ASSESSING THE EFFECTIVENESS FOR THERMAL MASS IN THE BUILDING ENVELOP

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ABSTRACT
The well known steady-state R-value traditionally used to measure energy performance of a building element does not reflect the dynamic thermal behaviour of the envelope, in particular it does not account for the possible benefits of thermal mass in reducing energy consumption for heating and/or cooling. This paper describes research to provide simple design guidance on the benefits of thermal mass. The paper is set in the context of building code requirements in Australia. The first part of the paper gives a brief history of understandings on the role of thermal mass in improving building performance. The so called m-Factor and similar techniques are described and examined. A new technique is proposed to show the effectiveness of thermally massive walls constructed of precast concrete sandwich panels. Using advanced thermal performance computer software data are derived to construct a Calculator that determines a Mass Enhanced R-value. This R-value can be used to demonstrate Building Code compliance.

INTRODUCTION
It has been long understood that thermally massive building elements reduces the instantaneous heat transmission under transient conditions and that this in turn can lead to reduced overall energy consumption for heating and cooling a building. The Australian Government’s Your Home Manual (DCCEE, 2010) says, “Appropriate use of thermal mass throughout your home can make a big difference to comfort and heating and cooling bills” and further “Thermal mass is particularly beneficial where there is a big difference between day and night outdoor temperatures.” However, an Environmental News Article from a leading promoter of green building states, “The issue of thermal mass and its effect on the energy performance of buildings is one of the most confusing issues facing designers, builders, and buyers of buildings today” (Building Green, 2011). These confusions are particularly focused on the design of residential buildings were for the majority of buildings full thermal simulation is rare, and designers rely on simplified aids or rules-of-thumb for guidance. Confusion and misinformation can flourish because in most cases building regulations based only on the steady-state R-value (or U-value) of elements do not account for this effect.

This paper outlines work aimed at providing information on the mass effects of precast concrete sandwich panel construction. While the work concentrates on the context and requirements in Australia the methodology has wider applications.

BACKGROUND
For many years the development of a robust method to account for the thermal mass effect has been the Holy Grail for those involved with thermally massive building construction methods. During the 1970s the Masonry Industry Committee (MIC) in the USA developed the m-Factor concept to account for the mass effect in exterior walls of buildings (MIC, 1976). The m-Factor provided a correction to conventional steady-state heat flow through massive building elements. By the late 1970s the m-Factor had found its way into a number of codes and standards in the US, including ASHRAE Standard 90-75 Energy Conservation in New Building Design.

The development of the m-Factor method was done on behalf of the MIC by Hsing-Chung Yu working for the consulting engineers Hankins and Anderson Inc. (Yu, 1978).

1 The Masonry Industry Committee consisted of a consortium that included Brick Institute of America, National Concrete Masonry Association and Portland Cement Association.
represented the most critical time for heating during the year. The derived m-Factor chart (see Figure 1, converted to SI units) is given as a function of Heating Degree Days (HDD). It shows that the m-Factor correction is less in areas having large heating degree day values.

The validity of the m-Factor method was, however questioned by a number of authors because of the empirical basis of its development. A conference paper by Godfrey, Wilkes and Lavine (1979) concluded “the m-Factor, as defined by Yu, has been shown to be without technical justification” and recommended that “reference to the m-Factor method in codes and standards be deleted”(p 50). A larger study by Childs (1980) prepared for the US Department of Energy reached the same conclusion.

In 1983 the US Oak Ridge National Laboratory (Childs, Courville, & Bales, 1983) conducted research aimed at addressing the controversy regarding building mass and energy consumption for heating and cooling, and in particular Building Code requirements. They investigated a number of techniques suggested for taking into account the beneficial effects of mass (including the m-Factor). They found no simple theoretical way of accounting for the mass effects because the heat flow through individual elements was dependent *inter alia* on form of construction, orientation, colour, building use pattern, thermostat settings and climate. They did find, however, that in addition to the effect on energy consumption mass also affected on peak loads, equipment cycling, thermostat setback, and importantly it could have a beneficial effect on overall comfort.

