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# Evaluation of phase change materials for improving thermal comfort in a super-insulated residential building

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ABSTRACT

The demand for high performance buildings is on the rise. As a result, several new building standards have emerged including the Passive House Standard, a rigorous energy-use standard based on a super-insulated and very tightly sealed building envelope. A common challenge with passive house designs is that they tend to overheat. This study explores the use of phase change materials (PCMs), which store heat as they melt and release heat as the solidify, to reduce the number of overheated hours and improve thermal comfort for a case study passive house duplex located in Portland, Oregon, USA.

In this study, a newly constructed passive house duplex was thoroughly instrumented to monitor indoor environmental quality metrics and building energy use. One unit of the duplex was outfitted with 130 kg of PCM while the other unit served as a control. The performance of the PCM was evaluated through analysis of observed data and through additional computer simulation using an EnergyPlus whole-building energy simulation model validated with observed data. The study found that installation of the PCM had a positive effect on thermal comfort, reducing the estimated annual overheated hours from about 400 to 200.



## 1. Motivation and background

The United States has seen increased demand for high performance buildings in recent decades. In fact, according to a report by ISBS World, the Green and Sustainable Building Construction industry saw revenue increase at an average annual rate of 26.9% between 2006 and 2011 [1]. Building occupants and owners alike are demanding more comfortable and energy efficient buildings. In response, several building standards and certifications have emerged to aid in the design and development of high performance buildings. One such standard is Passive House, which originated in Germany and is based on a super-insulated and tightly sealed building envelope. Although its name implies that the standard applies to residential buildings, the Passive House Standard has been successfully applied to offices, schools, factories, government buildings, and other non-residential structures [2]. The Passive House Standard requires that: (1) air infiltration is less than or equal to 0.6 air changes per hour at a 50 Pa indoor–outdoor pressure difference, (2) annual heating energy is less than or equal to 15 kWh/m$^2$, and (3) total annual source energy is less than or equal to 120 kWh/m$^2$. The result is a building that is roughly 90% more energy efficient than typical construction.

A common complaint of passive house occupants, however, is that, due to the highly insulated and air-tight envelope, these buildings tend to overheat during the summer months [2–4]. This results in either increased cooling energy demand or thermal discomfort in cases where no active cooling system is installed.

Numerous studies have shown that the addition of thermal mass can reduce temperature fluctuation and shift cooling loads to periods of lower outdoor air temperature [5,6]. This concept could be especially useful in a Passive House, where internal gains have a greater impact on indoor air temperatures. The use of thermal mass in buildings is certainly not a new concept. In fact, massive wall construction has been used for centuries throughout Europe and the Middle East. In the US, however, over 90% of new homes are framed with wood [7]. So, light weight construction will likely continue to dominate US residential construction for quite some time. However, thermal mass in the form of phase change materials

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(PCMs) could potentially meet the need of adding thermal mass to lightweight construction both for new and potentially for retrofit applications.

## 2. Overview of phase change materials

Compared to traditional thermal mass, the use of PCMs in building applications is a relatively new concept that was first introduced in the 1970s [8,9]. Like thermally massive building materials, PCMs offer the potential to reduce fluctuations in air temperature and shift cooling loads to off-peak periods. In contrast to traditional building materials, whose energy storage capabilities are restricted to sensible heat, the ability of a PCM to store energy is largely characterized by its latent heat of fusion. When heat is added to a solid below its melt temperature or a liquid above its melt temperature, the energy is stored as sensible heat and increases the temperature of the solid or liquid. However, when heat is added to a solid at its melt temperature, the material changes phase to a liquid while maintaining a constant temperature, effectively storing the heat. As the liquid freezes and returns to a solid, the stored heat is released to the surrounding environment. This characteristic is especially suited to building applications when the melt temperature of the PCM is approximately equal to the desired room air temperature and diurnal temperature swings enable full thermal cycling of the PCM between liquid and solid phases.

PCMs are broadly categorized into organic compounds, inorganic compounds, and eutectic mixtures [10]. Organic PCMs include paraffins, fatty acids, and polyethylene glycol and tend to be chemically stable, non-reactive, and resist sub-cooling. However, they also have a relatively low thermal conductivity, low latent heat storage capability, and may be flammable. Inorganic PCMs are typically salt hydrates and possess a high latent heat storage capability, high thermal conductivity, and are typically non-flammable. However, they are prone to sub-cooling, segregation, and experience high changes in volume during phase transition [11]. Eutectics can be mixtures of only organics, only inorganics, or a combination of the two. They tend to have sharp melting points and latent heat storage capabilities that are slightly above organic PCMs, but there is little information available regarding their thermal and physical properties [12]. PCM properties that are desirable for passive building applications include (1) high thermal conductivity, (2) high latent heat of fusion, (3) non-flammable, and (4) a melting point that is approximately equal to room temperature.

