials as hazardous material. Therefore, EAFD which is considered as special waste is very nearly isolated inside the EPDM matrix with PCM.

In summary, the PCM dense sheet present better thermal behaviour (remaining the ambient temperature 3 °C lower), better acoustic insulation properties (4 dB higher) and the leaching test show similar results, therefore, it can be applied in real building as part of walls where acoustic and thermal aspects need to be improved.

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References

[1] IEA, Energy Technology Perspectives (ETP) 2012, Int Energy Agency, 2012.
[2] Directive 2010/31/EU: European, 2010/31/EU: Directive of the European Parliament and of the Council of 19 May 2010 on the Energy Performance of Buildings, 2010. Available from: (10-30-2012), http://www.epbd-ca.eu.
[3] D. Ürge-Vorsatz, L.F. Cabeza, S. Serrano, C. Barreneche, K. Petrichenko, Heating and cooling energy trends and drivers in buildings, Renew. Sustain Energy Rev. 41 (2015) 85–98, http://dx.doi.org/10.1016/j.rser.2014.08.039.
[4] United National Environmental Programme in Buildings and Climate Change, 2012. Available from: (10-30-2012), http://www.unep.fr/shared/publications/pdf/DTIx0916xPA-BuildingsClimate.pdf.
[5] S.M. Hasnain, Review on sustainable thermal energy storage technologies, part I: Heat storage materials and techniques, Energy Convers. Manag. 39 (1998) 1127–1138.
[6] K.E. N'Tsoukpoe, H. Liu, N. Le Pierrès, L. Luo, A review on long-term sorption solar energy storage, Renew. Sustain Energy Rev. 13 (2009) 2385–2396.
[7] A.M. Khudhair, M.M. Farid, A review on energy conservation in building applications with thermal storage by latent heat using phase change materials, Energy Convers. Manag. 45 (2004) 263–275.
[8] A. De Gracia, L. Navarro, A. Castell, A. Ruiz-Pardo, S. Alvárez, L.F. Cabeza, Experimental study of a ventilated facade with PCM during winter period, Energy Build. 58 (2013) 324–332.
[9] R. Parameshwaran, S. Kalaiselvam, S. Harikrishnan, A. Elayaperumal, Sustainable thermal energy storage technologies for buildings: a review, Renew. Sustain Energy Rev. 16 (2012) 2394–2433.
[10] A. De Gracia, C. Barreneche, M.M. Farid, L.F. Cabeza, New equipment for testing steady and transient thermal performance of multilayered building envelopes with PCM, Energy Build. 43 (2011) 3704–3709.
[11] B. Yesilata, P. Turgut, A simple dynamic measurement technique for comparing thermal insulation performances of anisotropic building materials, Energy Build. 39 (2007) 1027–1034.
[12] C. Barreneche, A. De Gracia, S. Serrano, M. Elena Navarro, A.M. Borreguero, A. Inés Fernández, et al., Comparison of three different devices available in Spain to test thermal properties of building materials including phase change materials, Appl. Energy 109 (2013) 544–552.
[13] A.M. Borreguero, M. Luz Sánchez, J.L. Valverde, M. Carmona, J.F. Rodríguez, Thermal testing and numerical simulation of gypsum wallboards incorporated with different PCMs content, Appl. Energy 88 (2011) 930–937.
[14] M.M. Farid, S. Behzadi, Energy storage for efficient energy utilization in buildings, in: 1st Int. High Perform. Build. Conf., Purdue University, USA, 2010, pp. 12–15.
[15] C. Castellón, A. Castell, M. Medrano, I. Martorell, L.F. Cabeza, Experimental study of PCM inclusion in different building envelopes, J. Sol. Energy Eng. Trans. ASME 131 (2009) 410061–410066.
[16] A. De Gracia, L. Navarro, A. Castell, Á. Ruiz-Pardo, S. Álvarez, L.F. Cabeza, Thermal analysis of a ventilated facade with PCM for cooling applications, Energy Build. 65 (2013) 508–515.
[17] C. Barreneche, A.I. Fernández, M. Niubó, J.M. Chimenos, F. Espiell, M. Segarra, et al., Development and characterization of new shape-stabilized phase change material (PCM) – Polymer including electrical arc furnace dust (EAFD), for acoustic and thermal comfort in buildings, Energy Build. 61 (2013) 210–214.
[18] C. Barreneche, M.E. Navarro, M. Niubó, L.F. Cabeza, A.I. Fernández, Use of PCM-polymer composite dense sheet including EAFD in constructive systems, Energy Build. 68 (2014) 1–6.
[19] G. Salihoglu, V. Pinarli, Steel foundry electric arc furnace dust management: stabilization by using lime and Portland cement, J. Hazard. Mater. 153 (2008) 1110–1116.
[20] P. Oustadakis, P.E. Tsakiridis, A. Katsiapi, S. Agatzini-Leonardou, Hydrometallurgical process for zinc recovery from electric arc furnace dust (EAFD): part I: characterization and leaching by diluted sulphuric acid, J. Hazard. Mater. 179 (2010) 1–7, http://dx.doi.org/10.1016/j.jhazmat.2010.01.059.
[21] P.E. Tsakiridis, P. Oustadakis, A. Katsiapi, S. Agatzini-Leonardou, Hydrometallurgical process for zinc recovery from electric arc furnace dust (EAFD). Part II: downstream processing and zinc recovery by electrowinning, J. Hazard Mater. 179 (2010) 8–14, http://dx.doi.org/10.1016/j.jhazmat.2010.04.004.
[22] K.S. Price, K. Lenti, Processing Electric Arc Furnace Dust Through a Basic Oxygen Furnace, 2013. US 6562101 B1.
[23] C. Barreneche, Development and Characterization of New Materials Incorporating Phase Change Materials (PCM) for Thermal Energy Storage (TES) Applications in Buildings, University of Lleida, 2013.
[24] M. Niubó, A.I. Fernández, J.M. Chimenos, L. Haurie, A possible recycling method for high grade steels EAFD in polymer composites, J. Hazard Mater. 171 (2009) 1139–1144.
[25] M. Niubó, A.I. Fernández, L. Haurie, X.G. Capdevila, J.M. Chimenos, J.I. Velasco, Influence of the electric arc furnace dust in the physical and mechanical properties of EVA-polyethylene-butene blends, Mater. Sci. Eng. A 528 (2011) 4437–4444.
[26] A.I. Fernández, L.F. Cabeza, C. Barreneche, J.M. Chimenos, F. Espiell, M. Segarra, et al., Inertización de polvo de acería mediante su integración estabilizante en un material de construcción Title, 2010. P201131272.
[27] 2003/33/EC E directive. 2003/33/EC: Council Decision of 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of and Annex II to Directive 1999/31/EC n.d.
[28] A.I. Fernández, J.M. Chimenos, N. Raventós, L. Miralles, F. Espiell, Stabilization of electrical arc furnace dust with low-grade MgO prior to landfill, J. Environ. Eng. 129 (2003) 275–279.
[29] A. Castell, I. Martorell, M. Medrano, G. Pérez, L.F. Cabeza, Experimental study on using PCM in brick constructive solutions for passive cooling, Energy Build. 42 (2010) 534–540.