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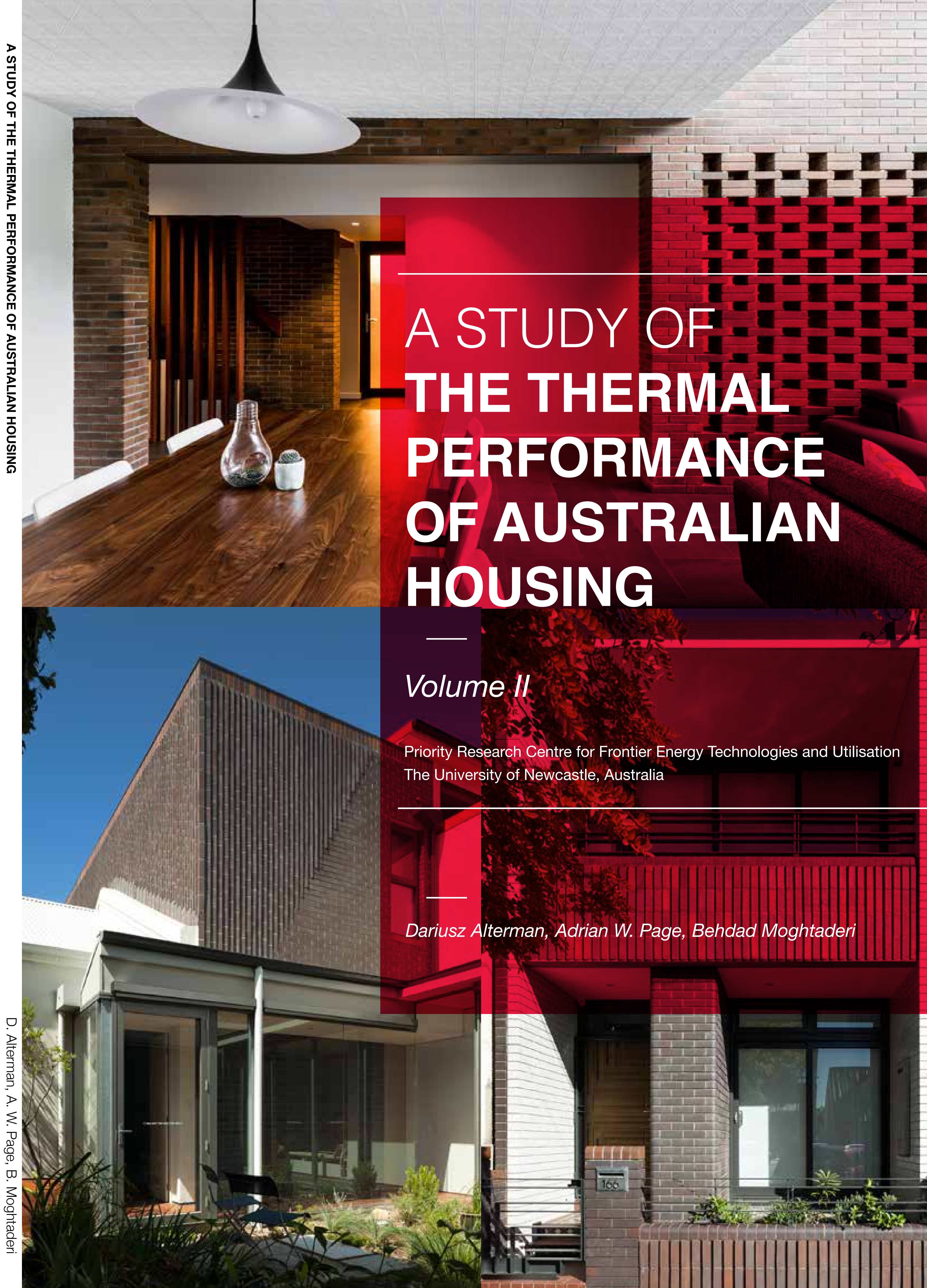
D. Alterman, A. W. Page, B. Moghtaderi



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Volume II

Priority Research Centre for Frontier Energy Technologies and Utilisation
The University of Newcastle, Australia

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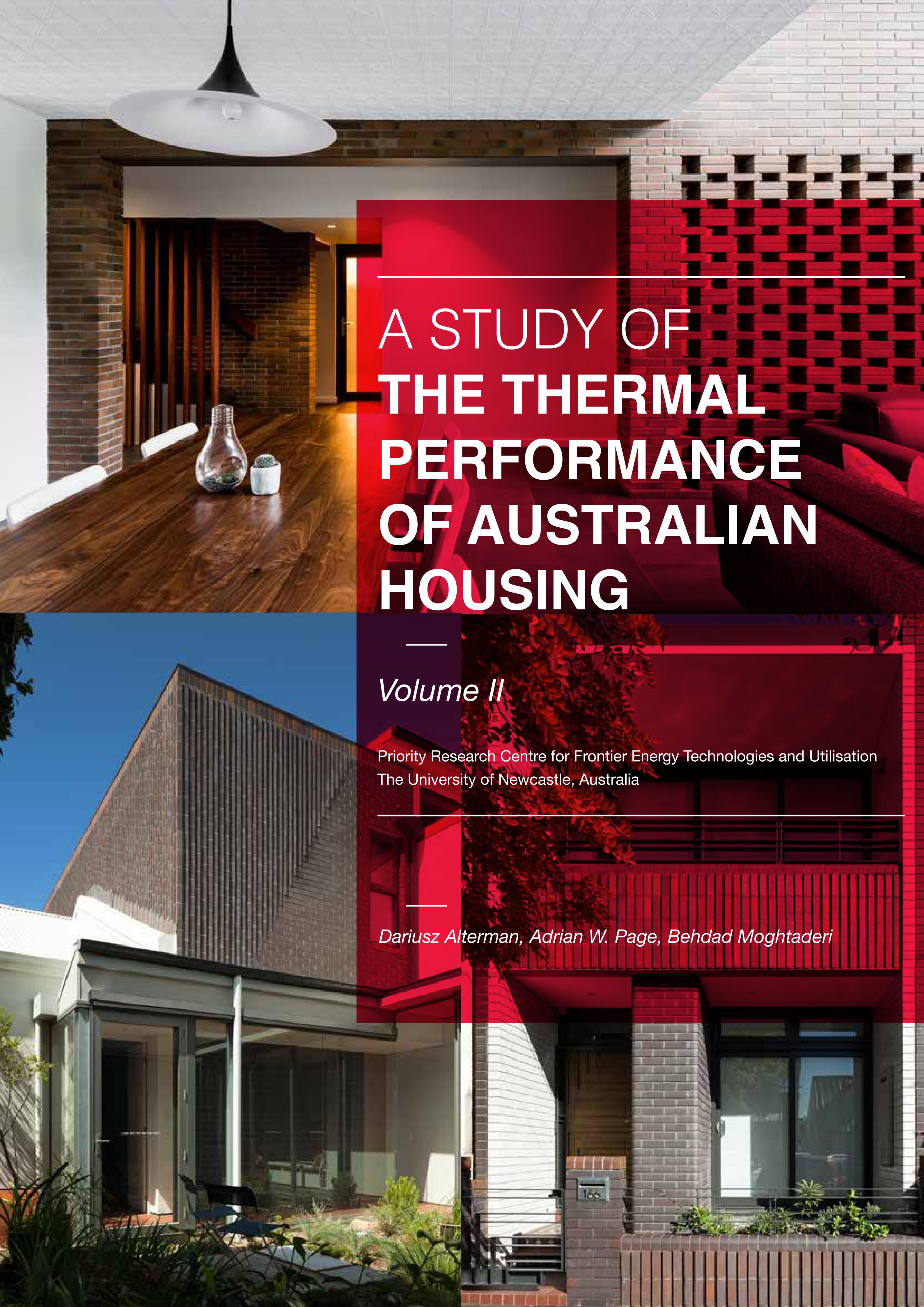

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Executive Summary

Due to global warming and other factors, there is an ever-increasing emphasis on energy conservation and efficiency. In Australia, a significant proportion of the end energy usage in domestic buildings is from space heating and cooling. Consequently, achieving improved energy efficiency in buildings has become one of the major challenges for architects and other building designers. One of the shortcomings of current simulations of thermal performance is the lack of real data on the performance of various housing walling systems under Australian climatic conditions. One particularly important aspect is the consideration of the contribution and interaction of the thermal resistance and thermal mass of each wall, which directly influences the wall and building performance under each (dynamic) diurnal temperature cycle.

With a view to overcoming the shortage of real data, the University of Newcastle, in partnership with Think Brick Australia, has undertaken a major theoretical and experimental study of the thermal performance of housing systems in a typical moderate Australian climate. This extensive 15 year study, commenced in 2001, has been based in the Priority Research Centre for Frontier Energy and Technologies (previously the PRC for Energy) and has involved the collaboration of research groups from Civil and Chemical Engineering. Funding for the project has been provided by Think Brick Australia and the Australian Research Council (through several linkage grants), together with substantial in-kind support from staff of the School of Engineering in the Faculty of Engineering and Built Environment. The first phase of the project (Phase 1) mainly involved data collection and analytical modelling, and was completed in 2009. A report of this section of the work has already been published (1).

This Phase 2 report directly follows Phase 1 and presents the outcomes of the research from the latter part of the project. The Phase 2 research has two major strands:

- Strand 1: continuation of the observation and analysis of the performance of the four full scale housing test modules located on the University of Newcastle campus (constructed as part of the Phase 1 research). Over the testing period, modules incorporating various walling systems (with and without internal partitions) have been used, with the interior of the modules being allowed to either "free float" or be controlled within a given temperature range by the use of artificial heating or cooling.
- Strand 2: the detailed study of the performance of walling systems and their components when subjected to dynamic temperature cycles simulating various Australian climate zones (in particular, the development of measures reflecting the contribution of both thermal resistance and thermal mass to the wall and building performance).

This report presents detailed results, for all four weather seasons, of the thermal performance of the housing modules incorporating a range of walling types. The contribution of other factors such as carpet, internal heavy and lightweight internal partitions and the specific roles of thermal mass and insulation are also studied. The outcomes of a parallel study of individual walls and wall components subjected to simulated dynamic diurnal temperature cycles are also presented, together with the subsequent development of the T- and S- value concepts which are able to represent the thermal behaviour of walls and building enclosures.

The main features and outcomes from Phase 2 of the study are outlined below.

Strand 1 - Housing Test Modules

Since each module was designed to allow the selective replacement of walling systems without disturbing the roof structure, a large range of wall types, wall configurations and wall opening conditions were able to be considered. The wall types reflected typical Australian construction practice and were uninsulated and insulated cavity brick (CB and InsCB), uninsulated and insulated brick veneer (BV and InsBV), insulated reverse brick veneer (InsRVB) and insulated lightweight (InsLW).

The tests were performed over a number of years and seasons, with the interior of each module being allowed to either free float under the external conditions, or be controlled within a set temperature range to maintain the thermal comfort of the interior. Data for all weather conditions and seasons with or without

the inclusion of a northern window opening was therefore potentially available. Some early results were presented in the Phase 1 Report published in 2011 (1). Aspects investigated in this Phase 2 Report include the following:

1. study of the significance and interaction of wall thermal mass and thermal resistance;
2. significance of wall thermal mass location;
3. influence of internal lightweight or heavy weight partitions;
4. influence of carpet on thermal performance;
5. influence of a major window opening in the northern wall and the associated mechanisms of heat transfer;
6. seasonal energy demands for the various walling systems to maintain reasonable internal comfort levels.

Detailed discussion and results of this section of the study are contained in Chapter 2. Some principal outcomes are briefly described below. The performance of the various walling systems in the module tests have also been used in research reported in subsequent chapters as background to the development of laboratory dynamic testing procedures and the formulation of the dynamic thermal response concept which can be applied to both individual wall assemblages and complete building enclosures.

1. *Seasonal Analysis of the Energy Demands for a Controlled Interior.*

   The energy required to maintain the internal thermal comfort of the CB, InsCB, InsBv and InsRVB modules was monitored over the four seasons. The study revealed the following:

   i. The two alternative extreme cases of high thermal mass with no insulation (the CB module), and insulation with external thermal mass (the InsBV module), both required higher energy consumption for every season. Despite the InsBV walls having an R-value 14% higher than the InsCB walls, the InsBV module required 20% more energy for all seasons. The worst performing module was the CB, with an energy demand 60% higher than the corresponding InsCB module. Note that a similar trend was observed in a parallel study of the performance of the modules under free floating internal conditions conducted as part of the Phase 1 investigation (1).This again confirms that there is no direct correlation between building performance and wall R-value alone; the best solution lies with an appropriate combination of wall insulation and thermal mass.

   ii. Investigations into the heat flow through the walls indicated that, compared to InsRVB module, the additional external thermal mass from the external brickwork skin in the InsCB module provided increased dampening of the external conditions and also helped to decrease the environmental impact on the cavity surface of the internal thermal mass. External insulation alone did not provide this formof cavity dampening.

   iii. The results clearly showed that internal comfort levels and energy demands are influenced by both the thermal resistance of the walls as well as the extent and location of the thermal mass. The best thermal performance will therefore be obtained by an appropriate combination of both thermal mass and resistance,rather than focusing on the wall thermal resistance (R-value) alone.

2. *Influence of Thermal Mass and Thermal Resistance on Wall Performance*

   Study of the thermal behaviour of four windowless modules with varying degrees of thermal mass and thermal resistance (CB, InsCB, BV and InsLW) revealed the following:

   i. The insulated cavity brick (InsCB) walling system had the best thermal behaviour, as it created the most stable internal air temperatures, followed by the cavity brick (CB) and brick veneer (BV) walling systems. The insulated light weight (InsLW) walling system had the poorest thermal behaviour followed by the BV module, with the worst amelioration of the diurnal temperature variations and the lowest average internal air temperatures in cold weather.

ii. A study of the influence of the walling system thermal mass and thermal resistance on the average internal temperatures found that neither the thermal mass nor the thermal resistance present in the walling systems had a significant influence on the average internal temperatures in summer (when the effects of solar radiation on the external walls were less). However, in the autumn and winter seasons, when the solar effects on the walling systems were larger due to the lower solar angle, the external walls with high thermal mass absorb and stored solar energy resulting in higher average internal temperatures. For external walls with high thermal resistance, the insulation acts as a barrier and reduces the ingress of solar energy resulting in lower average internal temperatures in cold weather.

iii. Both thermal mass and thermal resistance in walling systems influence the internal diurnal temperature variations, but each in a different manner. This, once again, illustrates the importance of both properties and the need for an appropriate combination of each in any walling system.

3. *Effect of Internal Thermal Mass*

The impact of internal thermal mass in the form of internal heavy and lightweight partition walls and the interior leaf of multi-layered enclosure walls on the overall temperature variations and energy consumption was investigated for the CB, InsRVB and InsBV modules. The following conclusions can be drawn

i. i. The R-value alone (a steady-state parameter) cannot represent the actual dynamic thermal performance of a building.

ii. The relative performance of the walling systems varied with season, but in general, the thermal mass of the partition walls and the internal skin of the enclosure walling system were more effective in absorbing energy from solar ingress and dampening the effects of the external diurnal temperature swings than a lightweight equivalent.

iii. For the InsBV module, the replacement of the lightweight partitions with heavy brickwork reduced the variations of the internal air temperature by approximately 20%, reflecting the dampening effect of the heavy weight partitions.

iv. With the same partition walls, the diurnal variation of the internal air temperatures for the CB module was about 30% lower than for the InsBV module, directly reflecting the contribution of the thermal mass of the heavy interior leaf of the enclosure wall.

v. For the various modules, the energy absorbed and released by the heavy partition walls was more than three times higher for heavy partition walls than for their lightweight counterparts.

vi. By reversing the internal thermal mass of the enclosure walls between the InsBV and InsRBV (both with similar R-values), a 35% reduction in diurnal temperature variation was observed. This illustrates the significance of the location of the heavy mass leaf in the enclosure wall in relation to the insulation layer, and demonstrates the advantages to be gained by incorporating a heavy thermal mass leaf on the interior side of the wall insulation.

vii. As conditions changed, significant amounts of heat were stored and released by the internal leaf of the enclosure for the InsRBV module creating a more stable internal comfort level for its occupants. On average, a reduction in diurnal temperature variations of about 26% across all seasons was observed for the InsRBV module.

4. *Effect of Carpet*

The study confirmed that the concrete slab, together with any heavy internal walls, provides a source of internal thermal mass. During a diurnal temperature cycle, these components absorb and released energy with a corresponding positive influence on the internal thermal comfort. The placement of a layer of carpet with its accompanying thermal resistance acted as a potential barrier to this mechanism with a resulting partial loss of the positive contribution of the thermal mass of the floor. The carpet effect was found to be more pronounced for the modules that had lightweight internal

skins (InsBV and InsLW), indicating that the thermal mass of the heavy internal brickwork skins of the CB and InsCB modules also had a positive influence on the thermal performance.

5. *Effect of Windows*

   The following conclusions can be drawn on the influence of windows:

   i. After the installation of the north facing window, the internal air temperatures for both the BV and CB modules became higher because of the extra energy input through the window. The peaks and variations of the internal air temperatures significantly increased under the "with window" condition for both modules, and varied with seasons. Winter had the biggest increase, while summer had the smallest. In addition, the thermal lags between the external and internal temperature profiles for the modules with window disappeared.

   ii. The internal thermal mass played a more important role in maintaining the thermal performance of the modules after the window was installed. This was mainly evident in the peaks and variations of internal air temperatures. In comparison to the "no window" condition, the CB module with high internal thermal mass had much lower peaks and variations than the BV module under the "with window" condition, because the internal thermal mass of the walling system was involved in two energy exchanging processes between the external environment and the internal module space - the energy exchange through the walling system, and the energy exchange through the window. With the installation of window, the second energy exchange process was activated and the internal thermal mass of the walling system played an extra role.

Strand 2 – Performance of Walling Systems and Their Components

1. *Testing Rig and Cyclic tests*

   In parallel with the housing module study, the second strand of the project consisted of the development of a purpose built dynamic hotbox followed by an extensive series of static and dynamic tests on individual walling systems and their components. This provided the data for establishing the key parameters which define the wall performance.

   The hot box apparatus incorporated an external temperature controlled surround to eliminate any effects of the varying laboratory ambient temperature. This apparatus, as well as being capable of providing a steady state controlled temperature environment for R-value tests, was also capable of providing a dynamic input temperature cycle to mimic the various Australian daily and seasonal temperature cycles. The apparatus included specialised instrumentation for temperature control, temperature and power consumption measurement, with the recirculating heating unit in one of the chambers able to simulate a dynamic cycle. The unit was capable of producing any dynamic temperature profile within the range -10°C and 80°C with up to 1000 time steps. Towards the latter stages of the project, an additional smaller hot box apparatus was also developed to allow a series of common walling systems to be tested under dynamic temperature conditions. This facilitated the study of the combined contribution of the individual wall properties previously determined in the larger dynamic hot box.

   The dynamic wall tests studied in detail the influence of thermal mass and thermal resistance, both individually and combined, on wall performance when subjected to typical Australian diurnal temperature cycles. Walls were constructed from materials with a wide range of thermal mass and thermal resistance with the walling systems ranging from a 25 mm thick Styrofoam panel (with very low thermal mass) to a 110 mm thick solid concrete panel (with high thermal mass). Between these two extremes, seven different brick and concrete masonry walling systems were studied, each with a different degree of thermal mass, depending on the presence and nature of perforations within the units. A range of walls and walling systems was subjected to daily dynamic temperature cycles which simulated summer and winter conditions in Brisbane and Melbourne. A combined temperature cycle capturing both hot and cold extremes was also developed.

   The role of insulation in walls subjected to a dynamic temperature cycle, together with the significance of the location of the insulation within the wall cross section was also studied.

Comparative studies based on the test results for a solid brick wall with and without the attachment of polystyrene insulation board on either the external or internal face under dynamic cycles has revealed the following:

i. The wall R-value alone (a steady-state parameter) cannot represent the actual dynamic performance which involves dynamic external and internal temperature environments. Work is proceeding on the detailed development of a method which takes into account wall performance under a dynamic temperature cycle with an appropriate measure and an accompanying standard test for its evaluation for various walling systems.

ii. The tests have shown that through effective design and correct implementation of thermal mass it is possible to minimise internal air temperature variations, reducing the need for heating and cooling during parts of a diurnal temperature cycle. The thermal mass acts as a temperature regulator producing interior fluctuations less than the exterior environment. Thermal mass can therefore be utilised in conjunction with a sound passive design principles to obtain the best results.

iii. The addition of insulation produced more desirable interior temperatures than the non-insulated wall whilst effectively moderating interior temperature changes. Both internal and external insulation arrangements, replicating insulated brick veneer and insulated reverse brick veneer walling systems respectively, had the same steady-state R-value, but the tests clearly illustrated how their performance varied considerably.

iv. The best thermal performance was achieved for the panel with an external insulation layer. This is consistent with the relative performance of the full scale insulated brick veneer and reverse brick veneer modules.

2. *Development of the Dynamic Thermal Response (DTR) Concept – T-value*

The development of the "Dynamic Thermal Response" or DTR concept for walling systems both in isolation in laboratory simulations and in building enclosures is described. The method considers the dynamic temperature profiles from the measured external temperatures, both wall surface or air, (influenced by external weather variables such as ambient temperature, solar radiation, and wind speed) and the response of the internal wall surface and air temperatures. The following are the key outcomes:

i. When the resulting dynamic temperature profiles are plotted for a diurnal dynamic cycle, the data takes the form of an ellipsoidal shape, with the slope of the principal axis being the main variation of performance between the various walling systems. This angle is taken as the DTR value (in degrees) or T-value for the wall and correlates directly with its thermal performance under dynamic external weather conditions.

ii. The principles of the concept developed in the wall tests were confirmed using data obtained from observations of the thermal performance of the lightweight and heavy walling housing test modules subjected to a wide range of seasonal conditions. When the DTR concept is applied to the observed external and internal wall surface temperatures, the T-value for the individual wall is obtained.

iii. The proposed DTR measure defines the behaviour of walls both in isolation and incorporated in the housing test modules. The measure takes into account the dynamic nature of the environmental conditions, the wall response to the environmental changes and more importantly, facilitates the assessment of the thermal performance of the complete building envelope.

iv. Work is proceeding on the detailed development of the DTR measure and an accompanying standard test for its evaluation for existing and new walling systems. The dynamic testing method also has the potential to form the basis of a standard testing procedure to predict the dynamic thermal response of both walling systems and building enclosures and which will reflect the influence of both the thermal resistance and the thermal mass of its components.

v. The T-value is an inherent characteristic of a particular walling system and is independent of climate zone.

vi. The T-value for a particular walling system directly reflects the contribution of each of its components including their relative location within a wall. For example, a 110mm single skin, solid brickwork wall with no insulation has a T-value of 36.3; with insulation on the "inner" face a T-value of 15.4; and with insulation on the "outer" face, a value of 0.40. Depending on the design circumstances and required wall response, knowledge of this nature can be used to advantage (particularly in solar-passive design), to maximise the contribution of the walling system and minimise energy consumption.

vii. There is certainly the potential for the use of the T-value in appropriate thermal modelling software to reflect the dynamic response of the various walling components, and to calculate the total energy consumption for a particular building.

3. *Dynamic Response Concept for Building Enclosures*

The assessment of the thermal performance of a building enclosure such as a house is critical for sustainable housing design and efficient retrofitting of existing stock. Such an analysis must consider the entire building as a system, taking into account the energy absorbed and released by the various building components under a continually changing dynamic environment.

