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THE EFFECT OF VERTICAL AND HORIZONTAL THERMAL MASS ON THE THERMAL PERFORMANCE OF AUSTRALIAN HOUSING

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ABSTRACT

An appropriately designed house leads to the reduction of greenhouse gas emissions and decreases in heating and cooling costs, as well as maintaining acceptable levels of comfort for the occupants. Good thermal performance of housing leads to lower energy consumption and an appropriate thermal comfort level regardless of the weather conditions. This paper presents the results of a study of the impact of internal partition walls and the interior leaf of multi-layered enclosure walling systems (such as cavity brick and reverse brick veneer), on the overall thermal performance of typical Australian housing systems. The thermal performance of several housing test modules incorporating different walling systems with various amounts of thermal mass with/without carpet on the slab-on-ground floor was observed over a range of weather conditions. The study empirically confirmed that the influence of the horizontal thermal mass of the floor slab was greater for those modules with lightweight or insulated brick veneer walling systems (modules for which the slab floor is the only interior component of thermal mass). The internal air temperature was also less impacted by external temperature changes when no carpet covered the floor and brick masonry was present in the internal leaf of the enclosure walls (i.e. for cavity brick and insulated cavity brick modules).

KEYWORDS: *thermal mass, thermal performance, thermal lag, temperature fluctuations*

INTRODUCTION

Material selection during the design of a building has a major influence on the energy consumption and performance over its life cycle. The increasing emphasis on energy efficiency and the resulting reduction in carbon emissions is increasing the focus on novel design principles

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for all buildings, supported by the use of suitable materials. Designing for energy conservation requires study of the combination of factors that affect energy consumption. This presents major challenges for builders and architects to deliver designs that are functional whilst also energy efficient.

Australian housing is typically constructed from brick veneer or cavity brick walling systems, with some single skin, partially grouted and reinforced hollow masonry construction in cyclonic areas. The environmental impact of Australian housing up to the 1990's was of the little concern, with designs being governed mainly by economic and aesthetic considerations. Over the years houses have also become larger with an increasing numbers of appliances and reliance on artificial means of heating and cooling. Although building methods have improved, there is still heavy reliance on heating and cooling systems to create comfortable interior conditions with little emphasis on energy efficiency and environmental impact.

The current regulatory climate now requires all housing to be assessed for energy performance. There is thus a need to establish the thermal characteristics of the typical walling systems in the range of Australian climates under all seasonal conditions. In this context, researchers at the University of Newcastle, in collaboration with Think Brick Australia, are involved in a major study of the thermal performance of Australian housing with a view to utilising more effectively the benefits of thermal mass which is inherent in walling systems [1-4]. In this study four full scale housing modules have been used to provide qualitative and quantitative data on the thermal performance of various walling systems (including various combinations of lightweight and masonry components; i.e. brick veneer; insulated cavity brick; cavity brick and insulated reverse brick veneer) under real climatic conditions. The typical heat flow mechanisms were then studied to assess the actual behaviour of various walls. This paper concentrates on the impacts of internal partition walls (consisting of either timber-framed plasterboard walls (LPW) or 110mm thick brickwork panels (HPW)) and the interior component of the enclosure walls (timber-framed plasterboard walls or 110mm thick brickwork).

One innovative walling system being investigated is "reverse brick veneer", which is made up of a lightweight external cladding supported by a timber frame with insulation and an internal non-structural brickwork skin (that is, the direct reverse of conventional brick veneer). The potential advantage of this system compared to brick veneer is that the benefits of internal thermal mass are provided by the internal brickwork skin.

In the building environment, a major component of energy consumption is directly related to the thermal performance of housing. A housing system with good thermal performance has a steady and comfortable internal environment and needs less energy to reach an appropriate thermal comfort level regardless of the weather conditions.

The temperature and solar energy varies with the seasons due to the changing of solar angle, (see Figure 1), and this with an appropriate location of thermal mass affects the thermal performance of the houses. Dampening effect of the diurnal temperature swings has been observed for the modules with the thermal mass of the heavy walling component within the interior of the houses.

