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A metric for characterizing the effectiveness of thermal mass in building materials

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HIGHLIGHTS

- Proposes a metric for interior thermal mass materials (floors, walls, counters).
- Simple, yet effective, metric composed of easily calculated 'local' and 'global' variables.
- Like Energy Star, the proposed metric gives a single number to aid consumer choice.
- The metric is calculated and compared for selected, readily available data.
- Drywall, concrete flooring, and wood paneling are quite effective thermal mass.

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ABSTRACT

Building energy use represents approximately 25% of the average total global energy consumption (for both residential and commercial buildings). Heating, ventilation, and air conditioning (HVAC) – in most climates – embodies the single largest draw inside our buildings. In many countries around the world a concerted effort is being made towards retrofitting existing buildings to improve energy efficiency. Better windows, insulation, and ducting can make drastic differences in the energy consumption of a building HVAC system. Even with these improvements, HVAC systems are still required to compensate for daily and seasonal temperature swings of the surrounding environment. Thermal mass inside the thermal envelope can help to alleviate these swings. While it is possible to add specialty thermal mass products to buildings for this purpose, commercial uptake of these products is low. Common building interior building materials (e.g. flooring, walls, countertops) are often overlooked as thermal mass products, but herein we propose and analyze non-dimensional metrics for the 'benefit' of selected commonly available products. It was found that location-specific variables (climate, electricity price, material price, insolation) can have more than an order of magnitude influence in the calculated metrics for the same building material. Overall, this paper provides guidance on the most significant contributors to indoor thermal mass, and presents a builder- and consumer-friendly metric to inform decisions about which products could best improve the thermal behavior of the structure.

1. Introduction

Thermal mass elements inside residential and commercial buildings represent an opportunity to achieve desirable load-leveling and peak-shifting behaviors with passive components which can be widely deployed in new and existing structures. While the thermal community has renewed its interest in the deployment of thermal mass elements in recent years [1–4], the realities of local and seasonal effects make thermal mass somewhat inaccessible to a general audience. Additionally, much work has gone into understanding thermal mass elements in the building envelope [5–8], while relatively little attention has been paid to materials commonly used in the interior of structures, in spite of demonstrated gains available from locating thermal mass on the interior of insulated walls [9,10]. This paper seeks to overcome a substantial obstacle in the widespread and thoughtful application of thermally massive interior building elements by examining

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salient local and seasonal characteristics alongside well-understood material properties and proposing a dimensionless metric which may be evaluated to capture the thermal mass 'benefit' for a variety of commonly available building materials.

At a fundamental level, thermal mass acts as a time-integrator for the temperature of a structure, slowing the unassisted heating and cooling rates of the occupied space. This behavior can be highly desirable; in the limit (for certain climates), it may allow a building to maintain a comfortable interior temperature at all times without mechanical heat transfer. This can lead to large energy savings, since at present about half of the end-use energy consumption in buildings in developed countries is devoted to space heating and cooling [11–14]. In a typical structure, the time-shifting accomplished via properly-designed thermal mass can move demand for cooling or heating away from the peak hours when power grids are most heavily stressed and prices are high. However, seasonality, local climate, structure orientation, and glazing all impact the design of a thermally-massive structure, rendering the topic somewhat difficult to generalize. Since thermal mass is a form of energy storage, we suggest that all materials found inside the building envelope have some effect on an energy management plan, though not always beneficial. For example, cryogenic systems employ extremely lightweight insulating materials – the addition of thermal mass would unacceptably lengthen cool-down times. In this sense, it can be helpful to think about a value of ride-through: a system that cannot tolerate fault events must have reserve capacity sized to a suitable fault (the size is a function of event probability and event severity). The power grid maintains excess generating capacity for this reason, and many offices have uninterruptible power supplies that allow safe shutdown of key equipment. There are costs associated with carrying reserve capacity; it must be built, maintained, and importantly, kept ready for use. If the costs associated with reserve capacity exceed its benefits, it becomes undesirable. It should be noted that cost may not be a factor for capacity which is inherent to a system, such as the thermal mass of building elements selected even for non-thermal reasons. In an occupied structure with a limited range of comfortable temperatures, heat may be stored in building elements at one end of the comfortable temperature range, allowing the occupied space and thermal mass to exchange energy and maintain acceptable air temperatures with reduced demand for mechanical heating and cooling. Building thermal mass allows a structure to absorb swings in ambient temperature within building elements, slowing the temperature response of the interior air, and allowing ride-through of temperature excursions such as a hot afternoon or a power outage.