A new measure, the "System Dynamic Temperature Response", (called SDTR (in degrees), or S-Value), has been developed. This measure accounts for the contribution of all of the building components and their subsequent influence on the dynamic thermal performance of a building enclosure under diurnal temperature cycles. The derivation of the S-value measure is an extension of the T-value study using external and internal "air to air" temperatures, rather than "surface to surface" temperatures used for the T-value. The main outcomes of this study are:

i. By simply using the external and internal air temperatures, the SDTR measure was able to define the behaviour of all the housing modules (both heavy and lightweight) under the cyclic nature of the environmental conditions, the wall response to environmental changes and more importantly, facilitate the assessment of the thermal performance of the whole building envelope.

ii. The SDTR value correlates directly with the thermal performance of the enclosure under dynamic external weather conditions. It is therefore a promising first step in the development of a convenient representative measure of the thermal performance of a building under dynamic conditions encapsulating inherently the contribution of all of the building components (for a multi-roomed building such as a house, this would require the selection of the location of a "representative internal temperature").

iii. Once fully developed, such a comprehensive metric has the potential to improve the accuracy and effectiveness of current energy efficiency assessment measures and ultimately lead to more thermally efficient house designs. It also provides a convenient measure to assess the performance of retrofitted existing housing stock by providing a means of direct comparison of the performance through the DTRS values before and after the retrofit.

iv. By nominating the temperature range considered reasonable for internal thermal comfort, the location of the SDTR elliptical curves in relation to that range gives a direct indication of the thermal performance of the building enclosure, and at the same time taking into account all of the external and internal variables influencing the thermal performance.

4. *Application of T- and S-value – the Way Forward*

The contribution of the thermal resistance and thermal mass of all of the building components need to be properly recognised using a measure which correctly encapsulates the behaviour of each wall and the overall building enclosure subjected to a dynamic temperature environment. The new measures have the potential to satisfy these requirements:

i. Ellipse Characteristics: The Dynamic Temperature Response concept uses external and internal temperatures as a driven parameter, and the response of a system to a diurnal cycle of temperature creates elliptical-shaped curves. The geometrical properties of the elliptical curves are related to the physical properties of wallingsystems (for the T-value) or entire enclosures (for the S-value). One of the parameters, the inclination of the ellipse principal axis, reflects the combined contribution of the thermal mass and thermal resistance of the wall or building under dynamic conditions. The parameter also reflects the influence of the location of the wall components (including the insulation) within a walling system. Other possible ellipse characteristics influencing the thermal performance include the angles of the two principal axes and the ellipse area and perimeter. Such elliptical shapes take into account the energy absorbed and released by the various building components under a continually changing dynamic environment and inherently reflect their contribution to the performance of the entire walling system or building enclosure. A detailed analysis of these characteristics across all weather seasons for brick masonry constructed from brick units with 28% coring is presented. (Note that similar trends were observed for the other walling types).

ii. T-values for wall systems and their components: The other area of research which is still in progress is investigating the relationship between T-values for each wall component and the combined value of the wall assemblage. Tests performed on typical walling components and combined walling systems are reported, and a relationship between them is being sought. This has obvious direct practical design implications.

iii. Thermal Lag: The dynamic panel tests allowed the analysis of the complex heat transfer pattern between internal and external environments for both surface to surface and air to air. This resulted in varying time lags for each panel configuration. It was found that the thermal lag for any particular wall configuration or unit type was not affected by seasonal variations.

iv. Dynamic Thermal Resistance: One promising area of research relates to a parameter termed the "dynamic thermal resistance", a property which reflects the combined effects of mass and resistance. The thermal resistance (R-value) is a static parameter which does not reflect the ability of a wall to respond to a dynamic temperature cycle. In contrast, the elliptical hysteresis patterns observed in all of the dynamic wall tests in this investigation effectively summarise the daily thermal performance, and reflect what could be termed "the dynamic thermal resistance" of the wall. One potential version of this parameter which can be evaluated from the observed elliptical curves is based on the ratio of the square root of the area of the ellipse and the corresponding temperature variation. This characteristic, like the static R-value, is a constant value for a particular wall configuration and is independent of season, but now also reflects the dynamic response of the wall including the combined effect of thermal mass and thermal resistance. This promising research is still in progress, but progress to date is presented.

Contents

1. Introduction and Project Overview

Due to global warming and other factors, there is an ever-increasing emphasis on energy conservation and efficiency. In Australia, a significant proportion of the end energy usage in domestic buildings is from space heating and cooling. Consequently, achieving improved energy efficiency in buildings has become one of the major challenges for architects and other building designers. To help address this challenge, an energy performance rating system is now applied to all new residential developments prior to building approval. This rating system involves the estimation of the energy required to maintain the interior of the building within a set temperature range taking into account the building fabric, insulation, design orientation and location. A star rating system is obtained by comparing the energy estimate against set values for the relevant climate zone.

Several commercial packages are available to simulate building performance. However, one of the shortcomings of these simulations is the lack of real data on the performance of the various housing walling systems under Australian climatic conditions. One particularly important aspect is the consideration of the contribution and interaction of the thermal resistance and thermal mass of each wall, which directly influences the wall performance under each dynamic diurnal temperature cycle.

With a view to overcoming the shortage of real data, the University of Newcastle, in partnership with Think Brick Australia, has undertaken a major theoretical and experimental study of the thermal performance of housing systems in a typical moderate Australian climate. This extensive 15 year study, commenced in 2001, has been based in the Priority Research Centre for Frontier Energy and Technologies (previously the PRC for Energy) and has involved the collaboration of research groups from Civil and Chemical Engineering. Funding for the project has been provided by Think Brick Australia and the Australian Research Council (through several linkage grants), together with substantial in-kind support from staff of the School of Engineering in the Faculty of Engineering and Built Environment. The first phase of the project (Phase 1) mainly involved data collection and analytical modelling, and was completed in 2009. A report of this section of the work has already been published (1).

This Phase 2 report directly follows Phase 1 and presents the outcomes of the research from the latter part of the project.

The Phase 2 research has two major strands:

1. Continuation of the observation and analysis of the performance of the four full scale housing test modules located on the University of Newcastle campus (constructed as part of the Phase 1 research). Over the testing period, various walling systems (with and without internal partitions) have been used, with the interior of the modules being allowed to either “free float” or be controlled within a given temperature range by the use of artificial heating or cooling.
2. The detailed study of the performance of walling systems and their components when subjected to dynamic temperature cycles simulating various Australian climate zones (in particular, the development of measures reflecting the contribution of both thermal resistance and thermal mass to the wall and building performance).

One of the key practical outcomes of the research has been the development of a measure for wall performance which reflects the wall behaviour under dynamic, rather than static conditions. In contrast to the current emphasis on thermal resistance (R-value) alone, which reflects only the static behaviour, the new measure (the wall T-value, based on external and internal wall surface temperatures) directly reflects the performance under a dynamic temperature cycle, and captures the effects of thermal resistance, thermal mass and thermal lag in the one measure. As an extension of this concept, an additional parameter (the S-value) has also been developed, which provides the means to assess the overall performance of building enclosures (as distinct from individual walls) based on the internal and external air temperatures. Both these measures have the potential to be incorporated into “deemed-to-satisfy” building regulations to more accurately reflect the contribution of individual walls to housing thermal performance.

The report presents detailed results of the thermal performance of the housing modules incorporating a range of walling types under both controlled and free floating interior conditions for all four weather seasons. The contribution of other factors such as carpet, curtains, internal heavy and lightweight internal partitions and the specific roles of thermal mass and insulation are also studied.

A parallel study involving the development of a purpose built dynamic hotbox followed by an extensive series of static and dynamic tests on individual walling systems and their components is also described. These wall tests simulated typical Australian dynamic diurnal temperature cycles with the results being used for the development of the T- and S- value concepts for walls and building enclosures.

2. Housing Test Modules

2.1 Introduction and overview

The first strand of the project, which continued from Phase 1, involved the monitoring of the behaviour of the four full scale housing modules under a range of climatic conditions over all seasons for a range of different walling systems. As in Phase 1, the interior of each module was allowed to either "free float", or be controlled within a given temperature range by artificial heating or cooling. The construction systems for the modules covered the common forms of domestic construction in Australia (brick veneer, cavity brick and lightweight construction) as well as reverse brick veneer. The modules were constructed with an independent roof which allowed the easy installation or modification of the walling systems. Over the periods of the Phase 1 and 2 investigations, as well as the type of enclosure wall, the influence of factors such as wall insulation, windows and roof type, curtains, carpet, room ventilation and internal walls have been studied. The first two modules were constructed in 2003, and additional modules built in 2004 and 2005 as the program expanded. As the project continued, appropriate modifications to the walling systems were made at various times to facilitate the study of various aspects (see Table 2.1). Details of the walls and roof systems used are summarised in Table 2.2.

As described in the Phase 1 Report (1), the modules were initially built with no window openings in order to study the characteristics of each individual wall system. A major window opening was later incorporated in each northern wall to allow significant seasonal solar ingress to facilitate the study of passive solar effects. A detailed description of the construction and instrumentation of the modules is given in the Phase 1 report. For completeness, some previously reported details of the modules are included in the following sections. The Phase 1 Report was produced in 2011 and covered the selective analysis of module data collected for the period from the construction of the first two modules in 2003 through to 2009. These results are not repeated here, but for completeness, a summary of the analyses performed in Part 1 is given in Table 2.3.

2.2 Test variables investigated

As previously described, each module was designed to allow the selective replacement of walling systems without disturbing the roof structure. This has allowed a range of wall types and opening conditions to be considered. As the modules were constructed progressively, an increasing number of variables were considered over the testing period. Summaries of the module history and testing schedule are given in Figure 2.1 and Table 2.1. Testing commenced in February 2003 and has been on-going since that date. For each of the module types, at some stage during the investigation, the internal conditions were held constant and monitored for approximately 12 months to cover all four seasons. As can be seen from Table 2.1, because of the large number of walling systems

to be considered, the length of other tests for the various combinations of other variables was reduced, but in all cases the testing period included both hot and cold conditions.

2.3 Walling systems and their thermal properties

The five module walling systems investigated were: cavity brick (CB), insulated cavity brick (InsCB), insulated brick veneer (InsBV), insulated reverse brick veneer (InsRVB) and insulated lightweight (InsLW). These walls had a range of thermal resistance and varying degrees of external and internal thermal mass (see Tables 2.2 and 2.4). The thermal resistance (R-values) of each wall was first determined using a Guarded Hot Box Apparatus and then incorporated into the four housing test modules. In the overall testing program, the interior of each module could be allowed to "free float", or be controlled within a comfort range by a heating/cooling system with the energy consumption being measured. The study reported here investigates the relative performance of each of the walling systems operating under controlled internal conditions over the four seasons, based on the energy demand to maintain comfort levels. The performance of the same walling systems under free floating conditions has been previously reported (1).

An in-house facility conforming to ASTM C 1363–97 (2) was used to obtain the R-value of each of the four wall types incorporated in the housing modules. The test walls were 2.4 m (high) by 2.4 m (wide) with the

guarded hot box occupying the central 1.2 x 1.2 m area of the test panel. The R-values obtained for Δ18ºC temperature differential (air to air across each wall thickness) for the four wall types used in this study are shown in Table 2.4 (the air to air values are used for subsequent comparison in this chapter).

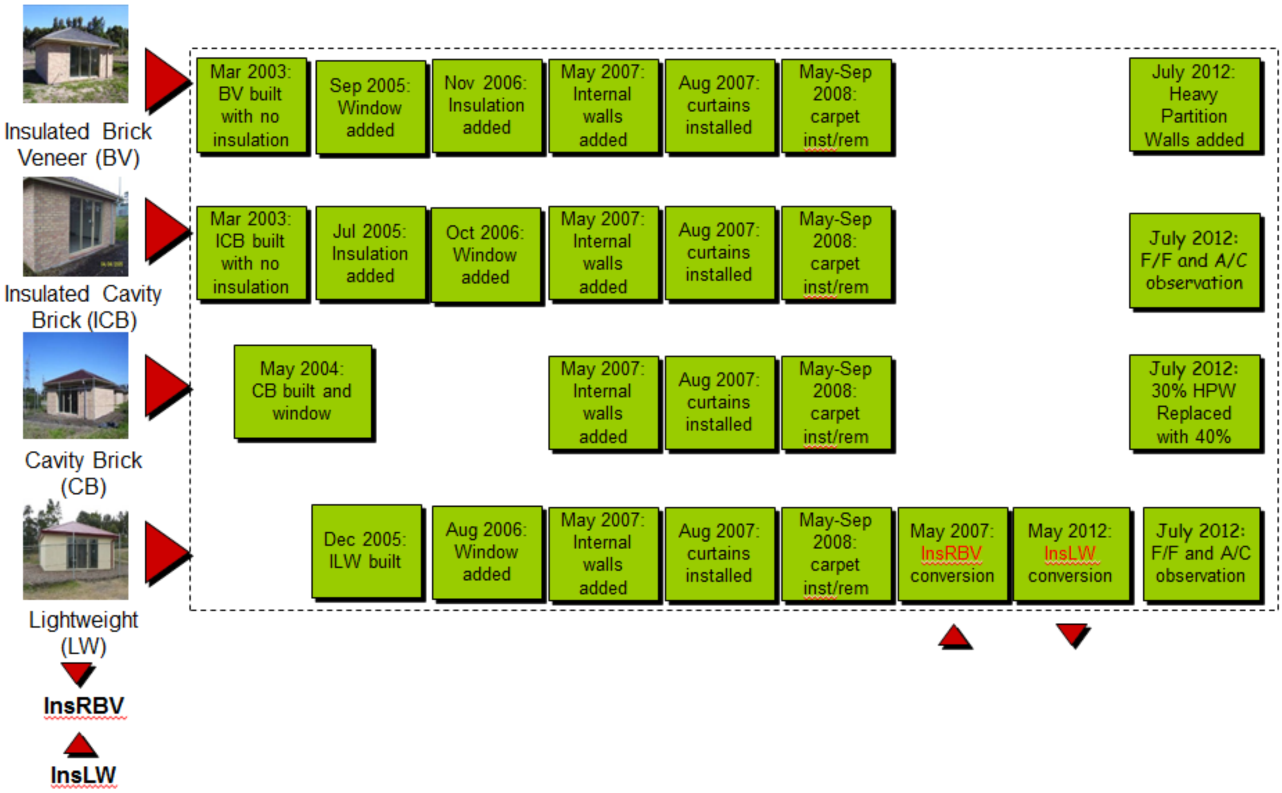


Figure 2.1: Testing schedule

Note: The module external wall types remained constant from 2012; F/F: free floating; A/C: air conditioned.

2.4 Housing test modules

The housing module tests were used to provide qualitative and quantitative data on the thermal performance of the walling systems under real climatic conditions. The modules were comparable in size to other buildings used in similar studies in North America (3,4)). Note that the intent of the module tests was not to reproduce the behaviour of an actual house but rather to observe and quantify the typical heat flow mechanisms for walls in a realistic context.

The modules were constructed on the University of Newcastle Callaghan Campus in suburban Newcastle (Newcastle is located in a moderate climate zone on the east coast of Australia at atitude 33°south). 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). The behaviour of the various modules was studied under controlled conditions with the interior being heated or cooled to pre-set levels of comfort, allowing the heating/cooling energy requirements for each walling system to be assessed.Heating energy was measured directly from electricity consumption whilst a chilled water heat exchanger system was used to measure the cooling demand (these systems are described in detail in the Phase 1 report).

The modules had a square floor plan of 6m x 6m and were spaced 7m apart to avoid shading and minimise wind obstruction. With the exception of the walls and roof, the buildings were of identical construction following normal Australian practice, being built on a concrete slab-on-ground and aligned in a manner so that the north wall of each building was perpendicular 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 and InsLW modules, 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 m2.K.W-1) 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.

Initial (Phase 1) tests were performed on windowless modules. However, the tests reported here were performed with a major window opening included in the northern wall of each module to allow solar ingress and to better reflect solar passive influences. The modules are shown in Figures 2.2 and 2.3. As shown in Table 2.1, for a proportion of the investigation, either heavy weight or lightweight internal partition walls were incorporated in each of the modules to assess the significance of internal walling on the overall thermal performance. The type of walling system was selected to reflect typical practice (eg lightweight (stud wall) partitions in the InsBV module and heavy weight (brickwork) partitions in the InsCB module). Details of the partition walls are shown in Figure 2.3.

Table 2.1: Summary of Module Configurations

Year	Month	Site 1	Site 2	Site 3	Site 4
2003	March	Brick Veneer Module	Cavity Brick Module		
	… …				
2004	May			Cavity Brick Module + Window	
	… …				
2005	July		Insulated Cavity Brick Module		
	August	+ Window			
	September				
	… …				
	December				Insulated Lightweight Module
2006	January	AC on	AC on	AC on	
	February				
	… …				
	July	AC on	AC on	AC on	
	August				+ Window
	September				
	October		+ Window		
	November	Insulated Brick Veneer Module			
	… …				
2007	May	+ Lightweight Internal wall	+ Brickwork Internal wall	+ Brickwork Internal wall	+ Lightweight Internal wall
	June				
	July	+ Curtain	+ Curtain	+ Curtain	+ Curtain
	August				
	September				
	October	+ Ventilation	+ Ventilation	+ Ventilation	+ Ventilation
	November				
	… …				
2008	April	Ventilation - + Carpet	Ventilation - + Carpet	Ventilation - + Carpet	Ventilation - + Carpet
	May				
	… …				
	September	Curtain & Carpet -	Curtain & Carpet -	Curtain & Carpet -	Curtain & Carpet -
	October				Insulated Reversed Brick Veneer Module
	November	AC on	AC on	AC on	AC on
	December				
2009	January				
	February	AC on	AC on	AC on	AC on
	March				
	April	AC on	AC on	AC on	AC on
	May				
	June				
	July	AC on	AC on	AC on	AC on
	… …	+ Ventilation	+ Ventilation	+ Ventilation	+ Ventilation
2009	November	Ventilation -	Ventilation -	Ventilation -	Ventilation -
	… …				
2012	February	Lightweight Internal wall - + Brickwork Internal wall			
	March				
	April				
	May				Insulated Lightweight Module
	… …				
2013	March – October	AC on	AC on	AC on	AC on
	… …				
2016	April				

Table 2.2: Details of Module Wall Components

Building Element	Material(s)	Insulation
Cavity Brick wall (CB)	2x110mm brickwork skins with 50mm cavity; 10mm internal render	Nil - standard 50mm cavity
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
Brick Veneer wall (BV)	110mm external brickwork skin; 50mm cavity; internal pine stud timber frame; 10mm interior plasterboard	Low glare reflective foil on timber frame
Insulated Brick Veneer wall (InsBV)	110mm external brickwork skin; 50mm cavity; internal pine stud timber frame; 10mm interior plasterboard	Low glare reflective foil on timber frame with R1.5 glasswool batts
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	Low glare reflective foil on timber frame with R1.5 glasswool batts
Insulated Lightweight (InsLW)	External 7 mm fibro-cement sheeting finished with polymer render; breathable membrane fixed to pine stud frame; 10mm internal plasterboard	Low glare reflective foil on timber frame with R1.5 glasswool batts
Heavy internal partition walls (HPW)	110mm brickwork	No insulation
Lightweight internal partition walls (LPW)	10mm plasterboard on 90mm timber stud frame	No insulation

2.5 Module instrumentation and data

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 at the rear south-east corner. Thermocouples were placed on the surface of the slab at various locations between the window and the centre of the room. 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, approximately 105 data channels were scanned and logged every 5 minutes for each of the modules for the duration of the testing program. A detailed description of the instrumentation is given in the Phase 1 Report (1).

2.6 Energy demands for a controlled interior - Seasonal analysis

2.6.1 Overview

The analysis was based on the assumption that the internal conditions were comfortable when the internal air space temperature was in the 18-24ºC range. It is recognised that other factors also affect thermal comfort (5,6) but this temperature range was used for convenience. For the controlled state, the heating/cooling system was activated whenever the internal room temperature rose or fell outside the above temperature limits. The systems were programmed to maintain this defined internal temperature range by a 'hysteresis' type cycle. The system operated by determining the average air temperature indicated by two thermostats located on the southern and western walls, situated so as to not receive any direct solar radiation. The analysis of the data involved studying the diurnal behaviour of the "controlled" modules for typical spring, summer, autumn and winter periods across 2008 and 2009. The analysis therefore allows the potential year round performance to be assessed, by examining the relative performance of each module for the "snapshot" of each season. This section of the study involved the CB, InsCB, InsBV and InsRVB modules.

Figure 2.2: Housing Test Modules with Window in North Wall
(Module 1 - CB; Module 2 - InsCB; Module 3 - InsBV; Module 4 - InsRVB (& InsLW))

Table 2.3: Analysis Performed in Stage 1

Item	Description
Windowless modules – free floating interior	**Comparison of BV and CB modules** Hot & cold weather conditions: Temperature variations & thermal lag; through-wall heat flux **Comparison of InsLW & InsCB modules** Hot & cold weather conditions: Temperature variations & thermal lag; through-wall heat flux
Modules with North Facing Window	**Impact of North facing window on internal temperature** Seasonal variations of solar gain; Energy envelopes; Slab response **Free Floating Internal Conditions** Spring weather conditions: Temperature variations; Through-wall heat flux and energy envelopes. Hot weather conditions: Temperature Variations; Through-wall heat flux. Cold weather conditions: Temperature variations; Through-wall heat flux and energy envelopes **Artificially Controlled Internal Conditions** Energy demands of the four modules in October, 2007; Energy demands of the four modules in July and August, 2008
12 Month Parallel Observation Period for CB, InsCB, InsBV and InsRVB modules October 2008 to October 2009.	**Free floating conditions** Summer; winter; autumn; spring. **Artificially controlled internal conditions** Energy demands in Spring 2008, Summer 2009, Autumn 2009 and Winter 2009.
Statistical Analysis of the Effects of Insulation and Internal Thermal Mass	**Statistical model:** Results and discussion

2.6.2 Energy demands of the four modules under Spring conditions

Heating and Cooling was observed for the spring season from 30/10/2008 to 27/11/2008, a period of 4 weeks. During this period, conditions were moderate with a few warm days in excess of 30°C and only a few nights reaching a temperature as low as 10°C. Figure 2.4 shows the typical external/internal air temperature variations for 3 days in the middle of November. It can be observed from the internal temperature plots that there were times when only the InsBV and InsRBV modules required additional heating at night or cooling during the day whilst at other times, under more extreme conditions above 30ºC, all modules required cooling.