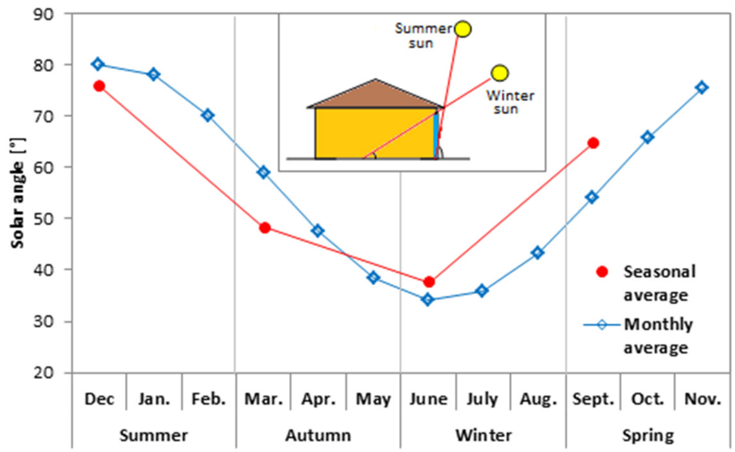

Figure 1: Influence of season on solar angle.

The thermal performance of four walling systems (insulated brick veneer; insulated cavity brick; cavity brick; and insulated reverse brick veneer) is reported and discussed for typical diurnal cycles. The relative performance of the four systems varied with season, but in general, compared to conventional brick veneer, the thermal mass of heavy walling systems located on the interior side of the buildings was more effective in dampening the effects of the diurnal temperature swings and maintaining the internal temperatures within acceptable levels of thermal comfort.

OVERVIEW OF EXPERIMENTAL MODULES

The research reported here is part of an on-going study which involves a detailed investigation of the performance of the various walling systems used in Australian housing, (detailed description of the project can be found in [1]). All wall elements as well as walling systems were tested in a Guarded Hot Box apparatus (constructed in accordance to the ASTM C1363) to obtain their thermal resistance (R-value). Each walling system was then incorporated into a representative full scale housing module to observe its performance in a complete building under real weather conditions.

The modules were constructed on the University of Newcastle Callaghan Campus in suburban Newcastle (Newcastle is located on the east coast of Australia at latitude 33°south which has a typical moderate Australian climate). Over the testing period, a range of walling systems have been used (cavity brick, insulated cavity brick, brick veneer with and without insulation, lightweight construction and insulated reverse brick veneer). For this paper, only the CB (cavity brick), InsCB (insulated cavity brick), InsBV (insulated brick veneer) and InsRBV (insulated reverse brick veneer) modules with R–values of 0.44, 1.30, 1.58 and 1.58 [m^2K/W] respectively are considered and described in Table 1. Each module was observed with the interior space being either in a 'free-floating' state (directly influenced by real weather conditions), or with the interior artificially heated or cooled to a present temperature range. The typical modules are shown in Figures 2(a) and 2(b).