![Figure 1: Mass Factor 'm' vs Heating Degree Days](image)

Despite these adverse findings defenders of the method maintained their claim that the results agreed with actual experience and the method continued to feature in prominent reference works (for example see Hunn, 1997)

In the late 1990s work in the US at the Oak Ridge National Laboratories by Kosny et al. (2001) further investigated the R-value equivalent for massive walls in comparison to the thermal performance of lightweight walls. They developed the notion of Dynamic Benefit for Massive Systems (DBMS) defined by equation (2); 

\[
DBMS = mR_{eqv} \times \frac{1}{R} \quad \text{Eq (2)}
\]

Where, \(DBMS\) - Dynamic Benefit for a Massive System;

\(mR_{eqv}\) - R-value equivalent for massive wall, and

\(R\) – steady state R-value

In this case DBMS is a dimensionless measure that expresses the benefits of thermal mass as a function of the material configuration and the climate. In a way the present work follows this approach.

**The Australian Building Code**

The 2010 update of the Building Code of Australia (BCA) increased the energy efficiency to a so called 6 Star energy rating or equivalent for new residential buildings, and as well as, provided for a significant increase in the energy efficiency requirements for all new commercial buildings. In addition the energy efficiency objective, functional statements and some performance requirements were revised to recognise that the goal is greenhouse gas emission reduction rather than energy efficiency per se. The revised Code sets stringency requirements for all elements covered by the deemed-to-comply provisions, for example, thermal resistance requirements for roof/ceiling, wall and floor elements. These stringency requirements are related to one of eight defined climate zones (see Figure 2). In simple terms the climate zones are graduated from Zone 1 (hot & humid) to Zone 8 (cold alpine). Earlier versions of the BCA specified the required R-value for walls as a function of the climate zone and also, in what seems in part like an echo of the m-Factor method, allowed for modifications of this value for walls of higher thermal mass and/or when shading was provided.

BCA 2010 continues with allowable R-value modifications for heavyweight wall elements with a surface density greater than 220 kg/m², albeit expressed a little differently. The reasons or logic for these ‘thermal mass’ allowances have never been documented by the Australian Building Codes Board (ABCB) and in fact a senior officer from the ABCB has told the author the allowances were “more politics than science It was about getting significant sections of the industry [for example, cavity brickwork construction] over the line.”

Looking particularly at the BCA Volume 2 that deals with residential construction, the minimum required basic R-value for a wall system is R2.8 for climate zones 1, 2, 3, 4, 5, 6 and 7 and R3.8 for climate zones 8. However these values may be modified or other allowances made in the case where the wall is shaded or is “heavyweight” with a surface density not less than 220 kg/m².

The modification options are generally in the form of packages of construction requirements that must all be fulfilled. A significant dispensation is that for

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2 Private communication
heavyweight walls in climate zones 1 to 7 (if other criteria relating to glazing performance and internal thermal mass are satisfied) the minimum required R-value of added insulation may be reduced to R0.5 or R1.0 depending on these other conditions. For climate zone 8 (the coldest regions) there is no allowance for heavyweight walls.

Figure 2: Map of BCA Climate Zones

The only documented explanation for these adjustments is given in the Information Handbook that accompanies the BCA Volume 2. It says in the energy-efficiency section,

Walls that achieve a surface density greater than 220kg/m² are considered to be high mass, which slows heat movement into and out of the building and can act to moderate temperatures inside the house.

INVESTIGATIONS

In order to explore the implications of the BCA allowances for thermal mass and to develop some comprehensive design advice a number of investigations were conducted. These are set out in this section of the paper.

Test Building and Simulations

Simulations of whole buildings involve complex input and it can be difficult to determine the impact of different factors. In order to try and narrow down some of the differences a BESTEST type building model was developed for the testing. This model is essentially a square single zone “building” 2.7m high. Four plan area variations were used including 8*8, 12*12, 16*16 and 32*32. Figure 3 shows a diagram of the 8m *8m test building. The basic model consists of a concrete slab-on-ground, flat ceiling with R3.0 insulation, external walls initially with insulation as specified for the location and standard aluminium-framed windows with glazing 3mm clear (U=7.32, SHGC=0.77) and 45% openable. The windows were equally disposed in the four facades with a total area corresponding to 18.75% of the floor area. A similar model was developed as an intermediate floor to assess the effects in multi-storey buildings. Occupancy profiles and thermostat controls, etc were set to conform to the appropriate requirements set out in the BCA for the type building.