Table 2.4: Thermal Characteristics of Module Walling Systems

Walling System	R-value m^2K/W (surface to surface)	R-value m^2K/W (air to air) *	Exterior skin thermal mass?	Interior skin thermal mass?
Cavity Brick (CB)	0.44	0.62	yes	yes
Brick Veneer (BV)	0.83	1.14	yes	no
Insulated Brick Veneer (InsBV)	1.58	1.72	yes	no
Insulated Cavity Brick (InsCB)	1.30	1.48	yes	yes
Insulated Reverse Brick Veneer (InsRBV)	1.57	1.93	no	yes
Insulated Lightweight (InsLW)	1.51	1.86	no	no
Heavy internal partition walls (HPW)	0.13	0.25	N/A	N/A
Lightweight internal partition walls (LPW)	0.4	0.52	N/A	N/A

** Air film values from [7]: 0.04 externally; 0.14 internally*

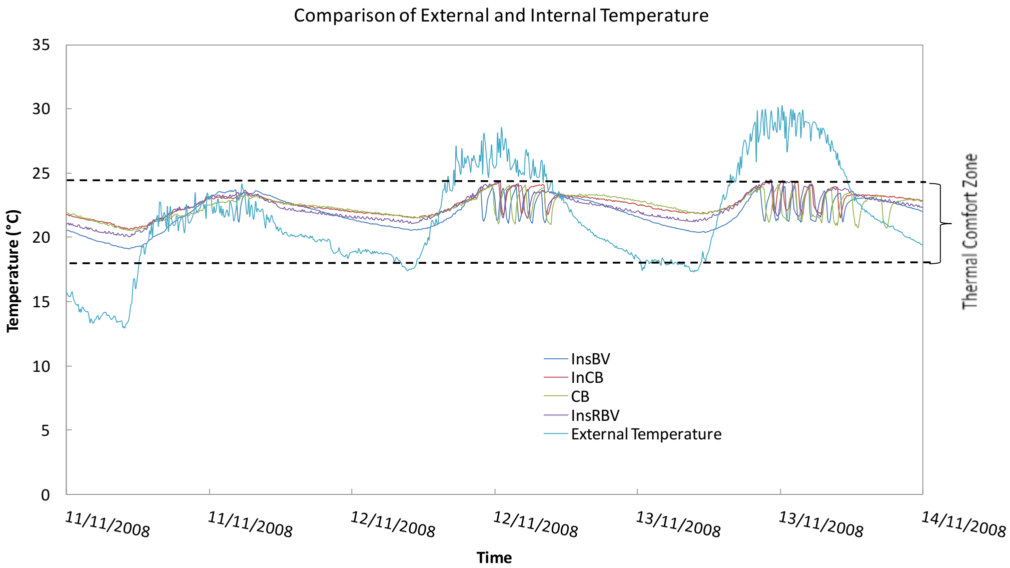


Figure 2.4. Example of temperature variations for the controlled modules under spring conditions

Heating and Cooling was observed for the spring season from 30/10/2008 to 27/11/2008, a period of 4 weeks. During this period, conditions were moderate with a few warm days in excess of 30°C and only a few nights reaching a temperature as low as 10°C. Figure 2.4 shows the typical external/internal air temperature variations for 3 days in the middle of November. It can be observed from the internal temperature plots that there were times when only the InsBV and InsRBV modules required additional heating at night or cooling during the day whilst at other times, under more extreme conditions above 30ºC, all modules required cooling.

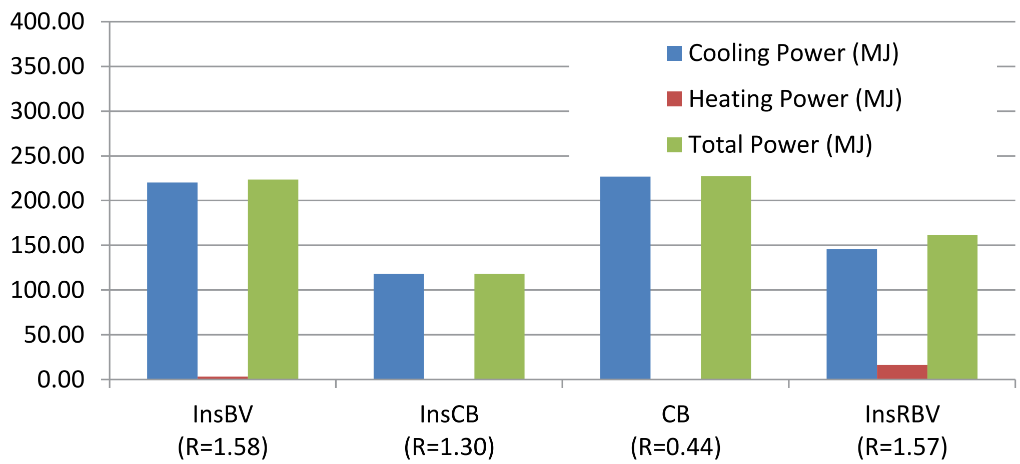


Figure 2.5. Total energy consumption for a 4 week spring period.

It can be seen that the InsCB module had the lowest energy demand of the four modules, due to the presence of both internal and external thermal mass (combined with the cavity insulation),. This was followed by the InsRBV module which required a small amount of heating energy. This indicates that the external skin of the InsCB module does have some influence, even though it is external to the insulation barrier. Neither of the two systems with the highest thermal mass (InsCB and CB) required any heating energy.

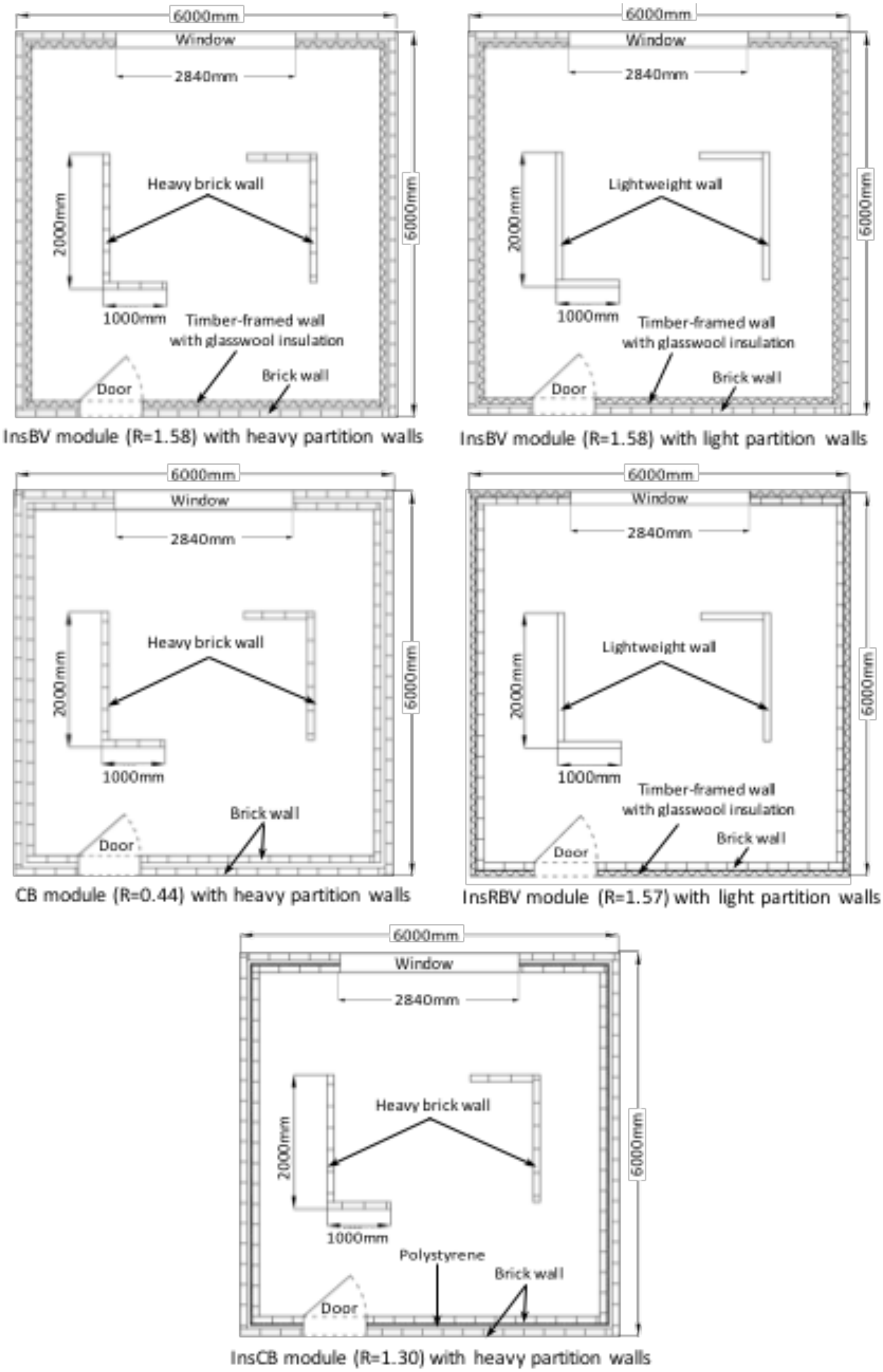


Figure 2.3: Plan view of modules incorporating partition walls

2.6.3 Energy demands of the four modules under Summer conditions

Controlled conditions were imposed for the summer period for a total of 4 weeks from 22/01/2009 to 19/02/2009. The summer weather was hot with consistent temperatures above 30°C regularly occurring from as early as 8am into the early evening. This was combined with high solar radiation due to limited cloud cover. An example of 3 days operational performance is presented in Figure 2.6. As a result of these conditions the heat pushed the external heat exchanger system to its practical limits and for two days in this period it was incapable of providing adequate cooling to all four modules.

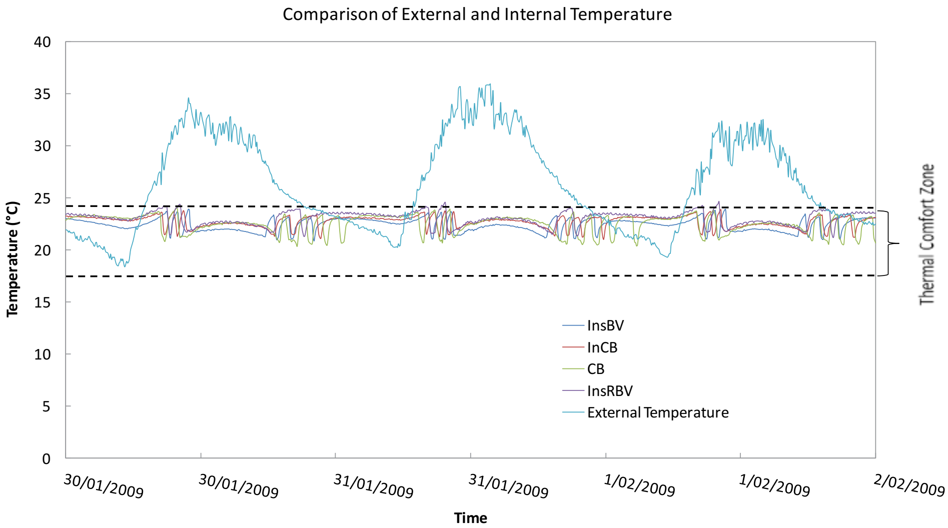


Figure 2.6. Example of temperature variations for the controlled modules under summer conditions

Due to the hot conditions, all the modules required daytime cooling (see Figure 2.7). Internal temperatures overnight were maintained between 22 and 23°C. These results do however confirm that the appropriate combination of thermal mass and insulation is required to keep the interior within an acceptable temperature range when high extremes in external temperature occur over a prolonged period (this was the case for the analysed period, as no cooler days occurred). Due to the lack of cavity insulation, the CB module performed the worst as it required additional energy in the evening to cool its interior due to the solar energy passing through the wall and being released internally later in the evening.

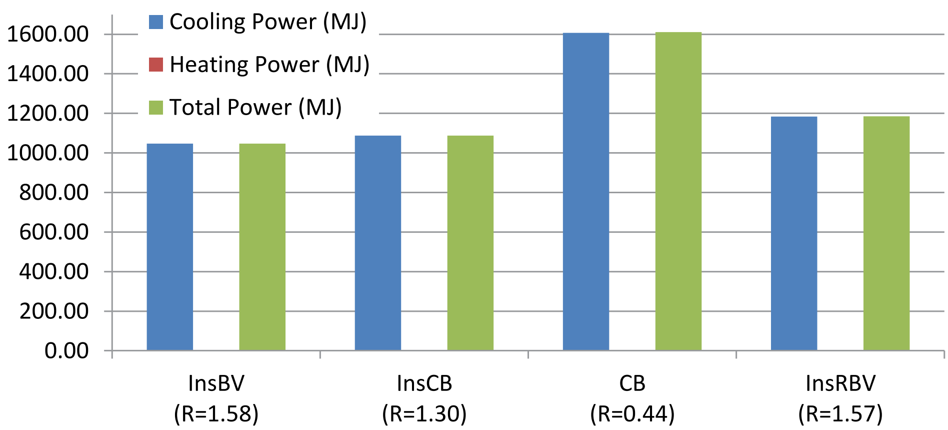


Figure 2.7. Total energy consumption for a 4 week summer period.

2.6.4 Energy demands of the four modules under Autumn conditions

The autumn air conditioning observation period was for four weeks of data obtained from 16/04/2009 to 14/05/2009. External temperatures often peaked at around 22-23°C; however the low solar angle created the need for artificial cooling to maintain the internal temperature below 24°C (see Figure 2.8).

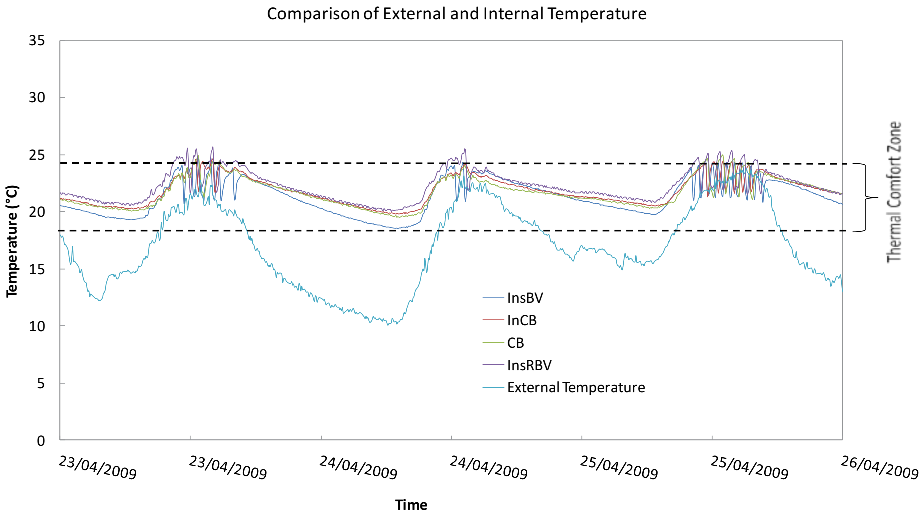


Figure 2.8. Example of temperature variations for the controlled modules under autumn conditions

The InsCB module was again the most energy efficient and required only cooling under autumn conditions, see Figure 2.9. The InsBV module was the most energy intensive requiring more than 200% more energy than InsCB due to lack of thermal mass in the internal side of the enclosure wall; the insulation layer reduced the incoming heat from the solar radiation and did not have any ability to store the incoming heat through the window. Both modules, InsBV and InsRBV required almost similar amounts of heating, yet cooling requirements differed.

The interior conditions for the CB module tended to deteriorate once heating was required and the module experienced more heating cycles for extended period of times due to the energy absorption by the bricks. However, the overall the energy requirements were much less than for the InsBV and InsRBV modules for the autumn conditions.

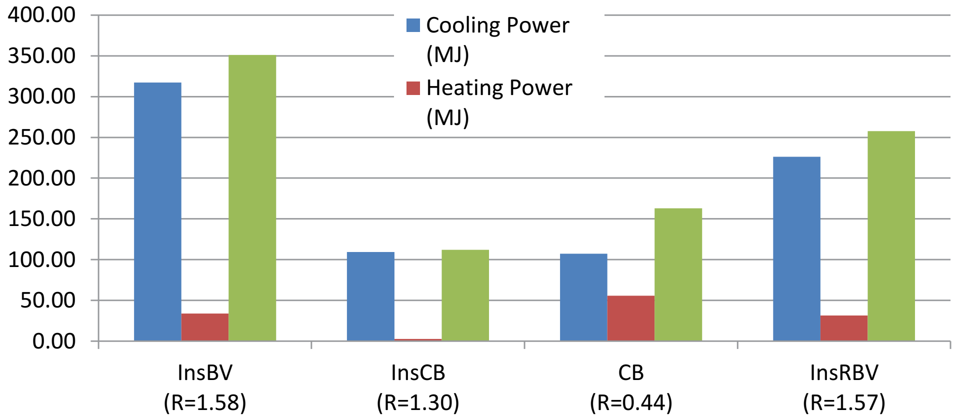


Figure 2.9. Total energy consumption for a 4 week autumn period.

2.6.5 Energy demands of the four modules under Winter conditions

The winter results were obtained for a 4 week period from 09/07/2009 to 06/08/2009. Peak daytime external temperatures during the period seldom reached 19°C with only several days exceeding 20°C. Night temperatures consistently dipped below 5°C. The typical behaviour of the modules for a 3 day period under controlled conditions is shown in Figure 2.10, together with the corresponding variations in external temperature.

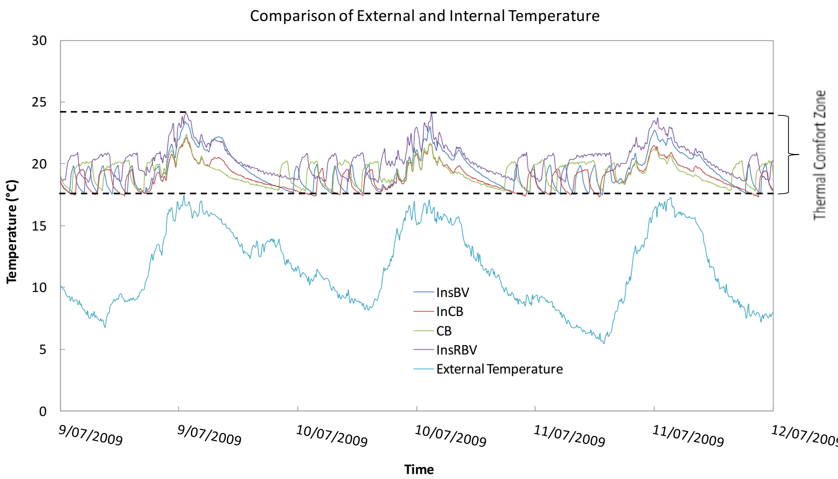


Figure 2.10. Example of temperature variations for the controlled modules under winter conditions

Heating was the predominant source of energy consumption during winter. Since the winter sun was low, it became an important influence on the behaviour of the modules, resulting in the occasional need for some slight cooling for the InsBV module to maintain the internal space within the comfort zone (see Figure 2.11). This was due to the tendency of these modules to overheat from solar ingress through the opening in the northern wall (due to the lack of internal thermal mass), and it was necessary for the air conditioning system to compensate for this. In contrast, the internal thermal mass of the InsCB, InsRBV and CB modules provided enough inherent absorption of the solar gain to avoid the need for additional cooling to keep temperatures from rising above the pre-set 24°C. This same effect was also observed under free floating internal conditions described in the Phase 1 Report.

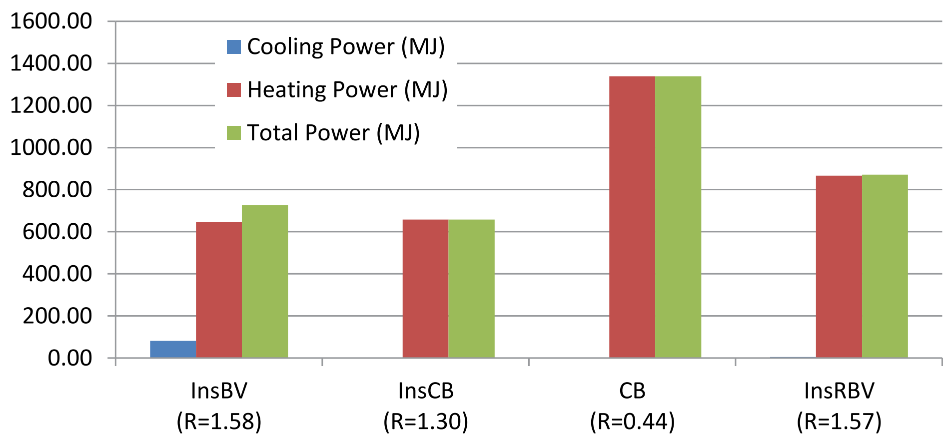


Figure 2.11. Total energy consumption for a 4 week period winter period.

Heating requirements for the InsCB and InsBV modules were very similar. However, the InsBV module often required more heating cycles in the early evening. As can be seen from Figure 2.11, the InsRBV module had greater energy consumption with earlier heating activation than for the InsCB module and more prolonged heating periods. The CB module experienced this effect to an even further extreme under these conditions with the lack of cavity insulation allowing a continual flow of heat from the interior skin into the cooler cavity.

It has to be highlighted that under cold weather conditions the InsCB module had the lowest energy requirements for both heating and cooling. In contrast to the heavy walling modules, the InsBV module (without internal thermal mass) had limited capacity for self-regulation, with the heat flows being driven purely by the external conditions. The lack of internal thermal mass resulted in higher daytime temperatures and artificial cooling was required to offset the solar heat gain. Towards the end of the day, for the InsBV module the internal temperature dropped with the external conditions at a faster rate compared to the CB and InsCB modules as little heat was released back into the room from the walling system. During the day,

heating of the interior from the low winter sun was offset by the ability of the internal thermal mass of the CB and InsCB walls to absorb heat. This prevented the day-time overheating which was observed in the InsBV modules. The primary basis for the superior performance of the InsCB module was the contribution of the internal brick skin in combination with the cavity insulation which limited outward heat flow to the exterior of the wall. For these conditions, this illustrates the beneficial effects of the effective combination of thermal mass and thermal resistance.

2.6.6 Conclusions from energy demand study

1. The two alternative extreme cases of high thermal mass with no insulation (the CB module), and insulation with external thermal mass (the InsBV module), both required higher energy consumption for every season. Despite the InsBV wall having an R-value 14% higher than the InsCB wall, the InsBV module required 20% more energy for all seasons (over a 4 week period for each season). The worst performing module was the CB, with an energy demand 60% higher than the corresponding InsCB module. Note that a similar trend was observed in a parallel study of the performance of the modules under free floating internal conditions conducted as part of the Phase 1 investigation (1). This again confirms that there is no direct correlation between building performance and wall R-value alone; the best solution lies with an appropriate combination of wall insulation and thermal mass.
2. Investigations into the heat flow through the walls indicated that the additional external thermal mass provided increased dampening of the external conditions and also helped to decrease the environmental impact on the cavity surface of the internal thermal mass. Externally clad insulation alone did not provide this form of cavity dampening and the thermal mass of the internal masonry leaf was the only contributor to minimize the temperature variation and the capacity to lessen the temperature rise from the solar gain. This could also be one factor why, under driven conditions, the InsRBV module used more energy than the InsCB module. This does not mean that the InsRBV module cannot provide a comfortable passive living space, as its performance was still better than for some of the other systems. However, the lack of thermal mass in the outer skin reduced the degree of thermoregulation compared to the InsCB module under higher solar gain. Nevertheless, the InsRBV module performed strongly during the summer and winter observation periods.
3. The results clearly showed that internal comfort levels and energy demands are influenced by both the thermal resistance of the walls as well as the extent and location of the thermal mass. The best thermal performance will therefore be obtained by an appropriate combination of both thermal mass and resistance, rather than focussing on the wall thermal resistance (R-value) alone. This aspect is addressed in Chapter 5 by the development of a single measure for wall performance which reflects the contribution of both thermal mass and thermal resistance under the dynamic temperature conditions of a diurnal temperature cycle.

2.7 The influence of thermal mass and thermal resistance on the thermal performance of walling systems

2.7.1 Introduction

The thermal performance of the various walling systems in this study, and particularly the role of thermal mass, can be assessed by the direct comparison of the differences in internal temperature of the corresponding housing test modules. The external and internal air temperature profiles under real weather conditions for each module can be studied to identify the variations in performance between the modules. Such analyses were performed on the total data available to assess possible seasonal influences on the thermal performance of the modules.

The impact of thermal mass and thermal resistance on the performance of walling systems has been studied using the following comparisons of data collected for the windowless modules in the early stages of the program:

1. *Influence of thermal mass on an insulated walling system*

   This influence can be assessed from a comparative study of the performance of the InsLW and InsCB walling systems. Both walling systems were well insulated with similar thermal resistances

(R1.30 for InsCB and R1.51 for InsLW). However, there is a significant difference in thermal mass. The InsCB walling system has a total thermal mass of 21.2 MJ/K, which is almost 18 times that of the InsLW (TM 1.2 MJ/K). As a result, it can be assumed that variations in the thermal performance of the InsLW and InsCB walling systems are mainly due to the presence of the thermal mass.