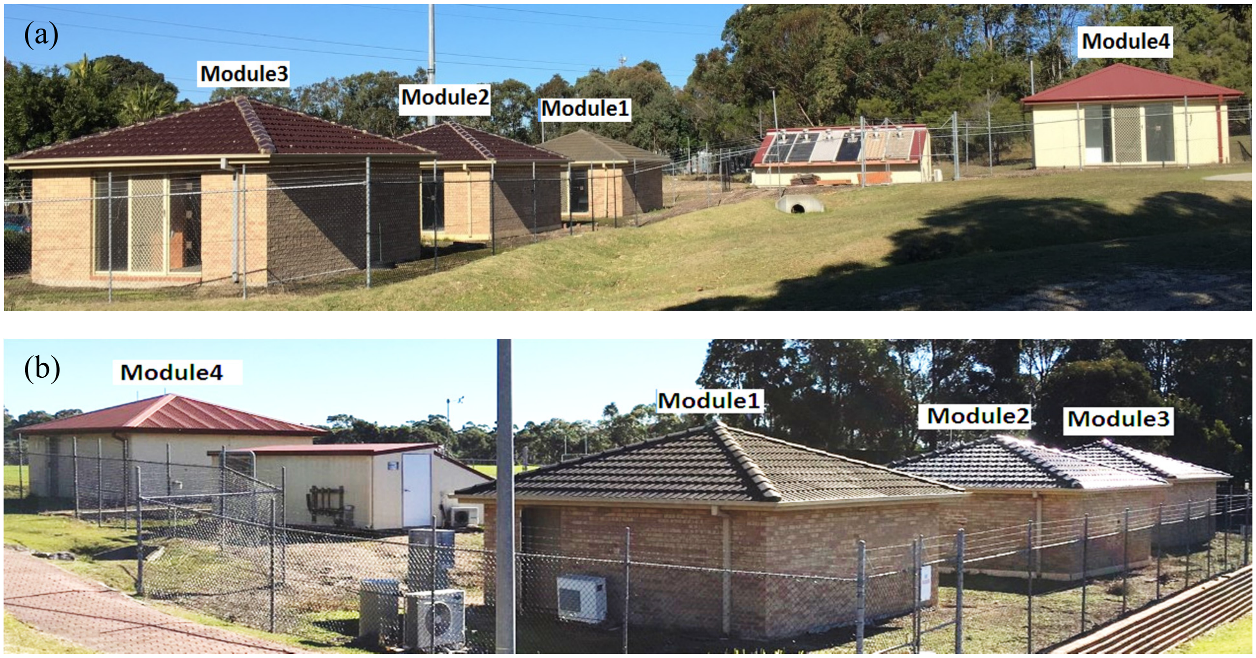

Figure 2: View of modules: (a) from Northern view and (b) from Southern view. Note: Module 1 – InsBV, Module 2 – InsCB, Module 3 – CB, Module 4 – InsRBV modules.

The modules had a square floor plan of 6 m x 6 m and were spaced 7 m apart to avoid shading and minimise wind obstruction. With the exception of the walls and roof, the buildings were of identical construction following standard Australian practice, being built on a concrete slab-on-ground and aligned in a manner so that the north wall of each building was aligned to astronomical north. Timber trusses were used to support the roof which consisted of tiles for the CB, InsCB and InsBV modules and steel sheeting for the InsRBV module, in both cases placed over a layer of sarking. The buildings had a ceiling height of 2450 mm. The ceiling consisted of 10mm thick plasterboard with glasswool insulation batts (R3.5, i.e. R=3.5 [m2K/W]) placed between the rafters. Since the emphasis of the investigation was on wall performance, the R3.5 insulation was selected to minimise the "through-ceiling" heat flow. Entry to the buildings was via tight fitting, insulated solid timber doors located on the southern face of the buildings. The roof was supported by an independent steel frame which allowed the removal and replacement of walls as required.

Table 1: Details of Module Components

Walling system	Material(s)	Insulation	R-value [m^2K/W]
Cavity brick wall (CB)	2x110mm brickwork skins with 50mm cavity; 10mm internal render	Standard 50mm cavity	0.44
Insulated cavity brick wall (InsCB)	2x110mm brickwork skins with 50mm cavity; 10mm internal render	Standard 50mm cavity and R1 polystyrene insulation fixed to cavity side of interior brick skin	1.30
Insulated brick veneer wall (InsBV)	110mm external brickwork skin; 50mm cavity; internal timber frame; 10mm plasterboard	Low glare reflective foil on timber frame with or without R1.5 glasswool batts	1.58
Insulated reverse brick veneer wall (InsRBV)	2-3mm acrylic render on 7mm fibro-cement sheets on timber stud frame; internal 110mm brick skin; 10mm internal render	R1.5 glasswool batts	1.58
Heavy Partition Wall (HPW)	110mm brickwork	No insulation	0.1
Lightweight Partition Wall (LPW)	10mm plasterboard on 90mm timber stud frame	Air gap	0.5