Figure 3: Basic BESTEST Building Model, 8m*8m

All simulations were conducted using the CSIRO AccuRate energy simulation software for buildings version 1.1.4.1. While perhaps outdated, MsDOS commands still provide an efficient means to process data and batch routines were written to perform the many AccuRate runs and data manipulations. These batch programs employed a text file editor to alter as required the AccuRate “Scratch” text file that contains all the input data for the computational engine. As part of the batch procedures Fortran routines interrogated the various output files and wrote the required data to a *.csv file for analysis.

Figure 4: Concrete Sandwich panel Wall

To investigate the effect of walls with different surface densities a simple concrete sandwich panel wall was assumed in all simulations. This wall shown in Figure 4 consists of an outer concrete cladding, extruded polystyrene insulation and an inner concrete layer. The dimensions of the layers were adjusted to
get a series of surface densities and the thickness of insulation adjusted to produce an overall required R-value. In each series of AccuRate runs the “base-case” lightweight wall consisted of 20mm external and internal layers of concrete with the thickness of insulation set to provide a wall with the required R-value. For all other runs the outer layer was held constant at 50mm.

**The Mass Effect Correction Factor**

Initial simulations studied the effect of mass on the annual energy loads – sum of heating & cooling MJ/m² - estimated by AccuRate. These were conducted for a number of locations representative of the BCA climate zones. In each case the thickness of the polystyrene insulation was modified so that the R-value of the wall was as required by the BCA (either R2.8 or R3.3). The starting or base building had a plan area of 8m*8m. The first results shown in Figure 5 give the reduction in total energy load from the base-case lightweight wall building as the surface density (thickness of the inner layer) increases. It is clear from these results that increasing the mass of the external walls (all other variables remaining constant) can produce a substantial reduction in the total energy load. The effect is greatest in climates Zones 2 & 3 (eg Mildura & Longreach) where both summer and winter seasons are prominent. A number of variations from the base building were tested. One of the main effects resulted from a change in floor area. As shown in Figure 6 an increase in the floor area results in a decrease in the energy load normalised by the floor area (MJ/m²), but of course there is a resulting increase in total energy consumption. Of the various changes investigated shading the walls had generally the largest effect on the total energy load.

**A NEW mass-FACTOR**

From the large series of investigations outlined above it is clear that thermally massive walls may be used to advantage in reducing the estimated overall energy load. The challenge however is to simplify the effects so that clear yet robust guidelines can be developed. The procedure below aims to achieve this objective.

\[ m = \frac{R'}{R} \]  

*Eq (2)*

Where, 

- \( R' \) = R-value determined for massive construction at constant Q
- \( R \) = R-value specified in BCA for location Q
- \( Q \) = energy load (MJ/m²) estimated for wall with \( R \)

For this research the values of the \( m \)-Factor were determined by the following method. First, the value of \( Q \) (the total energy load) was determined by AccuRate simulation for an assumed lightweight wall construction. Then a higher surface density wall was “constructed” increasing the thickness of the internal layer of the precast concrete sandwich panel (the thickness of the outer layer remains constant at 50mm). Simulations were then performed decreasing the thickness of the insulation layer until the total energy load matched the initial (lightweight) \( Q \) value. A Newton-Raphson iteration technique was employed to quickly converge the solutions. Once the thickness of the insulation was determined the \( R \)-value and therefore the mass-Factor could be calculated. The simulation procedure was repeated keeping the outer panel layer constant but increasing the inner layer in seven steps up to a surface density
of 880 kg/m², that is, an inner layer thickness of 300mm.

Figure 7 shows the outcomes for the 8m*8m base building in the same locations presented in Figure 5. The result show that the mass-Factor decreases with increasing surface density and the relationship between mass-Factor and surface density varies with climate.

Figure 7: m-Factor v Surface Density for various climates, 8m*8m building

The results indicate for this example that the R-value of heavyweight construction could be reduced significantly while keeping the total energy load constant in each location. While however interesting these results do not offer much in the way of general design guidance because the many variations due to, for example, building size, shading, window properties, occupancy patterns, etc are not accounted for. Another step is therefore introduced. For a given location (climate zone) a large series of simulations were performed corresponding to possible and permitted design variations. Figure 8 and 9 illustrate a number of simulations conducted for the Sydney and Brisbane locations respectively when the walls are unshaded. The variations correspond to different floor areas, window type and area, occupancy loads, etc. It will be noticed that for each case one “solution” provides a worst case scenario, that is, it has the biggest mass-Factor values. If the Building Code is aimed at providing “minimum” construction standards, then using this worst case has a functional legitimacy.