2. *Influence of thermal resistance on a high thermal mass walling system*

   This influence was assessed from a comparative study of the performance of the CB and InsCB walling systems, both of which have two brick masonry skins and thus have similar high thermal masses (TM 21.2 MJ/K for both). However, the thermal resistance of the InsCB walling system (R1.30) is much higher than that of the CB (R0.44) due to the additional layer of R1 insulation. Therefore, it can be assumed that the difference in the thermal performance of the CB and InsCB walling systems result from the contribution of the insulation.

3. *Combined influence of thermal mass and thermal resistance*

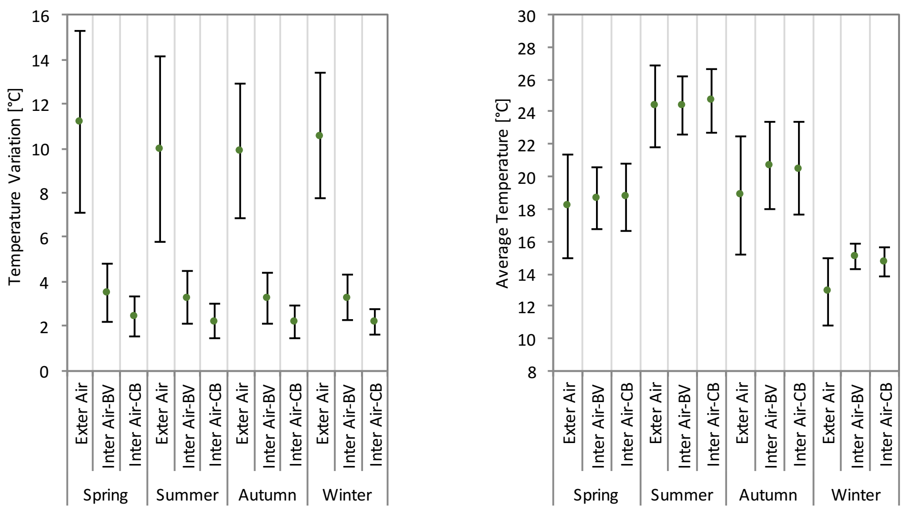
   The change in the thermal performance of a walling system when the thermal mass decreases but thermal resistance increases can be studied by comparison of the performance of the BV walling system (R0.83, TM 11.8 MJ/K, with medium thermal resistance and thermal mass), and the InsLW walling system (R1.51, TM MJ/K , with double the thermal resistance of the BV and little thermal mass).

4. *Thermal mass dominated walling system vs. thermal resistance dominated walling system*

   The CB walling system which has very low thermal resistance but high thermal mass can be considered as a thermal mass dominated system. In contrast, the InsLW walling system with the highest thermal resistance but low thermal mass can be considered a thermal resistance dominated system. Comparison of the performance of these two systems allows the relative contribution of each of these physical parameters to be assessed.

2.7.2 Influence of thermal mass and thermal resistance on diurnal temperature variations

Differences in thermal mass and thermal resistance of the walling systems had little influence on the average internal air temperatures in the summer season when solar effects on the walling systems were low due to the high solar angle. This is indicated by the similar observed average internal air temperatures during summer for the BV (R0.83 and TM11.8) and CB (R0.44 and TM 21.2) modules (Figure 2.12)) and for the InsLW (R1.51 and TM1.2) and InsCB (R1.30 and TM 21.2) modules (Figure 2.13)).



a) Average diurnal temperature variation for seasons *b) Average temperature for seasons*

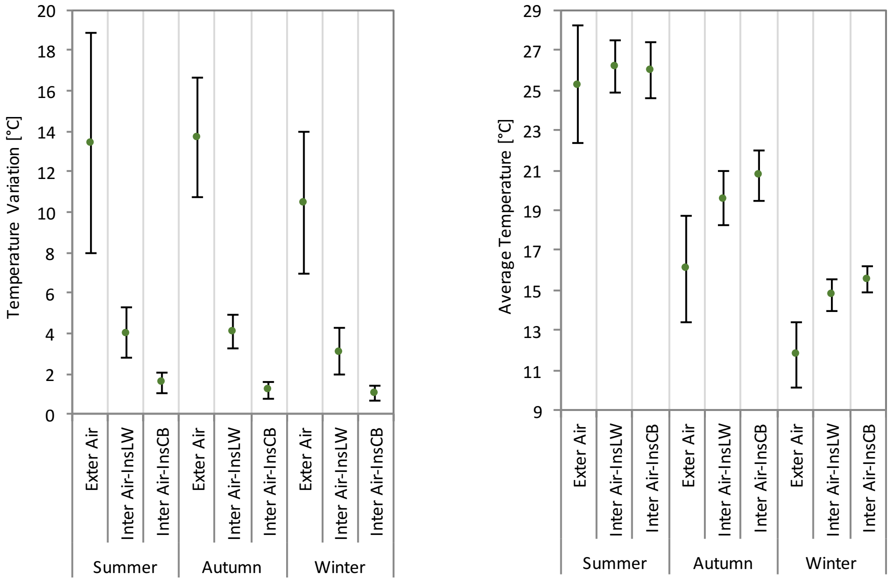
Figure 2.12: Seasonal effects on external and internal temperatures of BV and CB modules: a) Diurnal temperature variation; b) Diurnal average temperature

In the autumn and winter seasons, when solar radiation becomes an important component of the energy input to the walling systems due to the lower solar angle, the external skins of the walling systems play a more important role in the increase of internal air temperatures. For the BV and CB walling systems, with different overall thermal masses and thermal resistances but with the same

high thermal mass external brick walls, the respective internal air temperatures rose by similar amounts in autumn and winter, as shown in Figure 2.12(b)). In addition, the InsCB walling system, with high thermal mass external walls, maintained higher average internal temperatures than the high thermal resistance InsLW walls, as in Figure 2.13(b)). Thus, walling systems with high thermal mass external walls, which absorb and store more solar energy, maintained higher module internal temperatures compared to those modules with high thermal resistance walls which, in mild and cold seasons, restrict the passage of solar energy through the wall.

The diurnal internal temperature variations for the InsLW (R1.51 and TM 1.2) module were about three times those for the InsCB (R1.30 and TM 21.2) module, as shown in Figure 2.13(a). This indicates that with the increase of about 20 MJ/K thermal mass in the insulated walling systems, the internal temperature variations reduced by over 65%.

Figure 2.13: Seasonal effects on external and internal temperatures of InsLW and InsCB modules:



a) Average diurnal temperature variation for seasons *b) Average temperature for seasons*

a) Diurnal temperature variation; b) Diurnal average temperature

2.7.3 Influence of thermal resistance on high thermal mass walling systems (CB & InsCB)

As shown in Figure 2.14, the diurnal internal temperature variations for the InsCB (R1.30 and TM 21.2) module were about 10% of the external temperature variations. Figure 2.14 also shows that this variation was only half of that for the CB (R0.4 and TM21.2) module. This indicates that the internal temperature variations for the module with a high thermal mass walling system (TM21.2) was reduced to 50% of the original by the addition of R1 insulation.

2.7.4 Combined effects of thermal mass and thermal resistance (BV vs. InsLW)

The BV (R0.83 and TM11.8) module and InsLW (R1.51 and TM1.2) module had very similar thermal behavior in reducing the diurnal temperature variations. On average, the internal temperature variations for both the InsLW and BV modules were about 30% of the external temperature variations, as shown in Figure 2.15. This indicates that, with regards to internal temperature variation, the lack of thermal mass in the InsLW walling system (10MJ/K less) can be compensated by an increase of 0.7 in the thermal resistance of the light weight walls.

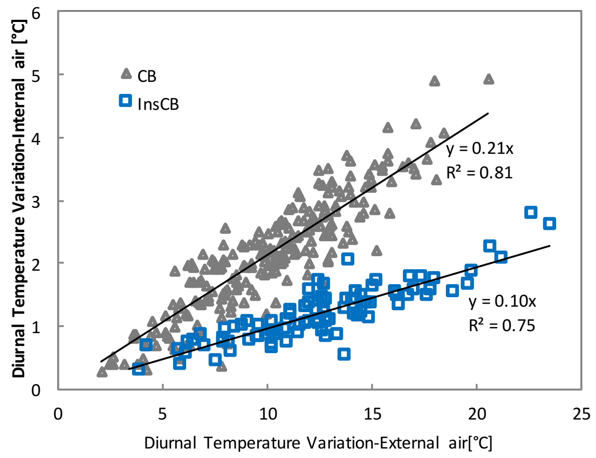


Figure 2.14: Internal vs. external diurnal temperature variations for the CB and InsCB modules

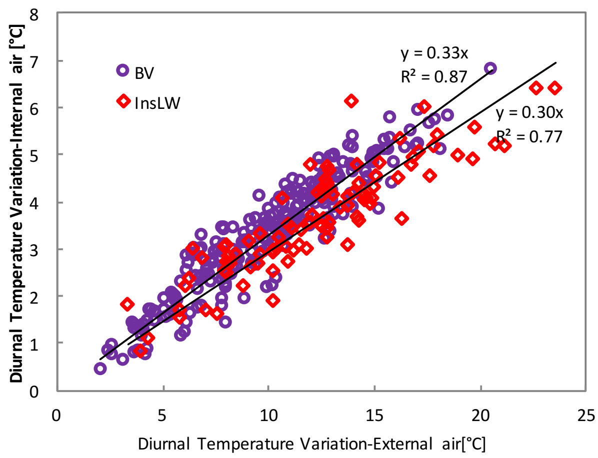


Figure 2.15: Internal vs. external diurnal temperature variations for the BV and InsLW modules

2.7.5 Thermal mass dominated walling system vs. thermal resistance dominated walling system (CB vs. InsLW)

As shown in Figure 2.16, the thermal mass dominated CB walling system (R0.44 and TM21.2) reduced the external temperature variations by almost 10% compared to those for the thermal resistance dominated InsLW walling system (R1.51 and TM1.2).

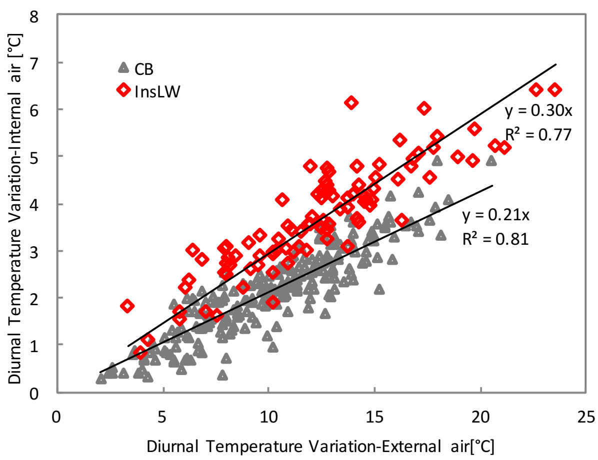


Figure 2.16: Internal vs. external diurnal temperature variations for the CB and InsLW modules

2.7.6 Relationship between thermal lag and thermal mass of walling systems

Thermal lags between external and internal air temperatures are directly related to thermal mass and almost independent of thermal resistance. This is illustrated by the similar thermal lags for the CB and InsCB modules, as shown in Figure 2.17. The walling systems for the CB and InsCB modules had similar thermal mass of about 21.2 MJ/K but different thermal resistances of 0.4 and 1.3 m²•K/W respectively. However, the thermal lags for both modules were very similar under a range of weather conditions with a maximum difference of 0.2 hours, as seen in Figure 2.17, thus confirming that the influence of thermal resistance on thermal lag was insignificant.

The relationship between the thermal lags of the four housing test modules and the thermal masses of their walling systems for different weather conditions is shown in Figure 2.18, together with an average trend line. It can be seen that there is a strong linear relationship between the thermal lag and the thermal mass of the walling systems. The intercept of about 2 hours reflects the contribution of other thermal mass in the housing test modules, particularly the contribution of the concrete slab. It was also found that with the increase of 1 MJ/K thermal mass in the walling system, the thermal lag increased by about 0.2 hours.

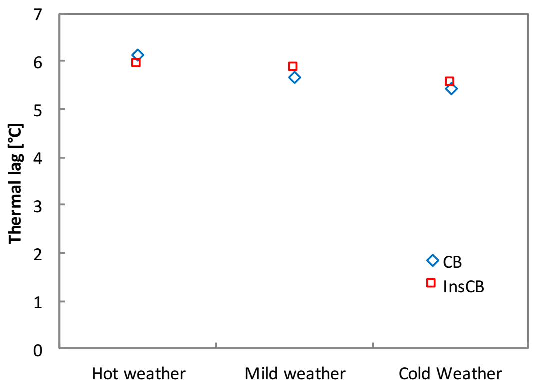


Figure 2.17: Thermal lags for the CB and InsCB modules under different weather conditions

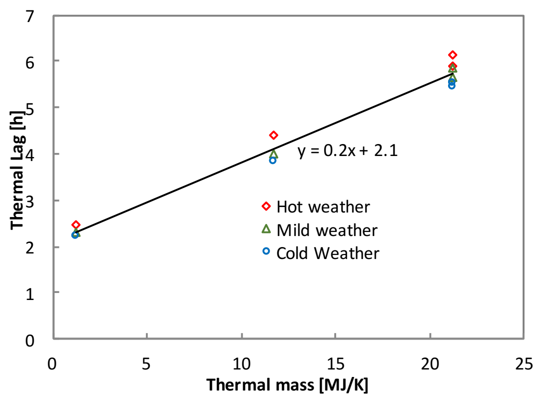


Figure 2.18: Thermal lags vs. thermal mass

2.7.7 Interaction between thermal mass and thermal resistance

Examination of the temperature profiles for each layer of the walling system indicates that there may be some interaction between the thermal resistance and the thermal mass. High thermal resistance wall elements will reduce the temperature variation which could subsequently reduce the effectiveness of the high thermal mass elements in the same walling system. This effect can be studied by a comparative study of the temperature profiles for the different layers of the CB and InsCB walling systems.

The temperature profiles for each layer of the CB and InsCB walling systems during a one week period from a similar time of different years are shown in Figures 2.19 and 2.20. Overall, the CB walling system reduced the diurnal temperature variations progressively, as shown in Figure 2.19. As shown in Figure 2.20, there was also a sudden decrease in temperature variation between both sides of the insulation panels in the InsCB walling system because of the thermal properties of the insulation. However, the variation of the reduction in temperature from the exterior brickwork skin of the InsCB walling system during the selected week was much less than for the CB module, as can be seen in Figures 2.19 and 2.20. The average diurnal temperature variations on the external wall surfaces of both walling systems during the two selected weeks for the two modules were very similar, 15.5°C for the CB and 15.3°C for the InsCB. However the average diurnal temperature variation on the internal side of the external brick walls for the CB walling system (about 8.5°C) was much smaller than for the InsCB walling system (about 11.5°C). This means that the external brick walls of the CB walling system reduced the temperature variations by about 50%, while that of the InsCB walling system, which had an extra insulation layer, reduced only by about 30%.

These findings illustrate that the overall thermal performance of a walling system should not be evaluated by simply accumulating the thermal properties of single wall elements, as interactions between the wall elements may inhibit or improve the overall performance. Understanding the interactions between wall elements with different thermal mass and thermal resistance can be helpful in finding the most thermally efficient walling system.

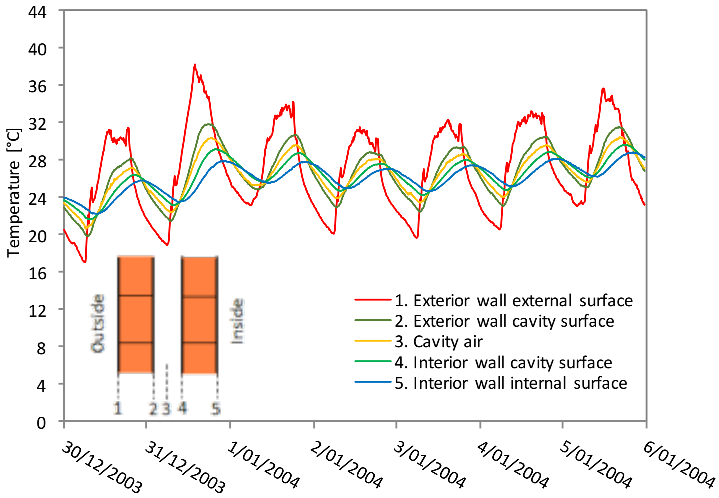


Figure 2.19: Temperature profiles for different layers of the CB walling system during a summer week, December 2003-January 2004

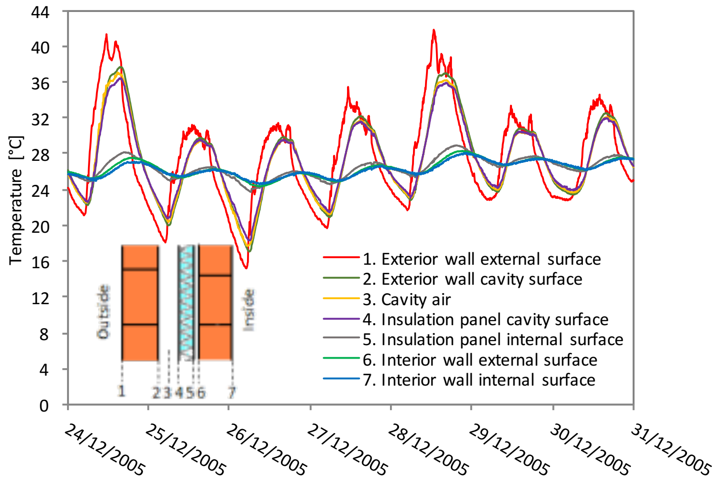


Figure 2.20: Temperature profiles for different layers of the InsCB walling system during a summer week, end of December 2005

2.7.8 Conclusions from thermal mass and resistance study

This study has assessed the thermal behaviour of four commonly used Australian domestic walling systems by studying the thermal performance of four windowless full scale housing modules. The following conclusions can be drawn:

i. The insulated cavity brick (InsCB) walling system had the best thermal behaviour, as it created the most stable internal air temperatures, followed by the cavity brick (CB) and brick veneer (BV) walling systems. The insulated light weight (InsLW) walling system had the poorest thermal behaviour followed by the BV module, with the worst amelioration of the diurnal temperature variations and the lowest average internal air temperatures in cold weather.

ii. A study of the influence of the walling system thermal mass and thermal resistance on the average internal temperatures found that neither the thermal mass nor the thermal resistance in the walling systems had a significant influence on the average internal temperatures in summer (when the effects of solar radiation on the external walls were less). However, in the autumn and winter seasons, when the solar effects on the walling systems were larger due to the lower solar angle, the external walls with high thermal mass absorb and store solar energy resulting in higher average internal temperatures. For external walls with high thermal resistance, the insulation acts as a barrier and reduces the ingress of solar energy resulting in lower average internal temperatures in cold weather.

iii. Both thermal mass and thermal resistance in walling systems influence the internal diurnal temperature variations, but in a different manner:

iv. For the insulated lightweight walling system (R1.51), the addition of 20MJ/K of thermal mass reduced the internal temperature variations by a further 65%

v. The installation of R1 insulation in the high thermal mass CB walling system (TM21.2) reduced the internal temperature variations by a further 50%.

vi. The BV walling system with a thermal mass of 11.8MJ/K and a thermal resistance of 0.8m^2•K/W had a similar thermal performance to the InsLW walling system which had almost no thermal mass but a thermal resistance of 1.5^2•K/W (almost double the thermal resistance of the BV).

vii. The "thermal mass dominated walling system" (CB with TM21.2) reduced the external temperature variations by an extra 10% compared to the "thermal resistance dominated walling system" (InsLW with R1.5).

viii. The thermal lags between the external temperatures and the internal module temperatures were closely related to the thermal mass of the modules rather than the thermal resistance. Other contributions of thermal mass from module components other than the walling system created about 2 hours of thermal lag. An increase of 1MJ/K in the thermal mass of the walling system increased the thermal lag by about 0.2 hours on average.

ix. Additionally, it was found that the insulation in a high thermal mass walling system can partially offset the influence of thermal mass in reducing diurnal temperature variations. This indicates that there are some interactions between elements with different thermal properties within the walling system itself. By understanding how elements in the same walling system potentially interact (both positively and negatively), it may be possible to find more thermally efficient walling systems, in which the potential of all its component elements are fully developed.This effect will not be captured by summing the thermal properties of the individual elements in a walling system.

2.8 Effect of internal thermal mass

2.8.1 Introduction

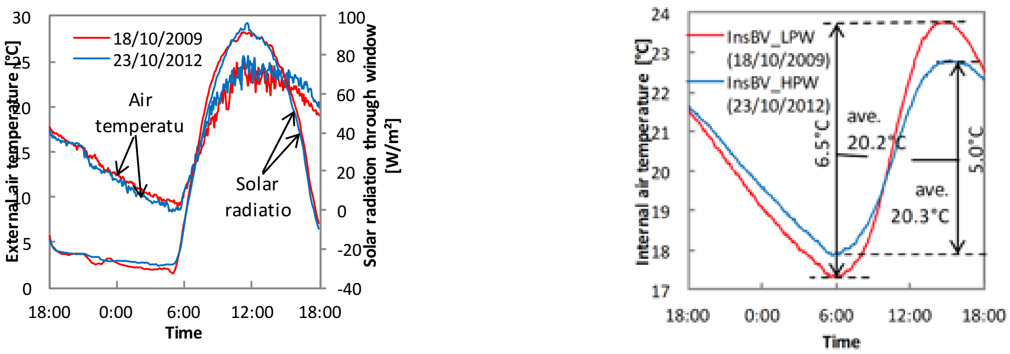
This section presents the results of a study of the impact of internal masonry walls, in the form of internal partition walls and the interior leaf of multi-layered enclosure walling systems (such as cavity brick and reverse brick veneer), on the overall thermal performance of a building enclosure. It was found that the internal thermal mass of masonry walls had a significant influence and the mobilisation of this effect is thus a useful potential means of improving 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.

Most past experimental and theoretical studies of the thermal performance of Australian housing have concentrated on the performance of the overall house rather than the influence of its individual components. Very little attention has been paid to the specific impacts of internal thermal mass, even though in general, internal partitions, the interior of the enclosure walls and concrete floor slabs all contribute to and enhance the overall thermal performance. This can be used to advantage in both new dwellings and in the retrofitting of existing houses to improve their thermal performance and minimise the need for artificial heating/ cooling.

In the following investigation, the influence of internal partition walls and other building components was studied by the selective addition of instrumented heavy (HPW) or lightweight (LPW) internal partition walls to the relevant housing test modules. The variations in module performance under actual climatic conditions could then be observed. As indicated in Table 2.1, these tests were performed on the modules with a window in the northern wall which allowed significant solar ingress to the module interior. Details of the heavy and lightweight partitions are given in Tables 2.2 and 2.4. The internal wall layout and locations are shown in Figure 2.3.

2.8.2 Comparison of the performance of the InsBV module with LPW and the InsBV module with HPW (significance of partition thermal mass)

The InsBV module was initially fitted with lightweight partition walls (LPW) and its performance observed. Subsequently, these were removed and replaced by heavy partition walls (HPW). By comparing the performance of the modules, the contribution and impact of the thermal mass of the internal partition walls could then be assessed. The performance of the InsBV module with the lightweight and the heavy partition walls were initially compared by selecting two different days (one for the lightweight and one for the heavy) from the same month of different years (18/10/2009 and 23/10/2012) with very similar external air temperatures and solar radiation (as shown in Figure 2.21). In response to the similar external weather conditions, the diurnal variation of the internal air temperatures for the InsBV module with the lightweight partition walls (InsBV_LPW) was larger than for the same module with heavy partitions (InsBV HPW), (6.5°C and 5.0°C respectively), see Figure 2.21(b)). This indicates that there was an approximately 23% reduction in diurnal temperature variation of internal air by replacing the lightweight partition walls with heavy brickwork walls, despite the fact that the average temperatures remained fairly constant with only 0.1°C difference.



a) External air temperature & solar radiation through window

b) Internal air temperature

Figure 2.21. External and internal air temperatures for the InsBV module with the lightweight and the heavy partition walls during one-day period in October 2009 and 2012

The heat exchanges through the lightweight and the heavy partition walls of the InsBV module during the two selected days (18/10/2009 atnd 23/10/2012) are shown in Figure 2.22. The heat energy absorbed and released by the heavy partition walls was over 3 times that for the lightweight counterpart; this means the heavy partition walls were able to store much more heat during the day and then release it back to the internal module space at night. Consequently, the InsBV module with heavy partition walls had lower internal daytime temperatures and higher internal night time temperatures with a more stable internal environment being maintained.