Initial tests were performed on windowless modules. The influence of a window was then assessed by the installation of a north-facing 3-panel sliding door assembly, 2050 mm high x 2840 mm wide, representing ≈20% of the floor area which is a typical living room window/floor area ratio. Instrumentation recorded the external weather conditions including wind speed and direction, air temperature, relative humidity and the incident solar radiation on each wall (vertical plane) and on the roof (horizontal plane). For each module, temperature and heat flux profiles through the walls, slab and ceiling were recorded in conjunction with the internal air temperature and relative humidity. Heat flux sensors were placed on the walls, ceilings and concrete slab, adjacent to the window (in direct sunlight) and in the south-east corner. Thermocouples were placed on the surface of the slab at various locations between the window and the centre of the room. For the window, three net radiation sensors were placed at heights of 600, 1200 and 1800mm up the glass panel to assess the incoming/outgoing radiation. The surface temperature of the glass was recorded and additional heat flux sensors were placed on the aluminium frame to assess the influence of the frame itself. Internal air space temperatures were also monitored at heights of 600, 1200 and 1800mm with the relative humidity and globe temperatures being measured centrally. In total, 105 data channels were scanned and logged every 5 minutes for each of the modules for the duration of the testing program.

To study the influence of internal thermal mass, two partition walls either a lightweight stud wall (LPW) or a 110 mm heavy masonry wall (HPW) was later installed into modules (see Figure 3).

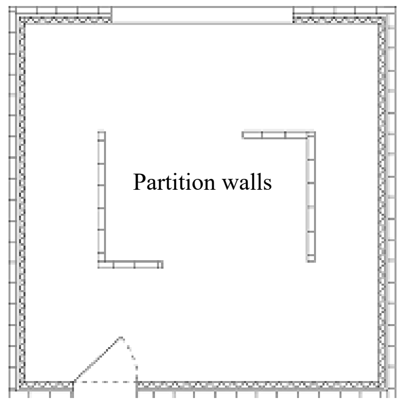

Figure 3: Arrangement of internal partition walls for the InsBV module.

Each season included periods in which the interior of the modules was allowed to “free float” or be “controlled” within a temperature range of 18-24ºC and the heating/cooling energy measured. There was no artificial ventilation and the concrete floor slabs were not fitted with carpet. Since the conditions for each module were identical, direct comparison of performance can be made.

DIRECT EFFECT OF LIGHTWEIGHT AND HEAVY PARTITION WALLS

The direct contribution of the internal thermal mass of the internal partition walls for the thermal performance has been assessed by comparison of the performance of the InsBV module fitted with either lightweight or heavy partition walls. The performance was compared for periods in two different years but in the same seasons and for periods with very similar external air temperatures and solar radiation.

The heat absorbed and released by both lightweight and heavy partition walls for two selected days (18/10/2009 and 23/10/2012) for the InsBV module is shown in Figure 3. The heavy partition wall was able to store much more heat during the day and then release it back at night than its lightweight counterpart. This meant that the InsBV module with heavy partition walls maintained a more stable internal environment for the occupants, exhibiting lower daytime and higher night time temperatures swings.

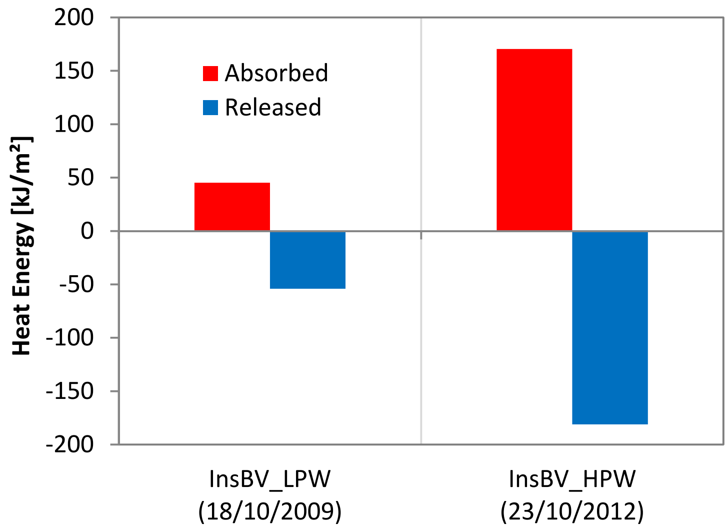

Figure 3: Heat absorbed and released by the lightweight and the heavy partition walls of the InsBV module during one-day period in October 2009 and 2012

The average diurnal temperature variations of the internal air for the InsBV module with the lightweight and the heavy partition walls in different seasons are presented in Figure 4. Generally, the diurnal temperature variations of the internal air for the InsBV module exhibited a similar trend across all seasons with a lower average diurnal temperature variation for the heavy partition walls of about 20%.