There are generally two ways to contain PCMs in building applications: direct impregnation into building materials and encapsulation. Direct impregnation can be accomplished by either dipping porous building materials into a PCM bath or mixing the PCM into the materials during the manufacturing process [10]. Encapsulation involves containing the PCM with another material and can further be categorized into micro- and macro-encapsulation. Micro-encapsulated PCMs are typically contained by microscopic polymeric capsules which form a powder-like substance that can be incorporated into various building materials [10,12]. Micro-encapsulated PCMs have been successfully incorporated into wallboard, concrete, insulation and acoustic ceiling tiles, but tend to be costly [13–15] and can adversely affect structural integrity [16]. Macro-encapsulation contains the PCM in larger pouches, tubes, or panels that interact with other building materials through conduction and convection. Macro-encapsulated PCMs are typically less costly than their micro-encapsulated counterparts, but may not release stored heat as effectively due to solidification of the PCM around the edges of the capsules [12].

## 3. PCM applications in buildings

There are multiple ways to incorporate PCMs into buildings to take advantage of their high thermal storage capacity. They can be used in both active and passive systems for heating and cooling. In passive applications, PCMs can be incorporated as separate components in the building's construction or integrated directly into building materials. Examples of PCM as a separate component include PCM panels installed below finish flooring and sheets of macro-encapsulated PCM pouches that are installed in a wall behind the gypsum board [17]. Examples of PCM integration into building materials include PCM-impregnated wallboard, concrete, ceiling tiles, and insulation. When used in this manner, PCMs will simply store or release energy if the adjacent air or surface temperature is above or below the melting point. Several studies using numerical simulation, experimentation, or both confirm that passive applications of PCMs can help moderate indoor air temperatures that would normally experience greater fluctuation due to direct solar gains, indirect solar gains, and other internal gains [8,10–12,17]. Behzadi and Farid [18] simulated a typical 171 $m^2$ house in Auckland, New Zealand and found that the use of PCM-impregnated gypsum board could reduce indoor temperature fluctuation by up to 4 °C on a typical summer day. Fernandes and Costa [19] used computer simulation to study the effect of PCM in a typical house in three locations in Portugal. Using gypsum board containing 3 $kg/m^2$ 25 °C PCM on the walls and ceilings, they found that reductions of 24–34% in hours over 25 °C were possible. The amount of temperature reduction and energy savings varies significantly and is influenced by local climate, internal gains, and other thermal characteristics of the building.

Considering that PCMs are a form of thermal energy storage, they require some means of dissipating their stored energy when used in passive cooling applications. By dissipating stored heat, the PCMs return to a solid phase and are then ready to begin the melt–freeze cycle again. While a melted PCM still offers some component of sensible heat storage, not allowing it to completely freeze at night hinders its ability to perform in a passive cooling application, as latent heat storage is the primary mechanism used to absorb heat throughout the day [19]. In certain climates with large diurnal temperature swings, natural nighttime ventilation can be used to take advantage of free cooling. Otherwise, dissipation of the PCM's stored energy results in additional demand on the mechanical cooling system.

Applications of PCMs in active systems have also been researched extensively [8,12,17]. Active systems use fans and pumps to transfer energy to air and water, which serve as the working fluids to move thermal energy. PCMs can be incorporated to store heat from the sun for later use when heating is desired, lessening the demand from active heating coils. Similarly, they can be used to absorb heat that would otherwise increase the load on active cooling coils. Persson and Westermark [20] simulated a PCM "cool storage" device designed to help cool a Passive House in Sweden and found that reductions of 22–36% of degree hours over 26 °C were possible with the inclusion of 50–400 kg of PCM. Zhu et al. [8] provide a review of PCM applications in active systems including solar heat pumps, in-floor heating, and a thermally active ceiling panel. The authors state that PCM applications in active systems are effective and technically feasible, however the economic feasibility of such applications should be carefully considered prior to their implementation.

Of particular interest in this study is a product called BioPCM$^{TM}$, a macro-encapsulated PCM made by Phase Change Energy Solutions, BioPCM$^{TM}$ is available in 0.42 m wide mats that come in lengths of 1.22 m or 2.44 m. The mats are designed to be fastened to wood or metal studs between the insulation and interior finish layer (e.g., gypsum board) of a wall or ceiling. It can also be installed