The 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 2.23. These seasonal results were obtained by averaging the diurnal temperature variations for all available days in the same season. Overall, the diurnal temperature variations of the internal air for the InsBV module with different partitions showed a similar trend for all seasons, with the highest and the lowest diurnal temperature variation occurring in winter and summer respectively, as in Figure 2.23. Furthermore, the difference in diurnal temperature variation of the internal air between the InsBV module with the lightweight and the heavy partition walls was consistent for all seasons, with the heavy partition walls being, on average, about 20% lower.

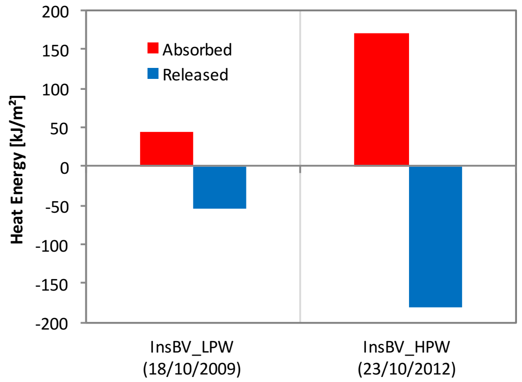


Figure 2.22. Heat absorbed and released by the lightweight and the heavy partition walls of the InsBV module during one-day period in October 2009 and 2012

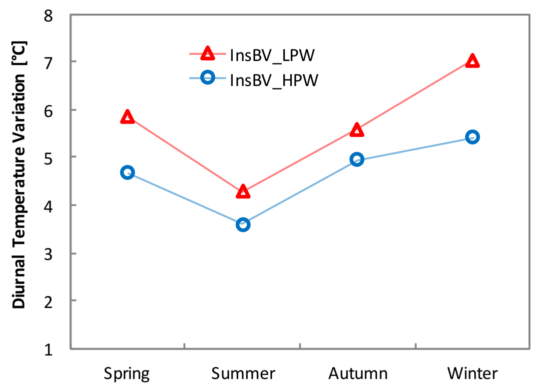


Figure 2.23. Diurnal temperature variations of internal air for the InsBV module with the lightweight and the heavy partition walls in different seasons

2.8.3 Comparison of performance of the InsBV module with HPW and the CB module with HPW (significance of thermal mass of internal leaf of 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 being the internal leaf of the enclosure walls; i.e. for the InsBV module (timber-framed plasterboard wall with low internal thermal mass) and the CB module (110mm thick brickwork with high thermal mass), see Tables 2.2 and 2.4.

Differences in internal air temperatures for the InsBV and CB modules during a one-day period (23/10/2012) are shown in Figure 2.24. Although the average internal air temperatures for the InsBV (20.3°C) and the CB (19.8°C) modules during the selected day remained reasonably constant, there was approximately a 30%

difference in the diurnal variation of the internal air temperatures for the CB and InsBV modules (3.4°C and 5.0°C respectively).

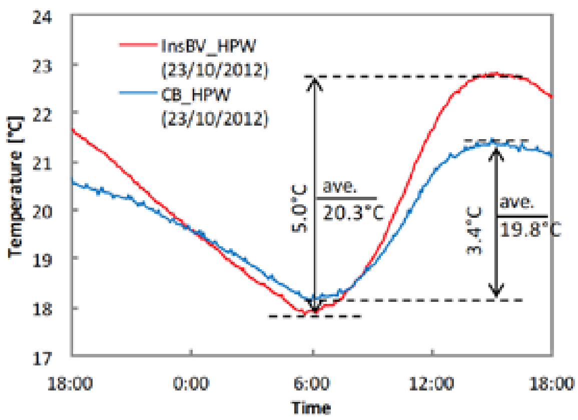


Figure 2.24. Internal air temperatures for the InsBV and CB modules with heavy partition walls during one-day period in October 2012

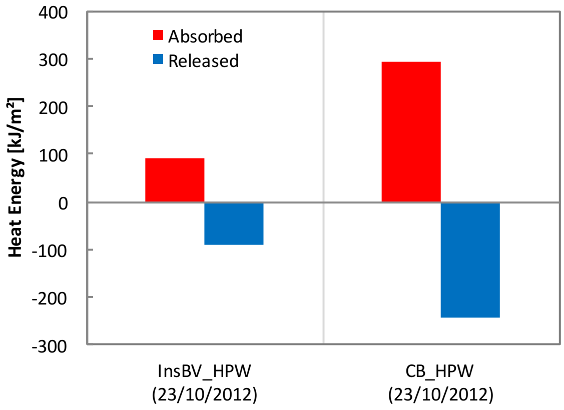


Figure 2.25. Heat absorbed and released by the internal surface of the enclosure walls for the InsBV and CB modules with heavy partition walls during one-day period in October 2012

The total energy absorbed and released by the internal surface of the enclosure walls for the InsBV and CB modules during the selected day are shown in Figure 2.25. In comparison to that for the InsBV module, the interior skin of the enclosure walls for the CB module absorbed and released much more heat during the day and the night respectively, resulting in the more stable internal air temperatures in the CB module shown in Figure 2.24.

The diurnal temperature variations of the internal air for the InsBV and CB modules for the different seasons are shown in Figure 2.26. It can be seen that 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 (about 30% on average). The above performance clearly demonstrates the benefits of having a high thermal mass internal skin for the enclosure walls.

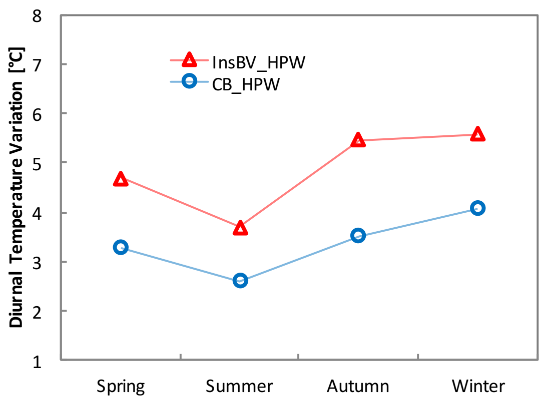


Figure 2.26. Diurnal temperature variations of internal air for the InsBV and CB modules with heavy partition walls in different seasons

2.8.4 Comparison of the performance of the InsBV module with LPW and the InsRBV module with LPW (significance of the location of the heavy leaf in the enclosure wall)

In this case, although the enclosure walls for the InsBV and InsRBV modules have essentially the same components and R-value of 1.58, the external and internal leaves of the enclosure walls are reversed. The major difference is therefore the location of the heavy skin of the external walling system, with the brickwork being located inside or outside the insulation layer for the InsRBV and InsBV respectively.

The impact of this variation was identified by comparing the internal air temperatures for the InsBV and InsRBV modules during a one-day period (18/10/2009), as shown in Figure 2.27. It can be seen that a significant difference in diurnal temperature variations between the InsBV and InsRBV modules was observed (6.5°C vs. 4.2°C). This shows that a 35% reduction in diurnal temperature variation was obtained by simply locating the thermal mass for the enclosure walls for the InsRBV module on the inside of the insulation layer. This reduction was obtained despite the fact that the thermal resistance of the enclosure walls (R1.58), as well as their overall thermal mass, were almost the same. Despite these differences in diurnal temperature variations, the average internal air temperature was found to be insensitive to the changes of internal thermal mass, with a negligible difference of less than 0.2°C between both modules.

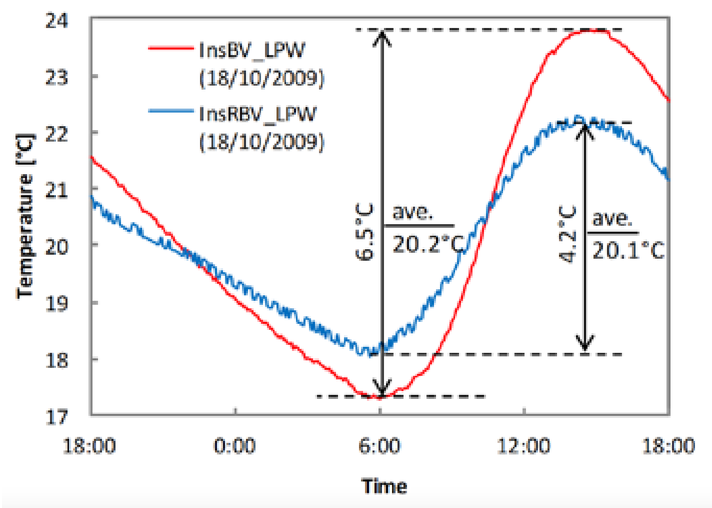


Figure 2.27. Internal air temperatures for the InsBV and InsRBV modules with lightweight partition walls during one-day period in October 2009

The heat energy envelopes of the internal surface of the enclosure walls for the InsBV and InsRBV modules during the selected one-day period (2009/10/18) are shown in Figure 2.28. It can be seen that significantly larger amounts of heat were stored and released by the internal leaf of the enclosure for the InsRBV module during the day and the night respectively, creating a more stable internal air temperature profile.

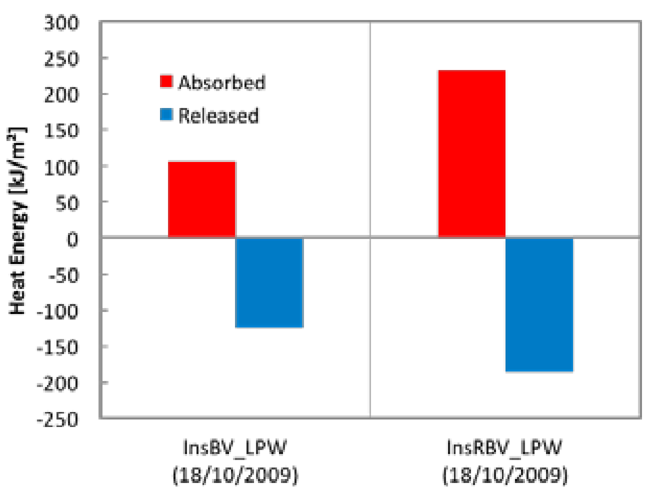


Figure 2.28. Heat absorbed and released by the internal surface of the enclosure walls for the InsBV and InsRBV modules with lightweight partition walls during one-day period in October 2009

The diurnal temperature variations of the internal air for the InsBV and InsRBV modules across the seasons are presented in Figure 2.29. By reversing the brickwork layer within the enclosure walls, an average reduction of about 26% in diurnal temperature variation across all seasons for the InsRBV module was consistently observed. Note that the key to this behaviour was the location of the inner brickwork skin for the InsRVB on the internal side of the insulation barrier, compared to the InsBV where the brickwork skin was located on the exterior of the building.

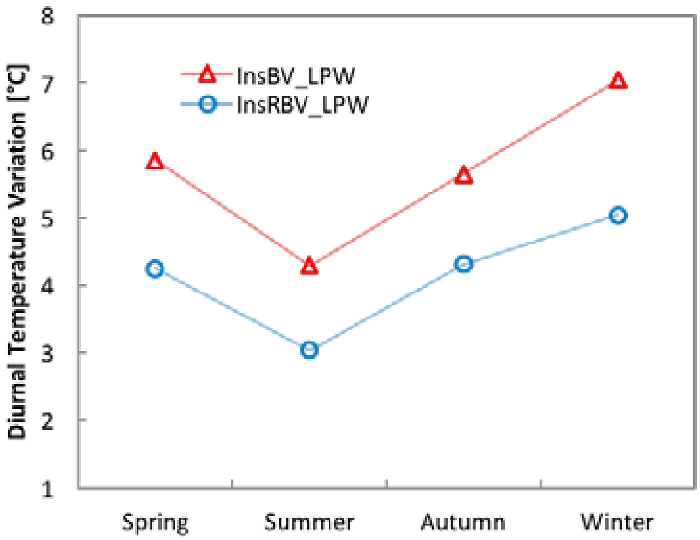


Figure 2.29 . Diurnal temperature variations of internal air for the InsBV and InsRBV modules with lightweight partition walls in different seasons

2.8.5 Conclusions from internal thermal mass study

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 have been investigated. The following conclusions can be drawn:

i. The study confirmed the premise that the R-value alone (a steady-state parameter) cannot represent the actual dynamic thermal performance of a building.

ii. The relative performance of the walling systems varied with season, but in general, the thermal mass of the partition walls and the internal skin of the enclosure walling system were more effective in absorbing energy from solar ingress and dampening the effects of the external diurnal temperature swings than a lightweight equivalent.

iii. By replacing the lightweight partition with heavy brickwork walls for the InsBV module, despite the average temperatures remaining fairly constant, the variations of the internal air temperature were reduced by approximately 20%, reflecting the dampening effect of the heavy weight partitions.

iv. The diurnal variation of the internal air temperatures for the CB module was about 30% lower than for 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. Since both modules had similar internal partition walls, this reflected the contribution of the thermal mass of the heavy interior leaf of the enclosure wall.

v. For the various modules, the energy absorbed and released by the heavy partition walls was over 3 times higher for heavy partition walls than for their the lightweight counterparts.

vi. By reversing the internal thermal mass of the enclosure walls between the InsBV and InsRBV modules, a 35% reduction in diurnal temperature variation was observed. This was despite the fact that both wall types had the same R- value of 1.58 and the same overall thermal mass. This illustrates the significance of the location of the heavy mass leaf in the enclosure wall in relation to the insulation layer, and demonstrates the advantages to be gained by incorporating a heavy thermal mass leaf on the interior side of the wall insulation.

vii. As conditions changed, significant amounts of heat were stored and released by the internal leaf of the enclosure for the InsRBV module creating a more stable internal air comfort for its occupants. On average, a reduction in diurnal temperature variations of about 26% across all seasons was observed for the InsRBV module.

2.9 Effect of carpet

2.9.1 Introduction

The floors of all the housing modules were concrete slab on ground, which in itself, has significant thermal mass. Since carpet is often used in housing to cover the floor slab for aesthetic reasons, the test modules provided a convenient means of studying the contribution of carpet to their thermal performance. For a limited period, carpet was therefore installed in four housing test modules and their performance monitored.

The modules selected for this investigation were InsBV, InsCB, CB and InsLW (see Table 2.1). For each module, the concrete floor slab constitutes a significant proportion of the total internal thermal mass. To assess empirically the thermal influence of carpet on the concrete slab, a layer of carpet combined with a standard underlay was placed over the slab within each of the modules for a period of 4 weeks, with the interior of each module remaining in a "free floating" condition with no artificial heating or cooling.

The test period was between the middle of May and middle of June 2008, a period when the solar elevation angle was close to its lowest point. This allowed the most solar energy to be transferred into the internal module space through the north facing window, see Figure 2.30. For comparison with the "no carpet" performance, data for the modules without carpet were selected from the previous year (2007) at similar dates to ensure similar external weather conditions and solar angle. For suitable data to be used for statistical analysis, a complete set of temperature records for each module were ideally required from the same days in each year. Eleven days which met this requirement in each year were selected.

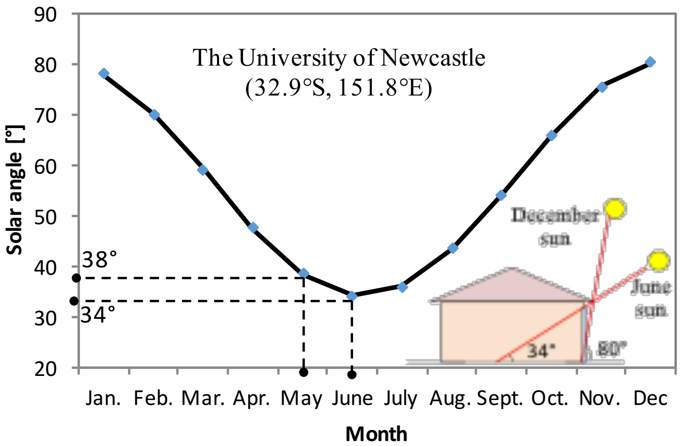


Figure 2.30: Solar angle for the University of Newcastle

2.9.2 Direct diurnal comparison

To enable direct comparisons of the influence of carpet, the data were inspected to find at least one day in each year that was close in dates (with similar solar angles) and had very similar external temperature conditions and solar radiation measurements. This method of comparison is a common approach that is used when experimental conditions can be controlled so that it is easy to make direct comparisons. However, it is difficult to use direct comparisons when experimental conditions such as weather can't be controlled and similar days cannot be found. For those cases statistical methods are required to make adjustments for the different conditions to allow comparisons to be made under "modelled" similar conditions. Both direct and statistically based comparisons
are made in this study.

Table 2.5 provides a summary of the maximum, minimum, variation and average internal air temperatures for the modules with and without carpet on 23-05-07 (without carpet) and 20-05-08 (with carpet). It can be observed that for these two similar days, modules with the presence of carpet had overall slightly lower average internal temperatures (<1°C difference), despite the average external temperature for 20-05-2008 being slightly higher. This therefore indicates that the presence of carpet might have some minor effect on the average internal air temperatures. However, because of the relatively small differences in average temperatures, this effect cannot be clearly assessed by this direct comparison method.

For the two similar days studied, significant differences were observed in the overall variations of internal temperatures for each of the modules, as can be seen in Table 2.5. The main changes observed related to an increase in the maximum temperature and a decrease in the minimum temperature, with an apparently far greater effect in the InsBV and InsLW modules. For modules having walls with an internal masonry leaf, the diurnal swing increased from 6.4 to 9.2ºC, due to the contribution of the carpet masking the thermal mass effects of the slab. For the modules without internal thermal mass in the walling system, the swing was even more pronounced (from approximately 10 to 17ºC), illustrating the greater relative contribution of the thermal mass of the slab in absorbing and releasing energy when not insulated by the carpet. These increased ranges for the InsBV and InsLW modules seem to be too large to be solely caused by slight differences in the weather conditions on the two similar days.

	External Air Temperature	CB Module	InsCB Module	InsBV Module	InsLW Module
23-05-07 (no carpet)					
Maximum [°C]	19.8	23.6	25.3	27.5	27.5
Minimum [°C]	6.1	17.2	18.9	18.0	17.4
Variation [°C]	13.7	6.4	6.4	9.5	10.1
Daily Average [°C]	11.5	19.8	21.8	22.2	21.7
20-05-08 (with carpet)					
Maximum [°C]	21.3	24.1	26.1	31.2	31.0
Minimum [°C]	6.5	14.9	16.9	14.8	13.6
Variation [°C]	14.8	9.2	9.2	16.4	17.4
Daily Average [°C]	12.4	18.7	21.1	22.2	21.0

Table 2.5 Comparison of internal air temperatures for the modules without and with carpet

This information is presented as time series comparisons in Figure 2.31 together with the solar radiation for each of the days and a direct comparison of the slab heat flux recorded near the window. It can be seen that the presence of carpet has reduced the peak heat flux absorbed by the slab from 150-200 W/m² to 60-75 W/m². The night-time radiation from the slab decreased from 35-40 W/m² (bare slab) to 11-16 W/m², once again due to the inclusion of carpet.

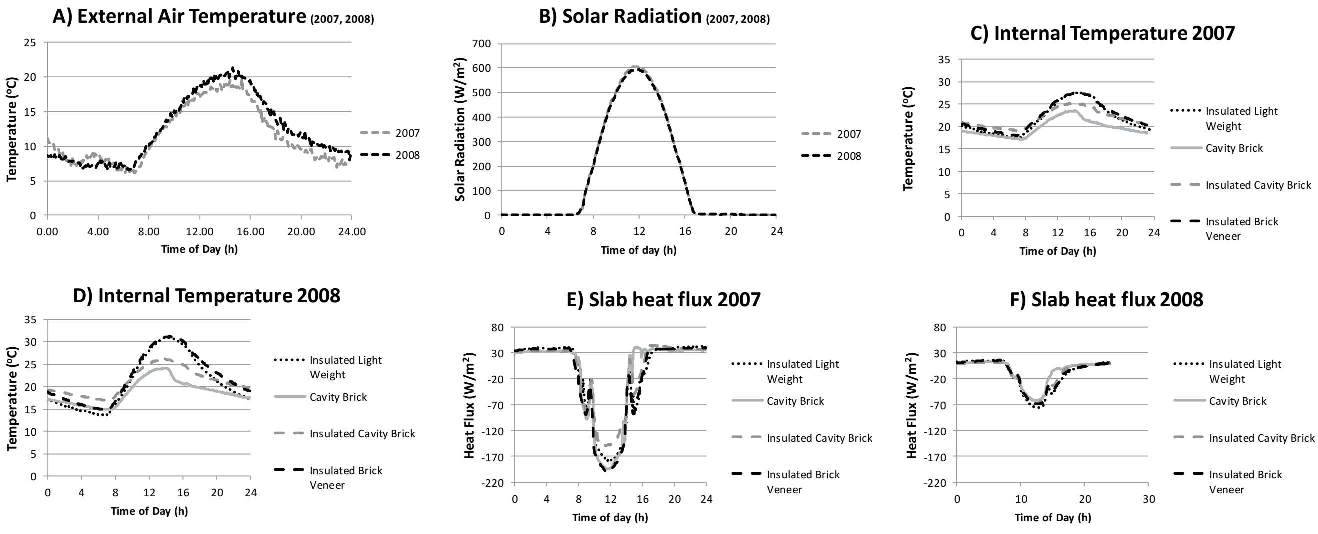


Figure 2.31: Diurnal comparisons for the modules without carpet on 23/05/2007 and with carpet on 20/05/2008

In summary, direct time series comparisons for the two similar days suggested that the carpet had a substantial influence on the internal diurnal temperature swing, particularly within the InsLW and InsBV modules. The introduction of carpet reduced the heat flux absorbed by the slab from direct sunlight by 60% (Figures 2.31 E and F) and increased the diurnal swing experienced within the modules (Figures 2.31 C and D).

These comparisons have illustrated the effects on internal temperature that can occur due to the influence of carpet in reducing the contribution of the slab thermal mass in each module. In effect, the carpet reduces the attenuation effect of the slab thermal mass resulting in a greater temperature variation in the room. The observed differences were too large to be solely attributed to any minor, additional environmental variations given that the two close calendar days were selected for their similarities of weather.

2.9.3 Comparison using statistical analysis

The sinusoidal models of the internal temperature profiles for modules with and without carpet are shown in Figure 2.32. The presence of carpet for all modules resulted in lower average internal air temperatures but with significantly larger temperature swings, which affected the internal thermal comfort level which was set between 18-24°C. Modules without the carpet experienced 13 and 24 hours within the thermal comfort range for the InsLW and InsCB modules respectively. However this was reduced to 7.7 and 16.8 hours when the carpet was installed, see Table 2.7. This indicates that the presence of carpet reduced the thermal comfort level for the InsCB module by 7.2 hours. This was followed by the InsBV and InsLW modules, with the least value of 2.2 hours for the CB module. However, in terms of percentages, the carpet effect had a more significant impact on the InsBV and InsLW modules (with lightweight internal skins), with more than a 40% reduction in thermal comfort level. In comparison, the InsCB and CB modules (with higher internal thermal mass) experienced reductions of 30% and 14% respectively in the thermal comfort range.