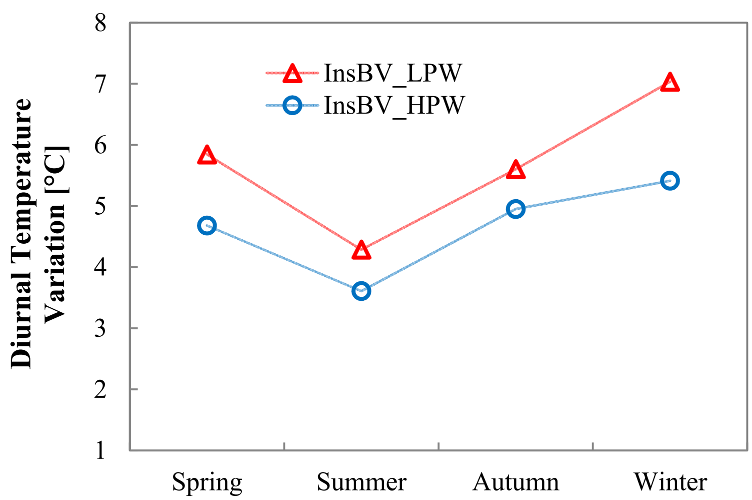

Figure 4: Diurnal temperature variations of internal air for the InsBV module with the lightweight and the heavy partition walls in different seasons

THE CONTRIBUTION OF THE THERMAL MASS OF THE EXTERNAL ENCLOSURE WALLS

A direct way to assess the contribution of the internal thermal mass of the enclosure walls is to compare the performance of two different modules with the only difference between them being the internal leaf of the enclosure walls. Comparison of the performance of the InsBV module, which has only a lightweight internal leaf (a timber-framed plasterboard wall with low thermal mass but high thermal resistance (R-value = 1.58 m^2K/W); and the CB module, which has a 110mm thick internal brickwork leaf of high thermal mass but low thermal resistance (R-value = 0.44 m^2K/W), see Table 1.

The total energy absorbed and released by the internal surface of the enclosure walls for both modules during one selected day is shown in Figure 5. The interior skin of the enclosure walls for the CB module absorbed and released much more heat during the day and the night respectively than the InsBV module, resulting in more stable internal air temperatures in the CB module.

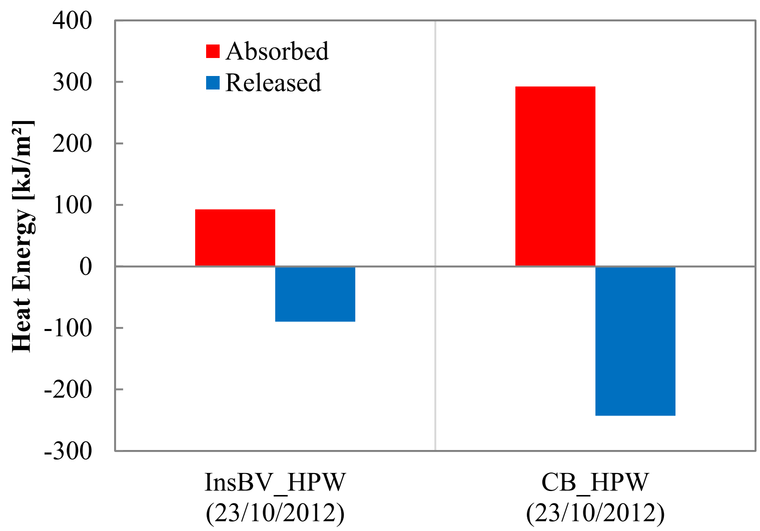

Figure 5: Heat absorbed and released by the internal surface of the enclosure walls for the InsBV and CB modules with heavy partition walls during one-day period in October 2012

The diurnal temperature variations of the internal air for the InsBV and CB modules for different seasons are shown in Figure 6. The CB module, with higher internal thermal mass (contributed by the interior leaf of the enclosure walls), had significantly lower internal temperature variations across all seasons than the InsBV module, (about 30% on average) as shown in Figure 7.