1.1. Thermal mass quantification

Much of the recent literature on thermal mass is devoted to developing and incorporating phase change materials (PCMs) for buildings. Osterman et al. reviewed over 60 articles on this topic, most of which were published in recent years [15]. While PCM materials show a great deal of promise [16], many face reliability, cost, aesthetic, and installation challenges. These issues are slowly being overcome [17–19], but builders and property owners may still lack awareness of the advantages of PCM products, and these materials are not always readily available or affordable. On the other hand, common building materials (flooring, wall materials, and countertops) are already incorporated into every operational building – whether or not they were selected or recognized for their thermal mass benefits.

Some authors have considered studies of limited geographical scope across certain materials, examining the effect of material thermal parameters on overcooling and overheating [20]. Other studies have considered the effectiveness of thermal mass incorporated into the building envelope [5–10], where the heat path to or from the interior space passes through the massive element. In this configuration, thermal mass behaves as an inductor, soaking up or releasing heat as needed to resist the change in the imposed indoor-outdoor temperature difference. This application of thermal mass has much merit, reflected by various credits and rebates awarded for its employment [21,22], and has been investigated and even incorporated into various modeling tools [23]. A metric has been proposed by Kosny et al. for building-envelope thermal mass [7]. The Kosny et al. Dynamic Benefit for Massive Systems (DBMS) yields an equivalent *R*-value which is readily comparable to standard building-code requirements for thermally massive building systems. Al-Sanea et al. [9] employ an "energy savings potential" approach, which baselines the gains of a massive wall against the ideal of no energy consumption. This method is interesting when wall materials are known *a priori*, and dimensions may be varied to optimize performance. The current study proposes a means to weigh the relative local merits of materials, linking thermal properties with dimensions to allow a rapid evaluation of benefit across a multitude of choices.

The indoor temperature of a passive structure with a thermally massive building envelope can be estimated from a simple 'lumped' mathematical representation, as follows:

$$m_w \cdot c_{p_w} \cdot \frac{dT_w}{dt} = \dot{Q}_{sol} + \dot{Q}_{ext-conv} + \dot{Q}_{ext-rad} - \dot{Q}_{int-conv} - \dot{Q}_{int-rad} \quad (1)$$

where m is mass, c_p the specific heat, T the temperature, t time, $\dot{Q}$ heat load, and the subscript w represents the generic walls or envelope, *ext* and *int* indicate effects external or internal to the structure, and *sol*, *conv*, and *rad* indicate the type of heat load, whether solar, convective, or radiative.

In this formulation, the interior convective and radiative heat loads are functions of the wall temperature and the interior temperature, which would be fixed at a comfortable value. The wall temperature would be a function of thickness, with the interior and exterior skin temperatures used in the heat transfer calculations and an average through the thickness employed in the differential. Clearly this formulation neglects various higher order effects, but it suffices to note that a large $m_w \cdot c_{p_w}$ value will reduce the magnitude of $\frac{dT_w}{dt}$, slowing the change in wall temperature, meaning that (all Qs of Eqn. (1) being equal) cool walls stay cool longer and vice versa during the winter heating season.

Fig. 1 displays another method of employing thermal mass elements in a structure – decoupled from the exterior ambient, but in good contact with the interior of the structure. This can be classified as interior thermal mass and has been observed to be beneficial by various researchers [2–4]. A helpful analogy may be the use of a hot water bottle to warm a bed in a cold climate; the heat should be kept where it is wanted, inside the insulation. In this configuration, every object inside of a building may be considered as a thermal mass element.

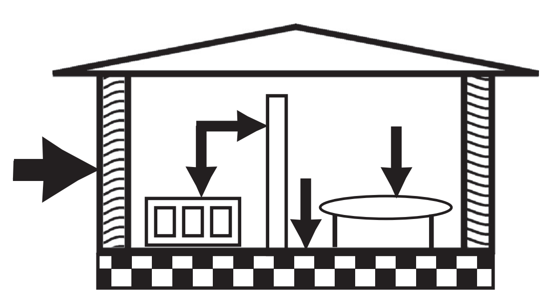

Fig. 1. Envelope and interior thermal mass accounting.