Module	Predicted Average Internal Temperature [°C]		Predicted Internal Temperature Variation [°C]	
	With carpet	No carpet	With carpet	No carpet
InsBV	20.8	21.4	11.6	7.4
CB	18.5	19.1	7.4	5.2
InsCB	20.2	20.8	7.4	5.2
InsLW	20.3	20.9	12.5	8

Table 2.6: Predicted internal air temperature average and variation

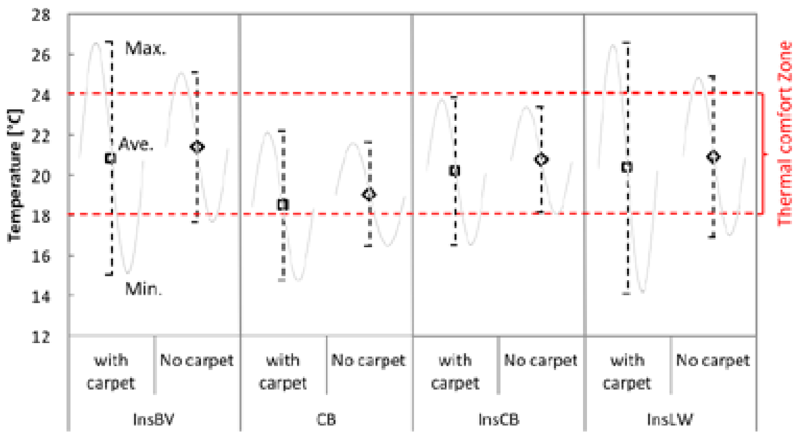


Figure 2.32: Predicted internal temperature profiles using statistical models and sinusoidal functions

Module	Thermal comfort time [h]			
	With carpet	No carpet	Difference	Difference %
InsBV	8.4	14.6	6.2	42
CB	13.2	15.4	2.2	14
InsCB	16.8	24	7.2	30
InsLW	7.7	13	5.3	41

Table 2.7: Predicted internal air temperature conditions

2.9.4 Conclusions from carpet study

The following conclusions can be drawn from this study:

i. When there is no carpet to mask the contribution of the horizontal thermal mass of the floor, the room interior air responds less to external temperature changes due to the effects of thermal lag in the slab, with a resulting improvement in the thermal performance. With the statistical method of analysis it was shown empirically that the effects of carpet were greater for those modules for which the slab floor was the only interior component of thermal mass (for the lightweight and insulated brick veneer systems).

ii. The concrete slab, together with any heavy internal walls, provides a source of thermal mass. During a diurnal temperature cycle, these components absorb and release energy with a corresponding positive influence on the internal thermal comfort. The placement of a layer of carpet with its accompanying thermal resistance acts as a potential barrier to this mechanism and a partial loss of the positive contribution of the thermal mass of the floor. The carpet effect was found to be more pronounced for the modules that had lightweight internal skins (InsBV and InsLW), indicating that the thermal mass of the heavy internal brickwork skins of the CB and InsCB modules also had a positive influence on the thermal performance.

2.10 Effect of windows

2.10.1 Introduction

This section focuses on a study the impact of a window (with accompanying solar ingress) on the thermal performance by comparing changes in indoor temperatures between “no window” and “with window” conditions. Previous studies of thermal performance of housing have been mainly based on existing houses or buildings where windows already exist, and the “no window” condition is therefore not available as a reference. As a result, the direct influence of a window cannot be fully captured. However, in the current testing program, the performance of the housing modules with and without the presence of a dominant window in the north facing wall was able to be observed over all seasons. This has allowed direct comparisons of the influence of the window on the thermal performance of the modules, including the contribution of internal thermal mass.

For the modules with no window, the energy exchange between the external environment and internal module space must predominantly occur through the walling system, as the roof and access door were heavily insulated. The external surface of the walling system is exposed to changes in the external weather conditions and triggers the energy exchange process. However, with the installation of window, a new energy exchanging route is created. Energy can now flow into or out of the internal module space directly through the window (a thin layer of glass), in addition to passing through the walling system. During the day, the north facing window allows solar energy to pass into the internal space. Some of this solar energy, in the form of radiation, can be directly absorbed by the internal mass of the modules. The remainder heats up the air near the window, with the heat spreading to the entire internal space by convection, and then being absorbed by the internal thermal mass. At night, the window becomes the weak link in keeping heat energy inside the module, because of its poor thermal properties. Thus, in comparison to the windowless modules,

due to the loss of heat through the window, more energy can be released from the internal module space at night.

The direct energy input through the window during the day (mainly the solar energy) accentuates the influence of the internal thermal mass properties on the overall thermal performance of the modules, with the main difference between the BV and CB modules being the internal thermal mass of the walling systems, i.e. low and high internal thermal mass for the BV and CB modules respectively. The energy exchange processes through the window for the BV and CB modules during day and night are shown in Figure 2.33. Because of its higher mass, much more energy can be absorbed and released by the internal skin of the CB walling system compared to the BV system.

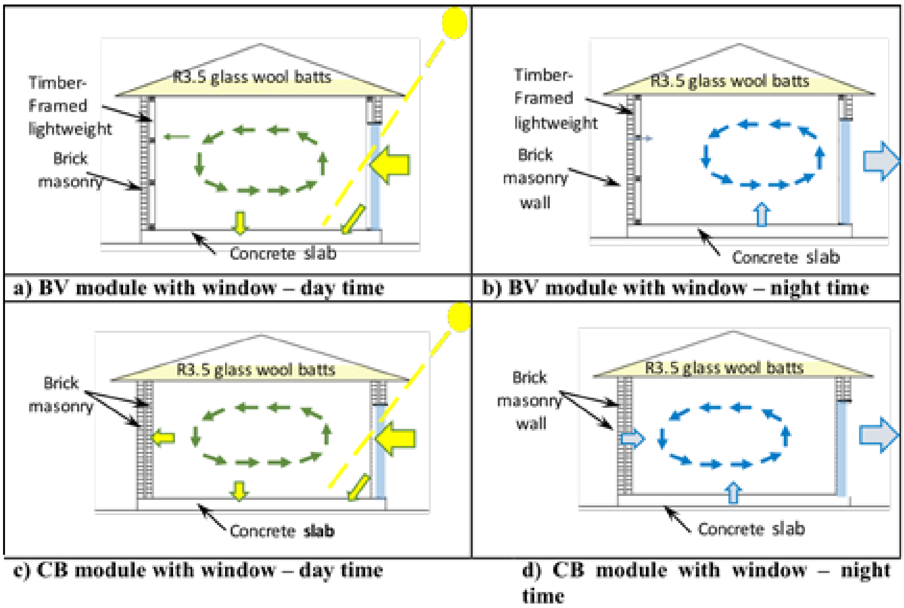
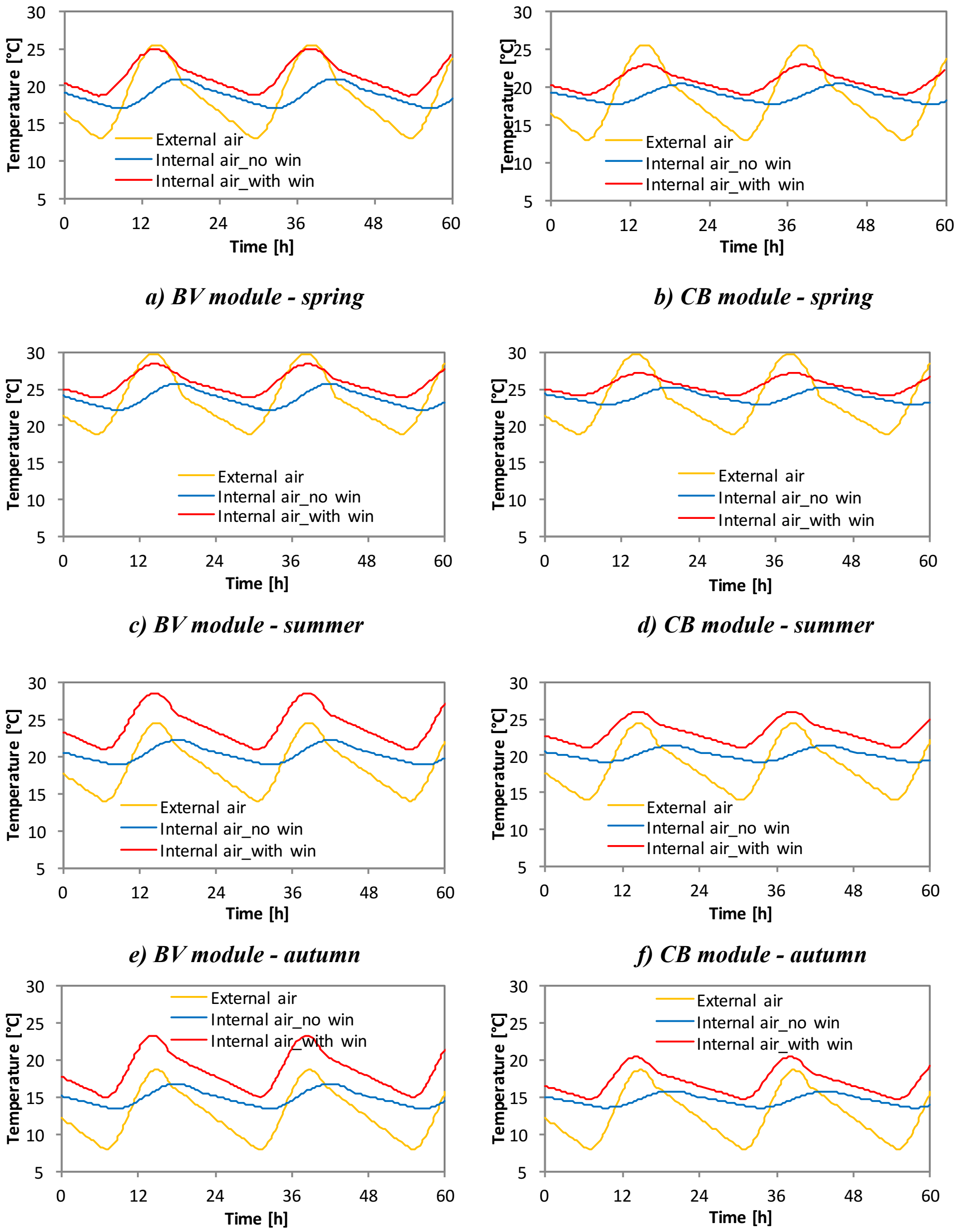


Figure 2.33: Energy exchange processes through the window for the BV and CB modules during day and night. Note: (1) yellow arrows indicate energy absorbed, the blue arrows energy released back into energy circulation; (2) no internal partition walls were present.

2.10.2 Impact of windows on thermal performance of the modules

The influence of the window on the thermal performance of BV and CB test modules can be directly compared by presenting the temperature profiles for the modules with and without a window in the same figures. The internal air temperature profiles under “no window” and “with window” conditions and the external air temperature profiles for both modules in different seasons are shown in Figure 2.34 a) to h). Internal air temperatures under the “with window” condition are always higher than the “no window” condition at any time for both the BV and CB modules for all seasons, because of the extra energy input through the window. Before the installation of the window, the peak internal air temperatures for both modules were always lower than the peak external air temperatures. However, those peak internal temperatures became higher than the external in autumn and winter after the window was installed, as in Figure 2.34 e) to h). Thermal lags between the peak external and internal air temperatures for modules without a window were very obvious, but this became insignificant for the modules with a window, as shown in Figure 2.34 a) to h). In addition, the internal air temperatures for both modules had larger variations under the “with window” condition, especially in autumn and winter.

The installation of a window had some different impacts on the two test modules with different internal thermal mass. The internal air temperatures for the BV module with low internal thermal mass had much higher peaks and variations than the CB module with high internal thermal mass in spring, autumn and winter under the “with window” condition, compared to the “no window condition, as in Figure 2.34 a), b), e), f), g) and h).



a) BV module - spring *b) CB module - spring*

c) BV module - summer *d) CB module - summer*

e) BV module - autumn *f) CB module - autumn*

g) BV module - winter *h) CB module - winter*

Figure 2.34: Temperature profiles for the BV and CB modules with and without a window for different seasons (Note: 0h and positive multiples of 24h represent midnight 12:00 am)

The maximum, minimum and average internal air temperatures for the BV and CB modules with and without windows for different seasons are shown in Figure 2.34 a), b) and c). Before the installation of the window, the differences in internal air temperatures (including the maximum, minimum and average) for the BV and CB modules were relatively small in all seasons. The average internal air temperatures for the BV and CB modules without a window were especially similar, as in Figure 2.34 c). After the window was installed, the maximum, minimum and average internal air temperatures all increased for both the BV and CB modules. However, differences in maximum temperatures between these two modules under the “with window” condition became significant, compared with the minimum and average, as in Figure 2.35 a). In comparison to the “no window” condition, the CB module with high internal thermal mass had much lower maximum internal air temperatures than the BV module with low internal thermal mass under the “with window” condition, due to the important function of internal thermal mass in dealing with energy input through window. In addition, the effects of season on the maximum internal temperatures can also be observed from Figure 2.35 a). For both modules, the maximum internal temperatures had the biggest increase in autumn and winter and the smallest in summer, with the installation of window, as in Figure 2.35 a). Furthermore, it can also be seen that the biggest differences between the BV and CB modules with window also occurred in autumn and winter, with the smallest occurring in summer.

The impact of a window on the internal temperature variations (i.e. the maximum minus minimum) for the BV and CB modules for different seasons is presented in Figure 2.35 d). The internal temperature variations were fairly similar across all seasons for the BV and CB modules before the installation of the window, but varied significantly after. For both modules, there were obvious increases in internal temperature variations after the window was installed, with the biggest and smallest increases occurring in winter and summer respectively, as in Figure 2.35 d). The internal temperature variations for the CB module with high internal thermal mass were about 3.1°C lower than for the BV module under the "with window" condition, while being only 1.3°C for "no window". This again demonstrates the importance of internal thermal mass in dealing with the impact of the window.

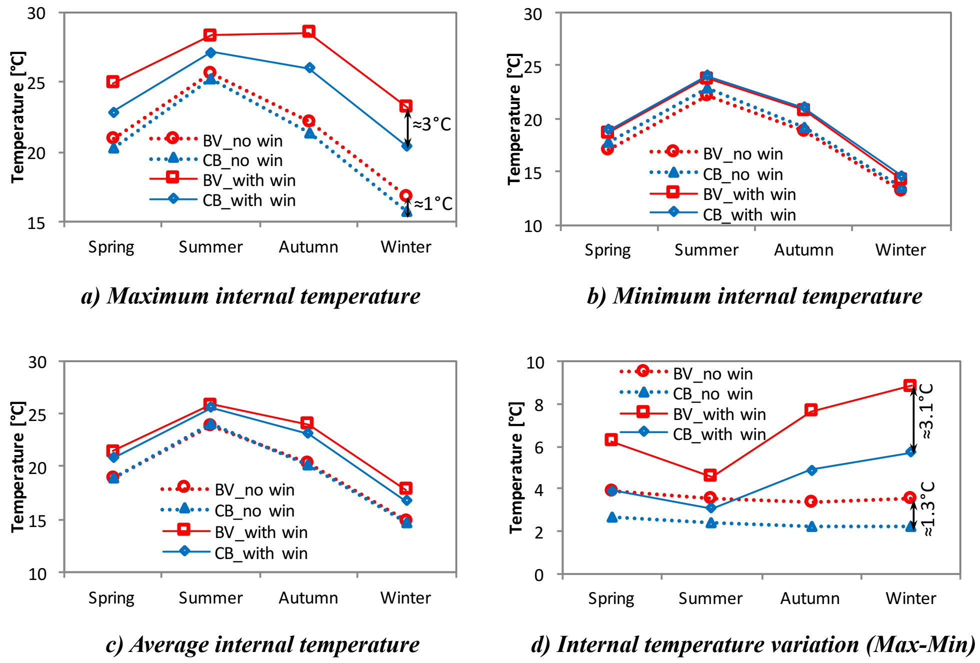


Figure 2.35: The internal air temperatures including the maximum, minimum, average and variation for the BV and CB with and without window for different seasons

2.10.3 Conclusion from window study

This section has assessed the impact of a north facing window on the thermal performance of two full scale housing test modules with different walling systems: brick veneer (BV), consisting of an external brickwork skin plus an internal timber-framed wall, and cavity brick (BV) made up of two brickwork skins. The difference between the BV and CB walling systems is the thermal mass of the internal leaf (internal thermal mass): low for BV and high for CB. The importance of internal thermal mass in treating the 'direct energy exchange' through the window was also studied. In order to assess the impact of the window, both modules were observed without and with the installation of the window under real climatic conditions over all seasons, but in different time periods. This meant that direct comparisons between the performance of the modules with and without a window were impossible. Statistical and mathematical modelling techniques were therefore used to enable comparisons to be made. The study revealed the following:

i. After the installation of the window, the internal air temperatures for both the BV and CB modules became higher because of extra energy input through the window. The peaks and variations of the internal air temperatures significantly increased under the "with window" condition for both modules, and varied with seasons. Winter had the biggest increase, while summer had the smallest. In addition, the thermal lags between the external and internal temperature profiles for the modules with window disappeared.

ii. The changing importance of the influence of the internal thermal mass with the installation of the window was mainly evident in the peaks and variations of internal air temperatures. In comparison to the "no window" condition, the CB module with high internal thermal mass had much lower peaks and variations than the BV module under the "with window" condition, indicating that the internal thermal mass played a more important role in maintaining the

thermal performance of the modules after the window was installed. This was because the internal thermal mass of the walling system was involved in two energy exchanging processes between the external environment and the internal module space - the energy exchange through the walling system, and the energy exchange through the window. With the installation of window, the second energy exchange process is activated and the internal thermal mass of the walling system starts to play its extra role.

2.11 Housing module study - Summary

This chapter has given an overview of an experimental study of the thermal performance of four housing test modules incorporating a range of different walling systems. Since each module was designed to allow the selective replacement of walling systems without disturbing the roof structure, a large range of wall types, wall configurations and wall opening conditions were able to be considered. The wall types were Cavity Brick (CB), Insulated Cavity Brick (InsCB), Brick veneer (BV), Insulated Brick Veneer (InsBV), Insulated Reverse Brick Veneer (InsRVB) and Insulated Lightweight (InsLW), and reflected typical Australian construction practice.

As shown in Figure 2.1 and Table 2.1, the tests were performed over a number of years with the interior of each module being allowed to either free float under the external conditions, or be controlled within a set temperature range to maintain the thermal comfort of the interior. Data for all weather conditions and seasons with or without the inclusion of a northern window opening was therefore potentially available. Some early results were presented in the Phase 1 Report published in 2011 (1).
Aspects investigated in this Phase 2 Report and presented in this chapter have included the following:

i. study of the significance and interaction of wall thermal mass and thermal resistance;

ii. significance of wall thermal mass location;

iii. influence of internal lightweight or heavy weight partitions;

iv. influence of carpet on thermal performance;

v. influence of a major window opening in the northern wall and the associated mechanisms of heat transfer;

vi. seasonal energy demands for the various walling systems to maintain reasonable internal comfort levels.

The performance of the various walling systems in the module tests have also been used in subsequent chapters as background to the development of laboratory dynamic testing procedures and the formulation of the dynamic thermal response concept which can be applied to both individual wall assemblages and complete building enclosures.

3. Laboratory

3.1 Overview

Buildings are exposed to a range of climatic conditions and dynamic temperatures which directly influence their thermal performance. Since material selection has a major influence on the thermal performance and energy requirements of a building over its life cycle, the selection of the building components needs to be appropriate to the local environment and the expected diurnal temperature profiles. Therefore, in parallel with the housing module study reported in Chapter 2, in the second phase of this project, an extensive series of static and dynamic tests on individual walling systems and their components were performed.

The focus of the wall tests in Phase 1 was mainly on wall performance under a static temperature environment, as required to determine the thermal resistance (R-value) of the wall. These tests were performed using a guarded hot box which was developed "in house" and located in the Civil Engineering laboratory at the University of Newcastle.. Since this area of the laboratory was not temperature controlled, the conditions surrounding the hot box did vary to a small degree. In the subsequent Phase 2 tests reported here, this effect (although minor), was avoided by locating the new guarded hot box in a dedicated, temperature controlled space. As described below, this new hot box was used to carry out a wide range of static and dynamic temperature tests on individual walls, to study in detail the influence of both thermal mass and thermal resistance on the wall thermal performance.

Towards the latter stages of the project, an additional smaller hot box apparatus was also developed to allow a series of common walling systems to be tested under dynamic temperature conditions. This facilitated the study of the combined contribution of the individual wall properties previously determined in the larger dynamic hot box. Several of the previous larger hot box tests were repeated to confirm the compatibility of the results from the two facilities.

Steady-state tests, using a Hot Box apparatus, have already been standardised (for example, ASTM C1363-11 (2). This test evaluates the thermal resistance (R-value), which directly indicates how well a material will restrict heat energy flowing through it. The higher the R-value the greater resistance to energy transfer. Steady state testing provides numerical data that is invaluable in comparing the thermal efficiency and the heat transfer through typical wall constructions but, has limited ability to predict how a material will perform under a variable temperature environment. There is a common misconception that the thermal efficiency of any structure depends solely on the insulating properties of the material. The efficiency of a structure can certainly be increased by adding insulation, but it is the correct combination of insulation and wall material (with its inherent thermal mass), together with building layout that achieves the best performance (1). Although a material may have a high R-value, this does not necessarily mean it will perform well when exposed to a dynamic temperature cycle.

This chapter presents a detailed description of the development of the wall testing rigs and test specimens. The results of the static and dynamic tests performed on individual walls and walling systems, together with a study of the significance and influence of wall insulation properties and location are reported in Chapter 4.

3.2 Apparatus development

3.2.1 Steady-state conditions

The hot box shown in Figures 3.1 and 3,2 was developed as part of the Phase 1 investigation and was predominantly used in steady state tests to determine the R-value of a wide range of common walling elements. This apparatus was located in the Civil Engineering laboratory in an area which was not temperature controlled. Consequently the laboratory ambient temperature varied marginally with the external seasonal conditions (although this effect was not considered particularly significant, it was eliminated in the refined hot box developed for the Phase 2 tests by incorporating the same metering chamber but with an external temperature controlled space to negate any external effects).

The hot box facility utilises the Guarded Hot Box (GHB) principle whereby a metering chamber is incorporated on the hot side of the apparatus. This chamber, measuring 1200mm x 1200mm (see Figure 3.1), is maintained at the same temperature as the outer hot (guard) chamber thus minimising any potential flanking loss along the specimen edge and heat loss via the meter box walls. A schematic diagram of this arrangement is shown in Figure 3.2. A more detailed description of this testing rig is given in the Phase 1 report. For the Phase 2 test, both the steady state R-value tests and the dynamic tests were performed in the refined hot box apparatus described in Section 3.2.2.

Figure 3.1 Guarded Hot Box Apparatus (1)

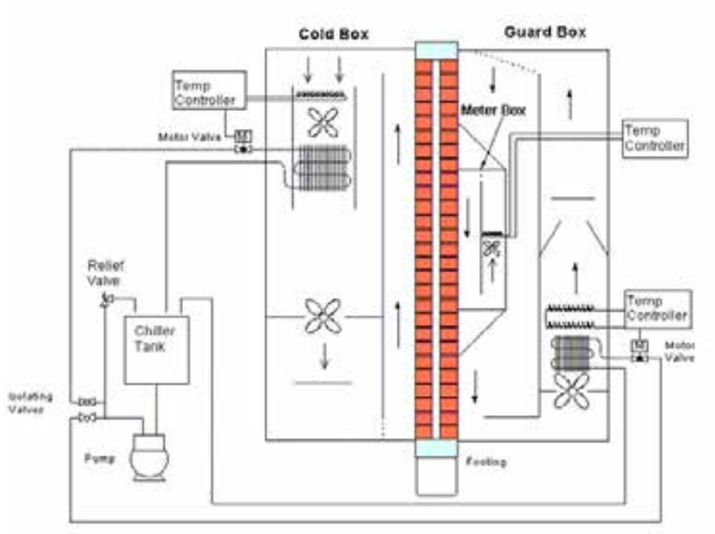


Figure 3.2 Schematic of the Phase 1 Guarded Hot Box Apparatus (1)

In the steady state R-value tests, a constant temperature differential is maintained between the two chambers. In the tests, temperatures were appropriately set in each chamber to provide a constant rate of heat flow through the test specimen. Energy and temperature measurements from sequential four hour periods were used to calculate average thermal properties. Testing was performed for two temperature differentials, 18°C and 12°C (air-to-air). In both cases the mean wall temperatures were adjusted to 23°C in accordance with AS/NZS4859.1 (7). The results of the various R-value tests are included with those for the dynamic tests described below.