It is also of interest to compare the performance of two enclosure walling systems with the same R-value of 1.58 [m^2K/W] but with different arrangements of thermal mass, i.e. the insulated reverse brick veneer construction (InsRVB) which has enclosure walls with a heavy internal leaf, and the insulated brick veneer construction (InsBV) which has enclosure walls with a lightweight internal leaf, see Table 1.

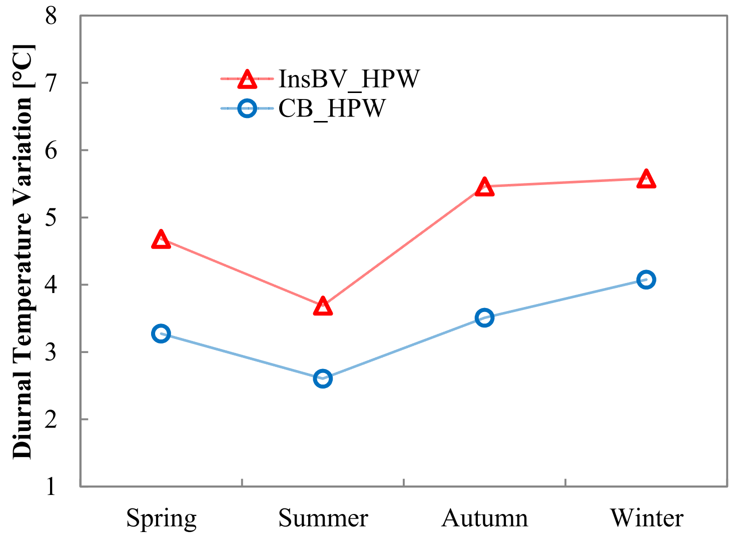

Figure 6: Diurnal temperature variations of internal air for the InsBV and CB modules with heavy partition walls in different seasons

Both modules also contained LW partition walls. The diurnal temperature variations of the internal air for the InsBV and InsRBV modules between seasons varied by approximately 26% (see Figure 7). The consistently higher temperatures in the InsBV module indicate that the brickwork leaf of the InsBV module, located on the outside face of the wall on the external side of the insulation layer, was less effective in influencing the internal temperature than the heavy internal leaf of its InsRVB counterpart.

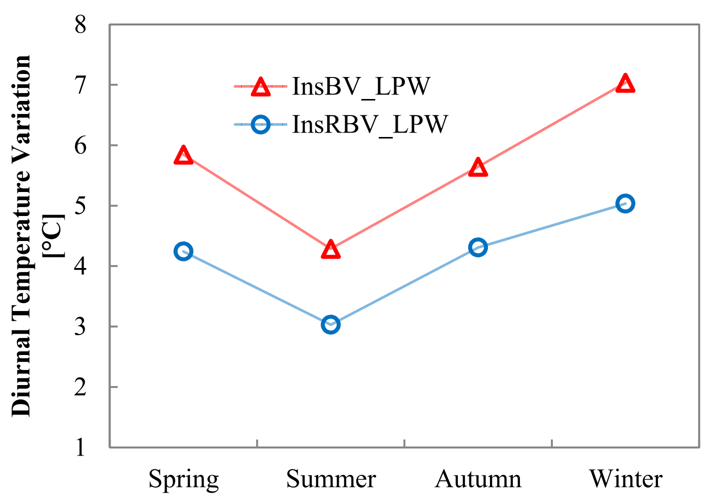

Figure 7: Diurnal temperature variations of internal air for the InsBV and InsRBV modules with lightweight partition walls in different seasons

