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Energy savings due to the use of PCM for relocatable lightweight buildings passive heating and cooling in different weather conditions

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A B S T R A C T

Relocatable, transportable or off-site constructed lightweight buildings typically undergo sharp indoor temperature fluctuations in the heating and cooling seasons due to the lack of sufficient thermal mass in their envelopes, resulting in high energy consumption to provide the zone with comfort temperature. The application of phase change materials has been suggested as a promising solution to control the indoor thermal condition in buildings. This work is an attempt to support the application of PCM technology in lightweight relocatable buildings as a passive alternative to save energy under different weather conditions. The numerical results highlighted the potential of using PCM-enhanced gypsum boards in lightweight buildings to increase the energy performance during both heating and cooling seasons in arid and warm temperate main climate areas.

1. Introduction

More than one-third of the global energy consumption comes from the building sector (residential and commercial) [1] which is estimated to 20–40% of the total final energy consumption in developed countries [2]. It also accounts for about 8% for direct energy-related CO_2 emissions from final energy consumers [3]. It is expected that without applying any energy efficient solutions, global energy demand will increase by 50% in 2050 [4].

Improving the building envelope is considered as an appropriate design solution for reducing the space heating and cooling energy consumption and increasing the thermal comfort [5,6]. In buildings, a major part of the energy is consumed by the air conditioning system, on this basis, several technologies have been developed to decrease the energy consumption and to maintain the thermal comfort of occupants. Examples of such technologies are insulation materials [7], development of heat insulation solar glasses [8], double-glazed window reversible systems [9], use of hybrid wall integrated with heat collectors, and solar thermal power generators [10]. Enhancing the building envelopes with thermal insulation has been extensively used as a basic strategy to diminish the heat dissipation from the building environment to the outdoor environment specifically in lightweight buildings [11]. However, major factors affecting the long-term performance of lightweight buildings correspond to the ability to adequately regulate the internal environment since the energy performance in such buildings can be limited because of the overheating problem coming from the high heat gains from internal sources and solar radiation [12,13].

The application of thermal mass has been highlighted as a promising technology for designing high efficient buildings [14–16]. However, traditional thermal mass materials (bricks, stone, etc.) are not appropriate choices for relocatable lightweight buildings since, on one hand, their transportation and implementation would not be feasible due to their massiveness, and on the other hand, they occupy more space because of their higher vol-

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Fig. 1. Fully self-sufficient mining camp for workers [46].

ume. The building envelope regulates the heat exchange between outdoor and indoor environments and highly affects the energy requirements and comfort of the occupants, besides, it has a high potential to be integrated with new building materials and systems.

Thermal energy storage (TES) systems can create a balance between diurnal and nocturnal energy demand using latent heat thermal energy storage [17]. A considerable amount of literature has been published on the application of phase change material (PCM) in buildings [18–21]. Further on, a great effort has been made by Cabeza et al. [19] and Barreneche et al. [22] in recent years to classify PCM for thermal energy storage (TES) in buildings. The PCM is distinguished from typical thermal mass materials because of its capability to store higher amounts of energy in small temperature interval due to its high heat of fusion [23]. PCM is a unique alternative to improve the energy efficiency and thermal comfort in buildings [24–28].

PCM can be incorporated into building construction materials in different ways to provide passive cooling and heating; such as, gypsum plasterboard with microencapsulated paraffin [29] which is a promising solution to enhance thermal capacity of lightweight buildings, plaster with microencapsulated paraffin [30] that could be applied on the surface of the walls, concrete with microencapsulated paraffin [31], shape-stabilized paraffin panels [32], PCM bricks [33], and wood with PCM [34]. Additionally, the PCM has vast applications for building components such as slabs [35], floors [36], blinds and windows [37–39].

For example, Cabeza el al. [31] experimentally investigated the impact of using microencapsulated PCM in concrete walls to improve the thermal performance of a concrete building. It was shown that the indoor temperature of the PCM-enhanced concrete building was 1 °C lower than the reference building without PCM inclusion, also, the maximum temperature in the PCM-enhanced wall was shifted two hours. In addition, it was shown by Lee et al. [40] that the integration of a thin PCM layer into the residential building walls can moderate the temperature and heat flux fluctuations. The experimental results showed 30–50% of peak heat flux reductions, 2–6 h delay in peak heat flux, and the maximum daily heat transfer reductions were estimated as 3–27%. Besides, through an optimization-based simulation Soares et al. [13] found that the application of PCM drywalls in lightweight steel-framed buildings can improve the energy efficiency of buildings by 10–60% depending on the climate zone.

The PCM passive system (passive cooling and heating) is a sustainable solution to improve the comfort quality and the energy performance by reducing the cooling and heating demands in lightweight buildings. Passive cooling plays an important role in the sustainable development of the building industry [41–43].

Off-site constructed buildings such as prefabricated lightweight buildings came into practice as an alternative to the on-site method in order to manufacture and preassemble building elements, components or modules before being installed in the building site [44]. Off-site construction is often referred as a modern method of construction which is more environmentally friendly since repeatable performance, minimal waste and high levels of quality can be guaranteed [45]. Other advantages associated with such buildings are rapid construction, minimal handling and lower need for resources which have led to growth of pre-fabricated (off-site) construction [41,45].

Portable, relocatable or transportable buildings are those which could be easily moved and relocated. They may be modular (made up of a number of modules) or single volumes (where there are transported as complete buildings) [46]. Such types of buildings are feasible alternatives for mining camps (Fig. 1), rapid post-disaster sheltering in regions with high vulnerability to natural disasters [47], refugee camps, temporary accommodation, and also they could be used in developing countries where there are problems of house delivery due to the lack of skill and housing quality [48]. Lightweight pre-fabricated buildings could be delivered to the job site at any time of the year and any place (on the mountains for example) regardless of the weather condition. As already mentioned herein, overheating or overcooling problems of the indoor environment is the main challenge in such buildings [49] due to their lightweight nature where high cooling and heating loads might be imposed to the HVAC system. Thermally enhancing the envelopes of these buildings using PCM could be an innovative solution to overcome the uncomfortable indoor condition in these buildings considering that a poor-conditioned zone may negatively affect the occupants and may cause sick building syndrome [50].

With this knowledge the authors would like to address the high energy consumption in Chile. The mining industry is a major consumer of energy and electricity in Chile. This country is the world largest producer and exporter of copper and it consumes 11% of the total country energy use, 32% of total electricity and 6% of total fuel [51]. These mining camps have their own residential, medical, leisure and sport areas which are built of single or modular prefabricated lightweight buildings such as the modular pre-fabricated construction. Also, the development of new mining projects demand the installation of temporary camps with this type of construction, such as Escondida mine located in the desert of Atacama, with the altitude of 3100 m and a capacity of inhabiting more than 5500 persons which was constructed in only 8 months (Fig. 2) [52,53].

In the extreme summer and winter weather conditions these buildings (modular or single) consume a huge amount of energy for air conditioning purposes both in cooling and heating season, especially in regions with high altitudes because of high irradiance all over the year. Due to this reason, PCM-based passive cooling and heating system can play an important role to control the air quality in these lightweight residential buildings. Further on, if sufficient energy saving is attained in such rapidly-built buildings the payback period of the PCM technology is feasible [5]. In the literature, little attention has been paid to such buildings despite to their