3.2.2 Dynamic conditions

3.2.2.1 Overview

As described above, the guarded hot box is normally used to evaluate the steady-state thermal performance of walls and wall assemblies. The apparatus developed for the Phase 2 investigation was a refined version of the Phase 1 apparatus and was designed to perform both steady state R-value tests as well as tests imposing

cycles of varying temperature corresponding to Australian weather cycles. As for the Phase 1 rig, the apparatus was able to test walls 2.4 m (high) by 2.4 m (wide).

3.2.2.2 Dynamic testing apparatus

For the Phase 2 investigation, a new hot box apparatus was developed to incorporate an external temperature controlled surround to eliminate any effects of the varying laboratory ambient temperature. This apparatus, as well as being capable of providing a steady state controlled temperature environment for R-value tests, was also capable of providing a dynamic input temperature cycle to mimic the various Australian daily and seasonal temperature cycles. For the R-value tests, the apparatus incorporated the metering box from the Phase 1 tests described above. For the dynamic tests, this metering box was removed and the dynamic temperature cycle was created in the space on the input side of the apparatus. The Phase 2 hot box details are shown schematically in Figure 3.3. The apparatus consists of two separate chambers with each enclosure surrounded by R3.5 insulation to maintain a constant temperature gradient across the 2.4m x 2.4m test panels. The apparatus included specialised instrumentation for temperature control, temperature and power consumption measurement, with the recirculating heating unit in one of the chambers able to simulate a dynamic cycle. The unit is capable of producing any dynamic temperature profile within the range -10°C and 80°C with up to 1000 time steps.

As shown in Figure 3.3, both the chambers and test panel were located in a controlled (constant temperature) space to create a steady ambient external environment for the test without any influence of external temperature variations. An air conditioning system in the surrounding constant temperature space capable of controlling the temperature to within 0.5°C created a steady state ambient environment for the test. This also allowed heat flux attenuation studies to be performed under cyclic (transient) temperature conditions which mimic day-night temperature variations. The Phase 2 modified Hot Box apparatus is shown in Figure 3.4.

The dynamic cycles, which represent the outdoor temperature conditions, are created in one chamber, called the "external" chamber. The other uncontrolled free-floating chamber (the "response" chamber) is used to observe the response of the panel under the external temperature profiles. Unlike the steady-state test, no specialised instruments to measure the energy requirements were installed as the temperature profile is the only input parameter. This realistically reflects the real conditions as the performance of a building depends on the outdoor diurnal temperature which is mainly affected by the solar radiation.

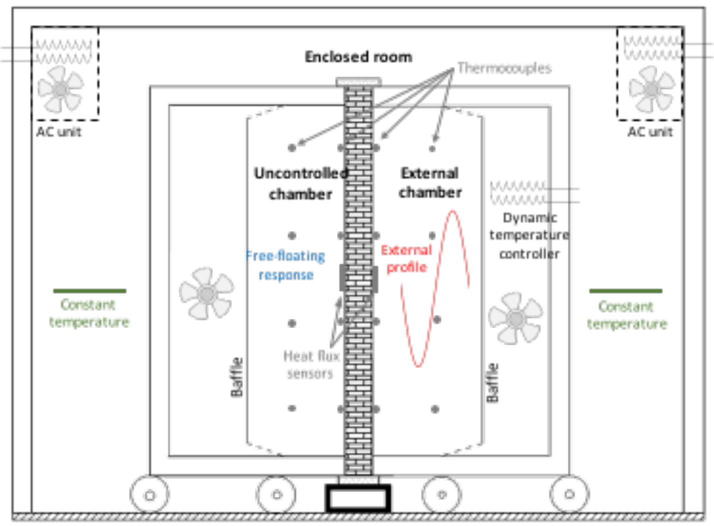


Figure 3.3: Schematic arrangement of the Phase 2 Hot Box apparatus

All temperature sensors were calibrated in accordance with the ASTM C1363-11 (2), and heat flux sensors were installed in the centre of both sides of the test panel. Prior to each dynamic test, the test environment was stabilised in a steady-state to minimize any inertia effects. During this step, both chambers, together with the test specimen, were located in the constant temperature space and exposed to that temperature. For 24 hours prior to each test, the enclosure space temperature was set to the average of the planned temperature

cycle. Both chambers were then closed to run the dynamic temperature cycle (the 24 hour requirement was calculated for a single skin brick wall to expedite convergence to a faster stable response). Following the initial set up, the dynamic temperature cycles were run in the external (controlled) chamber, with a few preliminary diurnal cycles being repeated until the consecutive temperature and heat flux profiles become stable. This depended on the temperature range of the cycle and the amount of the thermal mass present in the panel.

(a) External controlled temperature enclosure and internal hot box

(b) Air conditioning input and system monitoring
Figure 3.4. Phase 2 Hot Box Apparatus

The wall instrumentation for the static R-value tests and the dynamic tests was the same (except for the dynamic tests the central meter box was removed). As shown schematically in Figure 3.5, the instrumentation consisted of a central heat flux sensor, together with an array of thermocouples, all located within area within the meter box profile used in the R-value tests.

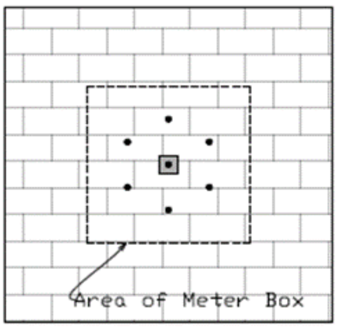


Figure 3.5. Instrumentation (circles indicate temperature sensors, square indicates heat flux sensor)

3.2.2.3 Supplementary dynamic testing apparatus

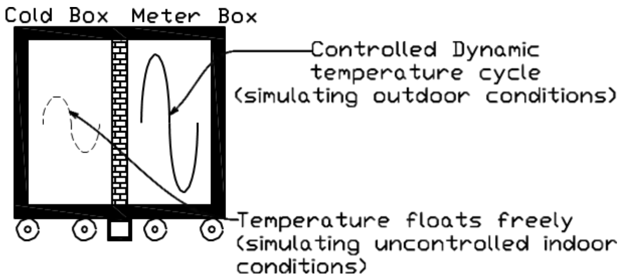
To facilitate the study of the combined contribution of the individual wall properties previously determined in the larger dynamic hot box, towards the latter stages of the project an additional smaller supplementary hot box apparatus was developed. This allowed a series of common walling systems and their components to be tested under dynamic temperature conditions in parallel with the larger wall tests. The smaller hot box was connected to the same heating/cooling system as the larger rig and was therefore able to reproduce the same

dynamic temperature cycles. In contrast to the larger rig, the hot box had no outer temperature controlled enclosure, and relied upon the ambient temperature within the laboratory space to be within reasonable limits. Any inaccuracies resulting from this effect were assumed to be small, and this was confirmed by parallel tests of the same component in the more elaborate and simple rigs. The supplementary hot box is shown in Figure 3.6.

3.3 Dynamic wall tests

3.3.1 Overview

The main purpose of the dynamic wall tests was to study in detail the influence of thermal mass and thermal resistance, both individually and combined, on wall performance when subjected to dynamic temperatures corresponding to typical Australian diurnal temperature cycles. To systematically investigate these characteristics, walls constructed from materials with a wide range of thermal mass and thermal resistance were studied. The walling systems ranged from a 25 mm thick Styrofoam panel (with very low thermal mass) to a 110 mm thick solid concrete panel (with high thermal mass). Between these two extremes, seven different brick and concrete masonry walling systems were studied, each with a different degree of thermal mass, depending on the presence and nature of perforations within the units. The masonry units used in the study are shown in Figure 3.7.



(a) Schematic arrangement

(b) Hot Box apparatus

Figure 3.6: Supplementary Hot Box apparatus

3.3.2 Construction of wall panels

The wall panels for the dynamic tests were 2400 mm x 2400 mm and constructed in the laboratory adjacent to the testing rig. The walls were constructed by an experienced bricklayer using a 1:1:6 mortar (cement:lime:sand by volume) to reflect typical practice (see Figure 3.8). Because the free standing walls were quite slender, they were constructed on a steel box section and within a steel supporting frame which was removed after construction. The walls were cured and conditioned in the laboratory for at least two months after construction before performing the tests. To maintain the integrity of the walls as they were moved into the testing chamber, they were lightly prestressed through a top spreader beam via rods located at each end of the wall (these were removed once the wall was in place).

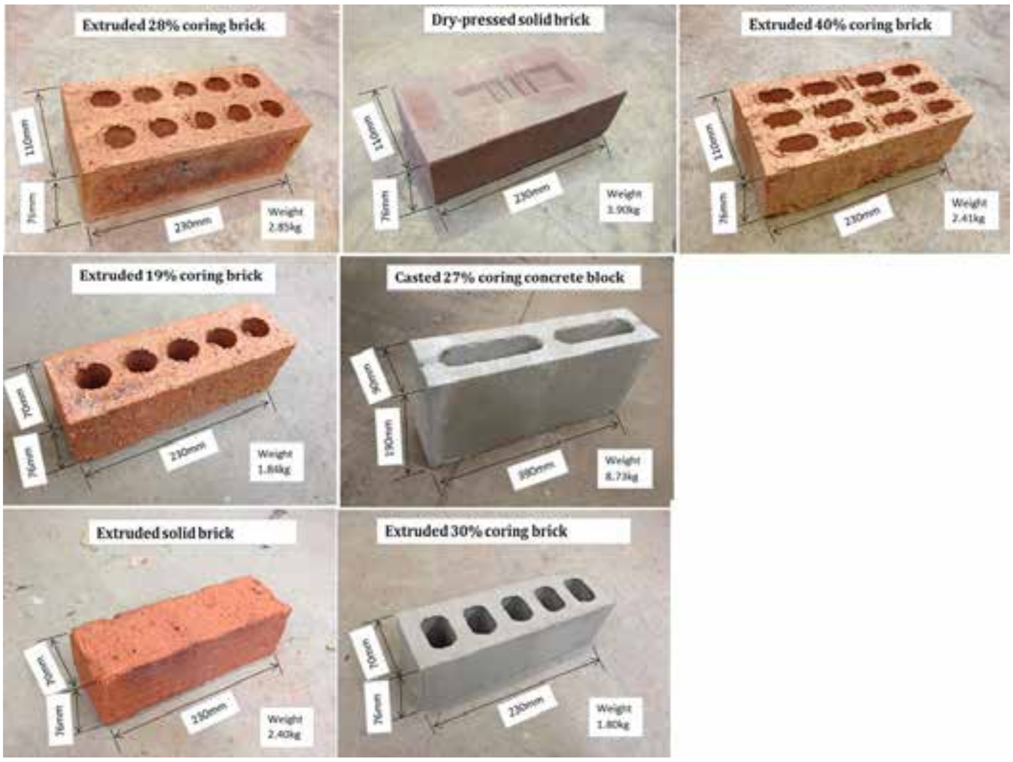


Figure 3.7. Masonry Units Used in Dynamic Tests

3.3.3 Influence of insulation

In addition to carrying out dynamic tests on the bare walls, the influence of insulation was also studied by additional static and dynamic tests on each wall with the insulation located on the “outside” or “inside” of the panel, corresponding to the external or inside face of the wall. The Styrofoam panel mentioned above (with an R-value of 0.69) was used for that purpose. In these cases, although the R-value for the combined wall/insulation is the same regardless of the location of the insulation, its dynamic performance will be significantly different for the “outside” and “inside” case (due to the location of the insulation in relation to the “external” temperature profile and the wall thermal mass). As a result, for each summer and winter weather cycle, threedynamic and three static tests were performed for each wall panel, with both the surface to surface and air to air profiles being monitored. The results of these tests are given in Chapter 5.

Figure 3.8 Construction of Wall Panels

3.4 Summary

This chapter has presented a description of the development of the wall testing rigs and test specimens. The modified Hot Box apparatus described here is capable of determining the thermal properties of materials under both static and dynamic conditions, so that the results under both conditions become more reliable and comparable. This assists in finding the potential links between static and dynamic thermal properties.

The following chapters describe the development of an appropriate dynamic testing regime together with the results of the static and dynamic tests performed on individual walls and walling systems. The significance and influence of wall insulation properties and location under dynamic conditions are studied in Chapter 4, and the results of a series of dynamic tests on a range of walling systems, together with the development of the Dynamic Response Concept are contained in Chapter 5.

4. Dynamic Testing Procedure

4.1 Introduction

The Guarded Hot Box apparatus has been used to measure the thermal properties of building assemblies under steady-state conditions for decades. However this approach only allows the determination of the steady state thermal resistance (R-value) and the thermal conductivity. It does not measure the thermal performance of walling systems under dynamic (changing) conditions which occur throughout a day, month or seasons. The new test facilities and the novel dynamic approach described here allows the assessment of the ability of a wall system to respond to these diurnal temperature fluctuations and to provide more realistic data on the performance of walls and wall components. As part of the study, the optimum combination and location of thermal resistance and thermal mass in walling systems is also identified and assessed through comparative studies of the relative performance of a solid brickwork panel combined with varying combinations of internal and then external insulation.

Dynamic cyclic tests on walling systems have the potential to provide a more realistic picture of how various materials perform when exposed to typical temperature fluctuations. By monitoring the temperature and energy flow at various points through the wall, information on heat flow and temperature variations can be obtained. Cyclic tests will also demonstrate the ability and mechanism of the material to attenuate the heat flow whilst storing and emitting heat after the exterior temperature begins to change. Since the changing nature of the dynamic cycles does not allow a constant heat flow mechanism to develop in the structure, in contrast to the determination of the thermal resistance (R-value), it is much more difficult define the performance with a single parameter.

This chapter describes a series of dynamic cyclic tests on a brickwork wall with and without insulation using the above approach, with different combinations of thermal mass and resistance being subjected to a varying temperature cycle. The results of tests on three different wall types are presented - a plane brickwork wall, and then the same wall with polystyrene insulation installed on either the "external" or "inside" face of the wall. Each wall combination was tested under several different temperature cycles. The detailed results for one particular cycle are presented here, to illustrate the response of each wall type to the temperature variations under the dynamic temperature cycle

4.2 Temperature cycles for the dynamic hot box tests

Australia has eight climate zones which define the range of conditions present in various parts of Australia. Through cyclic, rather than steady state hot box testing, it is possible to a large extent to replicate the different seasonal cycles applicable to a particular area and observe the performance of building materials when exposed to those cycles. The modified hot box system can be operated under predefined input summer and winter cycles from the external "hot" side simplified to a sinusoidal input which is as close as possible to the actual conditions.

The test cycles in the external chamber were replicated as equivalent sinusoidal functions simulating the outdoor temperature profiles. Figure 4.1 shows a typical two day diurnal temperature profile together with the assumed sinusoidal function which fits the original profiles with reasonable accuracy.

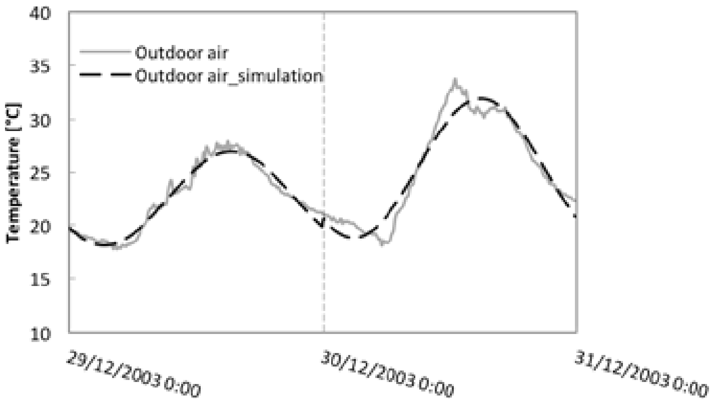


Figure 4.1: Two-day outdoor temperature profile and the sinusoidal model

The system is also capable of simulating any of the eight Australian climate zones, but in particular, summer and winter cycles for Melbourne and Brisbane were tested. For purposes of illustration, the summer cycle results are reported here. The temperature ranges of these cycles were determined from the temperature records, mainly reflecting the maximum and minimum diurnal temperatures, for the available years from the Australian Bureau of Meteorology

Daily 24 hour temperature cycles corresponding to Brisbane and Melbourne summer and winter conditions were chosen, as these represented typical Australian hot and cold weather conditions. In addition a combined temperature curve enclosing the temperature extremes was also derived and used in the tests. The temperature cycles for Brisbane and Melbourne and the combined cycle are shown in Figure 4.2. Initially it was proposed to test for a greater number of climate zones, but as the program progressed, it became apparent that the wall characteristics were reasonably independent of the climate zone (see Chapter 5).

4.3 Testing procedure for a selected wall panel

4.3.1 Overview

This section focuses on the thermal performance of the solid brick masonry wall under different dynamic cycles. As described in Chapter 3, this 110 mm thick wall was constructed from solid fired clay pressed bricks using a typical 1:1:6 mortar (cement: lime: sand by volume). The influence of an insulation material (a 25 mm thick polystyrene panel) on the dynamic-state thermal performance of test walls was also studied. This panel had the same width and height as the wall.

4.3.2 Walling configuration

The three walling configurations were “non-insulated”, “internally-insulated” and “externally-insulated” to simulate the internal (or indoor) and external (outdoor) conditions. To monitor the response from the conditions induced in the external chamber, temperature sensors were located in four planes corresponding to the internal air, the wall internal surface, the external surface and the external air respectively, as shown in Figure 4.3. More detailed dynamic test results are contained in Appendix A.

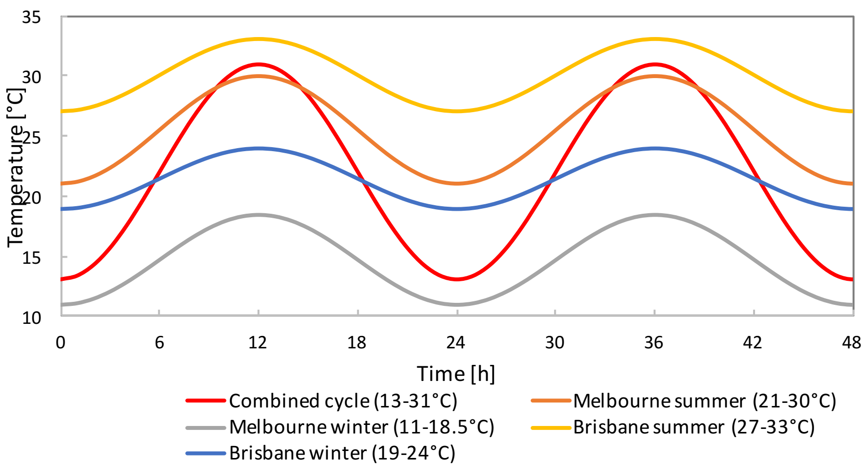


Figure 4.2. Temperature Cycles Used for the Dynamic Wall Tests

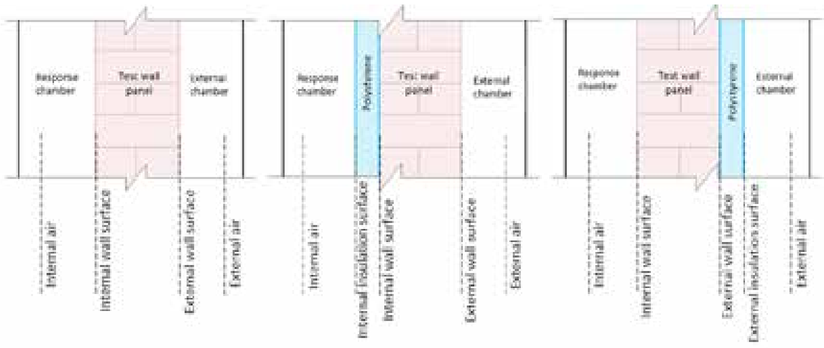


Figure 4.3: Temperature sensor locations for the test walls

The properties of the brick masonry wall and the insulation panel are given in Table 4.1. It can be seen that the masonry wall has a low thermal resistance and a high thermal mass. In contrast, the polystyrene insulation panel has very little thermal mass but a much higher thermal resistance.

Wall type	Thickness [m]	Density [kg/m³]	Mass [kg]	Specific heat [kJ/kg·K]	Thermal mass [kJ/K]	Thermal Resistance [m²·K/W]
Solid Brick Masonry wall	0.11	2030	1290	1.00	1300	0.10
Polystyrene Insulation board	0.025	24	4	1.25	4.5	0.69

Table 4.1: Wall properties

The normal steady-state testing approach illustrates the ability of a wall to resist heat flow and provides information on the temperature on each surface of the wall and the temperature gradient. The overall thermal resistance of the wall is the same when either the internal or external insulation layer is included, regardless of its location. The thermal resistance (R-values) for the polystyrene board, tested under the three different conditions shown in Figure 4.4, were 0.678, 0.690 and 0.688 respectively, which are all very similar. Since the R-values for the internally and externally insulated solid brick masonry wall are the same. the thermal performance of the polystyrene insulation can only be of influence through its location in the wall when changing (dynamic) conditions are considered.

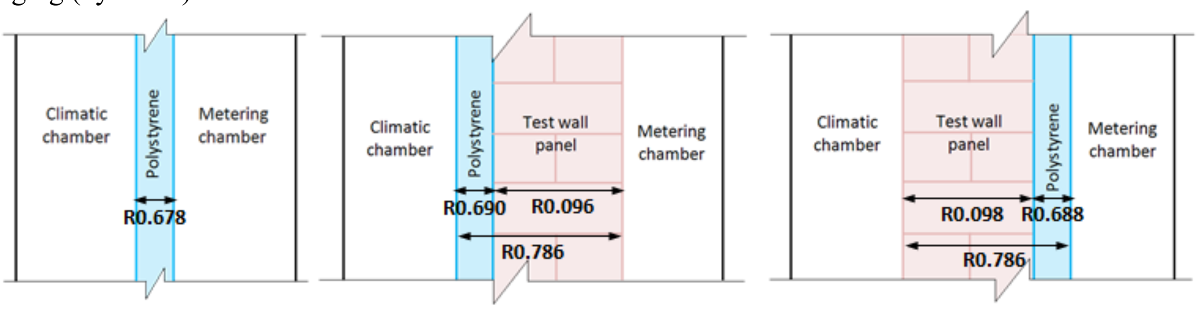


Figure 4.4: Thermal resistance characteristic under steady-state conditions

4.3.3 Performance under dynamic tests

Applying the dynamic external conditions for the brick masonry wall with/without an insulation layer, provides information on how heavy walling systems respond to cyclic dynamic weather conditions through absorbing, storing and releasing heat. The thermal behaviour of a wall with an internal insulation layer will be similar that of an insulated brick veneer walling system, whereas the externally insulated wall will have a similar response to a reverse brick veneer walling system, where the brickwork leaf is on the inner side of the insulation layer.