THE CONTRIBUTION OF HORIZONTAL THERMAL MASS

The concrete slab, together with any internal walls, provides a source of internal thermal mass. The covering of interior high thermal mass flooring with a carpet reduces the thermal mass effect of the flooring. However, the carpet will have a different impact within different buildings depending on the relative proportions of internal thermal mass of the flooring and other components such as partition walls. The comparison of the effect of horizontal (slab) thermal mass on the thermal performance of three modules in this study (InsBV, CB and InsCB) with and without carpet on the slab-on-ground floor is shown in Figure 8. Due to other experimental constraints, comparative data were only available for autumn/winter for the periods between June and July in both 2007 (no carpet) and 2008 (carpet). This was in a period of high solar gain through the north facing window due to the decreased solar angle which exists for this period (see Figure 1).

It can be seen from Figure 8 that the carpet influence was more appreciable for the module with a lightweight internal enclosure wall skin (InsBV). In this case, the slab was the major contributor to the internal thermal mass. The difference was less marked for the modules with heavy internal brickwork skins (CB and InsCB), where the thermal mass of these components, in addition to the concrete slab, also had a positive influence on the internal temperature.

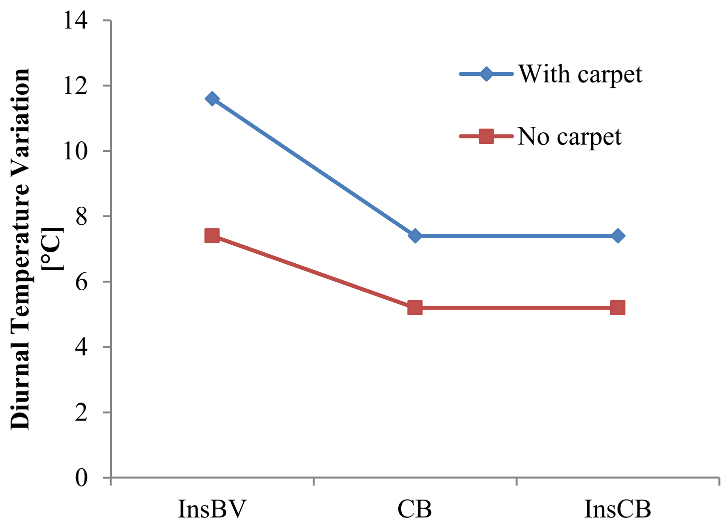

Figure 8: Diurnal temperature variations of internal air for the InsBV, CB and InsCB modules with and without carpet

CONCLUSIONS

The impact of internal thermal mass of masonry components in the form of internal partition walls and the interior leaf of multi-layered enclosure walls on the overall temperature variations and energy consumption of housing are discussed in the paper. The relative performance of the walling systems varied with seasons, but in general, the thermal mass of the partition walls and internal skins of enclosure walling systems was more effective in absorbing energy from solar ingress and reducing the effects of the external diurnal temperature swings.

The diurnal temperature variations of the internal air for the InsBV module exhibited a similar trend across all seasons with a lower average diurnal temperature variation for the heavy partition walls of about 20%. The energy absorbed and released by the heavy partition walls was also over 3 times higher than for the lightweight counterparts. The diurnal variation of the internal air temperatures for the CB module was about 30% lower than the InsBV module. The CB module with high internal thermal mass had significantly lower (about 30% on average) internal temperature variations across all seasons than the InsBV module.

Despite the walls having the same and overall thermal mass, a 35% reduction in diurnal temperature variation was obtained for the InsRBV modules by reversing the location of the thermal mass component of the enclosure walls compared to the InsBV, This confirms that significant amounts of heat were stored and released by the internal leaf of the enclosure for the InsRBV module, creating more stable and comfortable internal conditions.

Carpet reduces the thermal inertia effect of the floors which have the potential to act as a high thermal mass reservoir. When no carpet masks the contribution of the horizontal thermal mass of the floor, the room interior air is less sensitive to external temperature changes, with improved thermal performance.

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