A best fit polynomial expression is found for this case in each climate zone and these define the m-Factor for unshaded walls for that location.

Figure 8: Simulation Series for Sydney (unshaded walls)

Figure 9: Simulation Series for Brisbane (unshaded walls)

Figure 10 shows the results for unshaded walls for each climate zone. Each is the most conservative solution.

Figure 10: Composite mass-Factors (unshaded walls)

To complete the data required to formulate a systematic design guide further sets of simulations were done and mass-Factors determined with
different wall shading configurations as defined in the Building Code by the angle subtended by the overhang of a projection, see Figure 11.

![Figure 11: Definition of Shading Angle](image)

**MASS ENHANCED R-VALUE CALCULATOR**

A Mass Enhanced R-value $R_{ME}$ can be derived from a re-arrangement of Eq (2) as,

$$R_{ME} = \frac{R}{m}$$

Where, $m$ = mass-factor (m-Factor), and $R = \text{Steady state thermal resistance or R-value of element.}$

Based on the m-Factor data set described above a Mass Enhanced R-value Calculator has been developed specifically for precast concrete sandwich panels.

The Calculator, shown in Figure 12, allows a designer to easily determine $R_{ME}$ which is checked against BCA requirements to assess compliance. The only input required is, the thickness of the panel layers, the climate zone, the shading angle and the Class of building. In calculating the Mass Enhanced R-value the outer layer is constrained to a maximum thickness of 50mm. Some results are shown in Table 1 for an unshaded concrete sandwich panel comprising 50mm concrete outer layer, 80mm EPS insulation layer and 150mm internal concrete layer. The steady state R-value for this wall is 2.4 m²K/W.

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>Mass Enhanced R-value m²K/W</th>
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<tbody>
<tr>
<td>2</td>
<td>5.17</td>
</tr>
<tr>
<td>4</td>
<td>3.98</td>
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<tr>
<td>5</td>
<td>4.19</td>
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<tr>
<td>6</td>
<td>3.45</td>
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Corroboration of the method has been thoroughly demonstrated by a series of test cases. In these examples building performance is simulated first with a lightweight external wall with an R-value corresponding to the minimum BCA requirement for the class of building and climate zone. The total energy load (MJ/m²) for this base case is then compared with the case where all the external walls are of precast concrete panels have a Mass Enhanced R-value determined from the Calculator, again equal to the BCA minimum. No other changes are made for the simulation.

The results show that in all cases (within the limits of rounding errors, etc) the building with the precast concrete panel walls has an energy performance less than or equal to the lightweight wall case.

**CONCLUSION**

This paper has investigated the benefits of thermal mass in reducing the total energy load for heating and cooling. The aim has been to develop a methodology by which designers can, in a relatively simple way, assess the beneficial effects of thermally massive walls and allow for this effect in meeting deemed-to-comply provisions of a building code.

A new mass-Factor has been proposed and a study of its variations related to precast concrete sandwich panels made using the AccuRate thermal simulation software. A Mass Enhanced R-value Calculator has been created (based on more than politics) that provides a scientific approach to accounting for the mass effect of precast concrete sandwich panel walls. This can be used in conjunction with existing minimum R-value Code requirements.

What is clear from the results (see for example Figure 10) is that massive wall construction can be used in a beneficial way to reduce the simulated demands for building heating and cooling. The advantage of mass is reduced in colder climates (Zones 6 & 7) and for the other climate zones the benefit can be divined as a combination of the mean monthly daily temperatures, the average monthly diurnal temperature swings and importantly the relationship of these to the thermostat settings for heating and cooling established for the simulations. These thermostat settings fix the implied benefits of massive wall construction in the context of the building code. In actual practice the benefits may be enhanced or reduced depending on the actual operation of the building.

This research has been based on one particular wall configuration, changing this configuration is likely to have an effect on the mass-Factor. Therefore, additional research is needed to test the mass-Factor methodology against different high thermal mass construction configurations incorporating different materials and the placement of thermal mass.
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REFERENCES