The cyclic testing provides useful information on the heat flow attenuation and thermal lag of each individual wall element on a comparative basis for any wall type and demonstrates how the systems perform under the influence of a dynamic input. The current investigation using a "standard" cyclic dynamic input provides a

more realistic indication of how a wall system behaves under dynamic conditions and allows the evaluation of the heat transfer characteristics for any walling system. Through analysis of the results the information on the thermal lag, the influence of thermal mass and the position of the insulation can be obtained.

In the present study, relevant graphical representations of the temperature and heat flux fluctuations were analysed to compare the behaviour of various walling systems. Such dynamic tests provide the temperature and heat flux profiles for both surfaces of the test walls as well as the temperature of the internal air. All temperature profiles fluctuated along a "centre line", the air temperatures of the enclosed room, indicating similar averages for all profiles. However, the temperature variations were significantly different for every walling system under this dynamic cycle.

4.3.3.1 Non-insulated wall solid brick masonry wall

The response of the non-insulated solid brick wall under the dynamic cycle for one selected cycle (Melbourne summer) is presented in Figure 4.5. The external surface of the wall reached a maximum temperature of 27ºC occurring 2.5 hours after the peak exterior temperature of the cycle. The peak temperature of the interior surface was 26.5ºC and this did not occur until 5.5 hours after the peak of the exterior temperature. The peak of the interior surface temperature occurred at the same time that the exterior air temperature dropped below the brick interior surface temperature. The interior air temperature also peaked at this time usually around 26.4ºC. Heat energy was flowing back towards the exterior but at the same time a small amount is still flowing towards the interior. Because the heat flux did not completely reverse, the heat energy that was being expelled on the exterior was only from the energy that has been stored in the wall. The internal air fluctuation range was 3ºC from minimum to maximum for this cycle. The temperature fluctuation and thermal lag is shown in Figure 4.6.

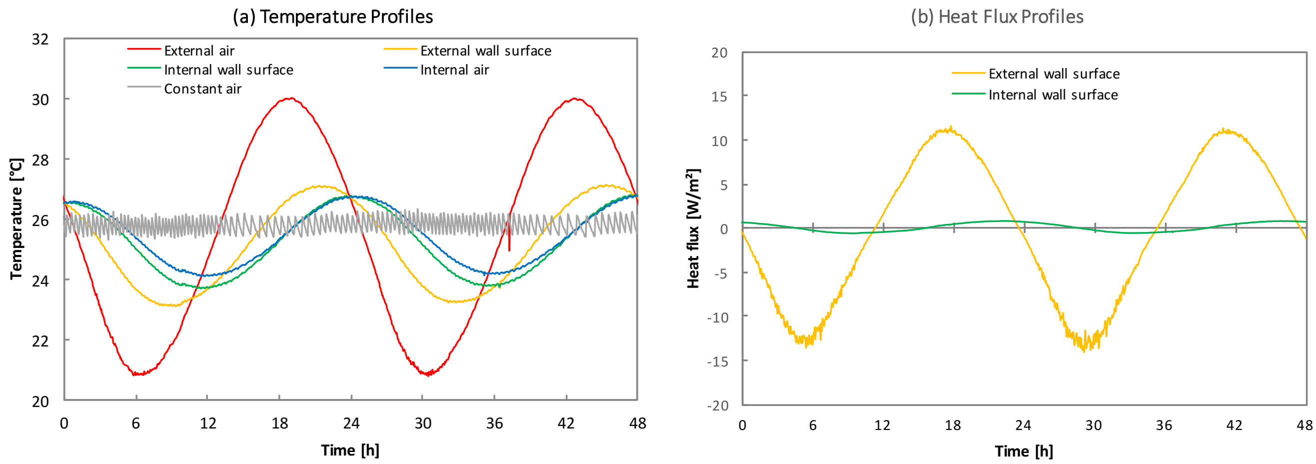


Figure 4.5: Solid brick wall under dynamic cycle; (a) temperature profiles, (b) heat flux profiles

The heat energy that has been stored in the mass is released in both directions. During the simulated cycle the thermal mass provided some resistance to the exterior heat energy by absorbing energy and releasing it back to the external environment during the drop of the external temperature. However energy that was stored in the mass was also continuously released into the interior air. This is shown in Figure 4.7.

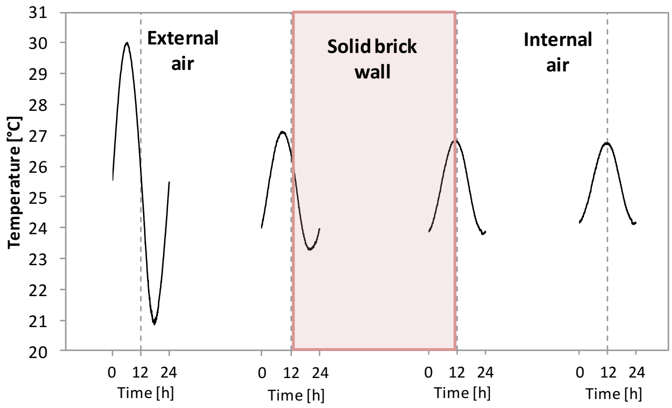


Figure 4.6:Temperature fluctuations for the solid brick wall, diurnal cycle

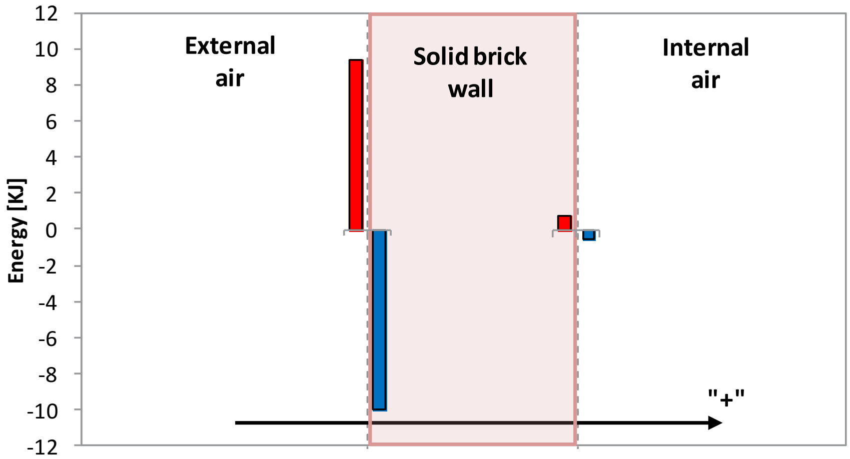


Figure 4.7: Heat exchange for the solid brick wall, diurnal cycle

4.3.3.2 Wall with internal insulation

With the layer of insulation on the side corresponding to the interior face of the wall, the exterior brick surface reacts in a similar manner to the non-insulated wall as there is the same exposure to this cycle (see Figure 4.8). The external surface temperature peaked at 27ºC, 2.4 hours after the peak of the summer cycle. The peak temperature of the interior surface of the brick wall was 26ºC occurring 6.5 hours after the peak of the exterior temperature cycle.

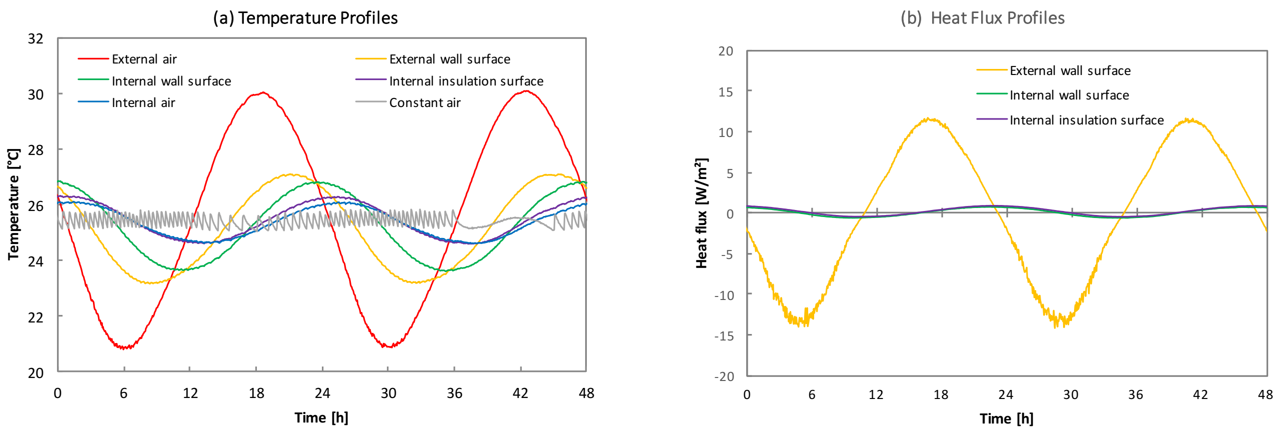


Figure 4.8 Internally Insulated solid brick wall under dynamic cycle; (a) temperature profiles, (b) heat flux profiles

The internal insulation decreased the internal air fluctuation, which ranged by 1.5ºC from minimum to maximum for this cycle (see Figure 4.8). This was significantly less than for the non-insulated wall.

The heat absorbed from the high exterior temperature continues to radiate towards the interior of the

structure even after the exterior temperature drops below the interior temperature. The temperature fluctuations and heat exchange mechanisms under the diurnal cycle are shown in Figures 4.9 and 4.10. This is also a typical representation of an insulated wall construction such as brick veneer, where the structural timber or steel frame is located on the interior side of the insulation layer.

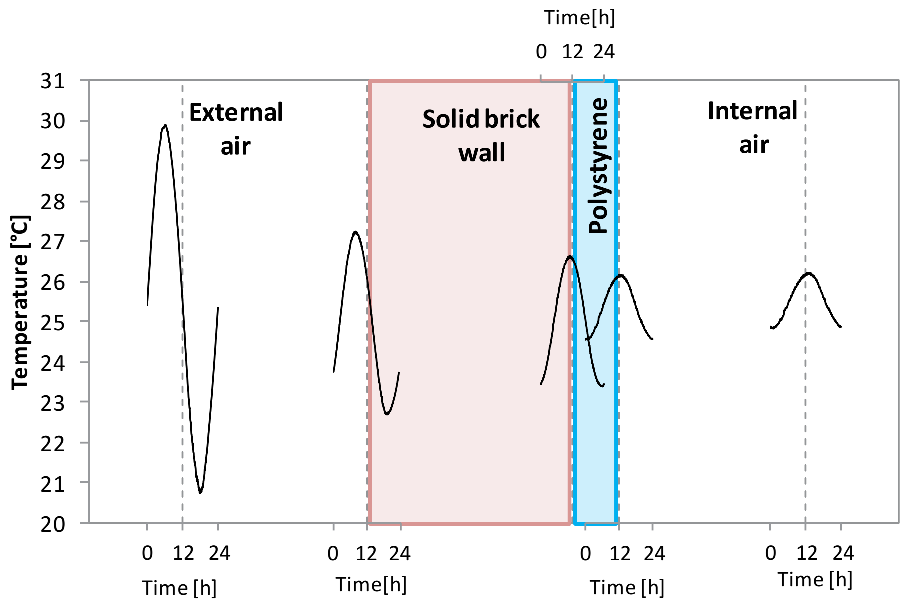


Figure 4.9: Temperature fluctuations for the internally insulated solid brick wall, diurnal cycle

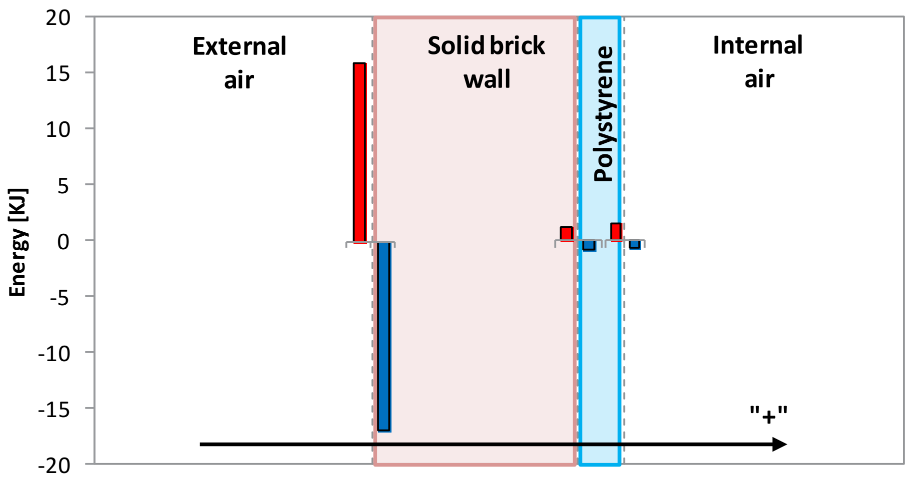
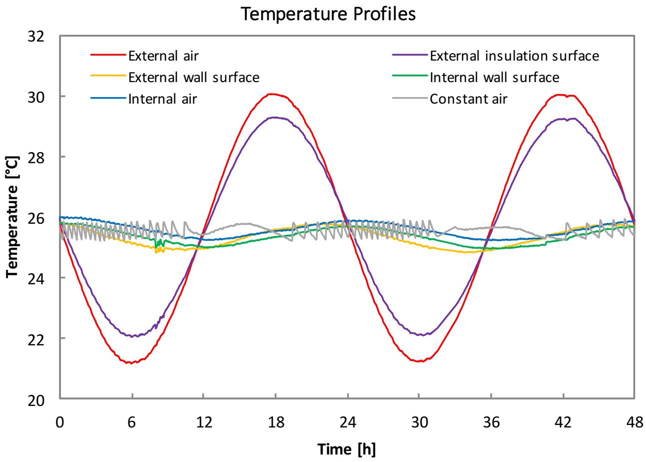


Figure 4.10: Heat exchange for the internally insulated solid brick wall, diurnal cycle

4.3.3.3 Wall with external insulation

With the insulation layer on the "external" face of the wall (Figure 4.4 (c)), under the imposed temperature cycle the exterior surface temperature of the insulation reached a maximum temperature of 29.2ºC (see Figure 4.11). Considering the exterior air temperature reached a maximum of 30ºC the surface of the insulation is extremely warm. The exterior surface of the insulation peaked 0.25 hours after the peak of the external temperature cycle. The peak temperature on the external brick surface was 26ºC which occurred 3.5 hours after the peak of the external cycle. The insulation panel reduced the temperature and energy passing towards the interior, see Figure 4.12 and Figure 4.13. Since the solid brick wall was receiving a reduced energy exposure from the external cycle, only a minimal internal temperature oscillation of 0.7ºC was observed.



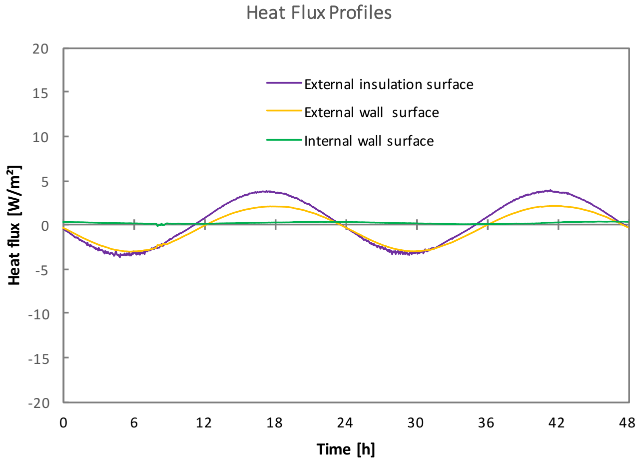


Figure 4.11: Externally Insulated solid brick wall under dynamic cycle; (a) temperature profiles, (b) heat flux profiles

The exterior insulation arrangement was the most efficient in reducing the interior temperature fluctuations and energy transfer. This is a result of the high resistivity of the insulation on the exterior face. The insulating panel prevents the majority of energy from reaching the thermal mass and penetrating through to the interior. To increase the temperature of the thermal mass a large amount of energy is required, and the insulation is essentially blocking this from occurring. The exterior surface of the insulation panel had a large temperature fluctuation in all cases mirroring the temperature cycle, with less than a 1ºC difference between the external temperature cycles.

A light weight material has less thermal mass and therefore requires less energy to raise its core temperature. As a result, the interior surface temperature for a light weight construction material will be greater than that of a high thermal mass material when exposed to the same external temperature cycle. The response of the low thermal mass construction is more immediate and it therefore adjusts faster to the exterior heat cycle than its heavy weight counterpart.

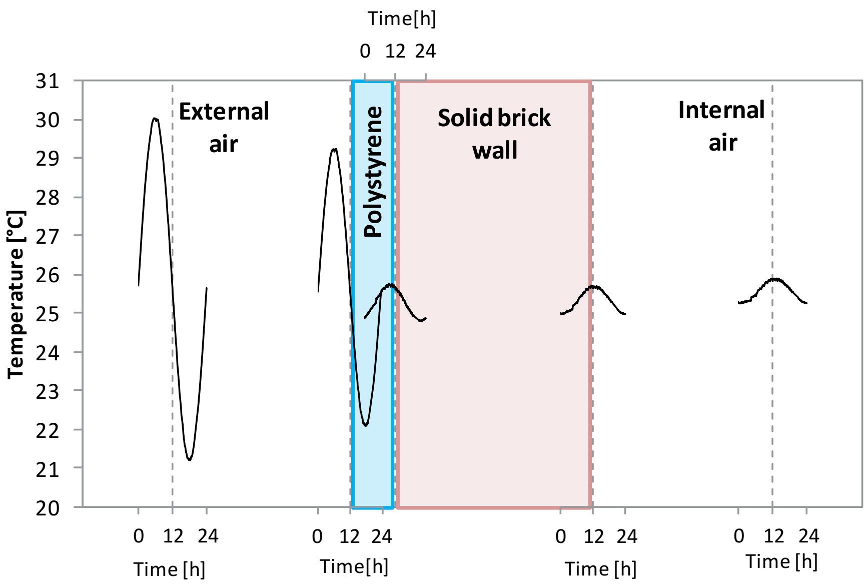


Figure 4.12: Temperature fluctuations for the externally insulated solid brick wall, diurnal cycle

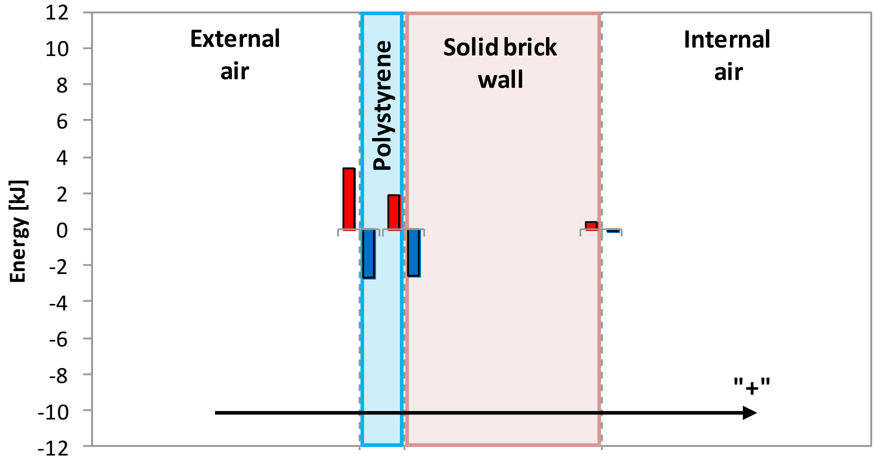


Figure 4.13: Heat exchange for the externally insulated solid brick wall, diurnal cycle

4.3.4 Conclusions from dynamic temperature profile study

Overall, an 80% reduction in amplitude between the non-insulated brick wall and the externally insulated wall was observed, with a 50% reduction between the internally and externally insulated walls. The ability of the brickwork wall to reduce the amplitude of the test cycle mainly depended on the thermal properties of the wall and wall configuration. During the dynamic test, much more heat energy was absorbed and released by the external brick wall surface than the internal. The peak heat flux through the external wall surface was about 12W/m², while that for the internal surface was less than 1W/m².

Such dynamic results show that for the heat energy which penetrated through to the "interior" air, the insulation provided a barrier that made it hard for this energy flow to reverse and flow back to the exterior. This indicates that for an insulated brick veneer house (incorporating internally insulated walls), where a significant amount of the internal energy internal temperature increase results from energy flow through the windows, further cooling energy would be required to reduce the temperature to a comfortable level. This is because the insulation provides a barrier that restricts the energy exchange from the surface of the thermal mass of the external masonry skin. The results also indicate that the insulation would be more effective in minimising internal air temperature fluctuations in a reverse brick veneer construction (external insulation), where the brickwork forms the inner leaf of the wall, with a layer of insulation in the cavity between the external veneer and the internal masonry. This insulation layer creates a barrier that will reduce the levels of energy exposure of the internal brick component.

The most effective masonry walling system will be an insulated cavity wall with the insulation located in the cavity. The external heavy skin of the wall will reduce heat loads passing through the wall. The insulation layer attached to the heavy internal skin will resist further the heat passing from the exterior towards the interior of the building. In addition, the internal heavy masonry skin will store heat coming from the solar radiation through the windows and minimise the air temperature fluctuations. However, the optimum position of the insulation layer within the cavity itself is still to be determined as part of the current research. The behaviour of a cavity brick walling system without insulation but with an air gap between two brick skins can be postulated from the mechanisms observed for the single layer brick wall. The internal brick skin will absorb energy from the solar radiation and transfer it back towards the exterior as the external conditions cool. The cavity, itself, also creates a certain level of insulation, but not of course as efficiently as an insulation layer.

4.4 Dynamic tests in the supplementary hot box

As described in Section 3.2.2, in the latter stages of the project, a smaller supplementary hot box was developed to accelerate the testing program and allow some selected systems to be tested under the same dynamic temperature regime as for the larger walls. The main purpose of this test series was to provide data on complete walling systems, as distinct from the single skin walls tested in the main rig, thus providing data to allow the later possibility of combining the results for the individual components making up a particular walling system.

In this case the smaller rig was located in the laboratory with no external temperature controlled space around it, thus making it susceptible to variations in laboratory room temperature. However, for the period in which the tests summarised in Table 4.2 were performed, the laboratory temperature was similar to the average dynamic temperature within the hot box, and it was therefore assumed that external effects would be minimal. This was confirmed by several control tests on a wall tested in both the testing rigs. The masonry specimens for these tests were obtained by extracting the appropriate sized panels from the larger masonry walls previously tested in the dynamic hot box. The detailed results of these tests are given in Section 8.6.

Wall type	Insulation	Thickness [mm]	Weight [kg/m²]
Brick wall (28% coring)	No insulation	110	163
	Internal polystyrene insualtion	135	164
	External polystyrene insulation	135	164
Timber framed wall	No insulation	110	23
	Glasswool insulation	110	25
25mm Polystyrene panel	-	25	0.6
InsBV	Glasswool insulation	260	188
CB	No insulation	270	326
InsRBV	Glasswool insulation	260	188
InsCB	Polystyrene insualtion	295	327

Table 4.2. Tests in Supplementary Hot Box

4.5 Summary and conclusions

The focus of the wall tests previously described in the Phase 1 Report was on wall performance under a static temperature environment as required to determine the thermal resistance (R-value) of the wall. For the subsequent Phase 2 tests reported here, a purpose built hot box was developed which operated in a dedicated, temperature controlled space, thus eliminating the influence of any variations in laboratory ambient temperature. This new hot box was used to carry out a wide range of static and dynamic temperature thermal tests on individual walls, to study in detail the influence of both thermal mass and thermal resistance on the wall thermal performance. A range of walls and walling systems was subjected to daily dynamic temperature cycles which simulated summer and winter conditions in Brisbane and Melbourne. A combined temperature cycle capturing both hot and cold extremes was also developed. The role of insulation in walls subjected to a dynamic temperature cycle, together with the significance of the location of the insulation within the wall cross section was also studied.

Towards the latter stages of the project, an additional smaller hot box apparatus was also developed to allow a series of common walling systems to be tested under dynamic temperature conditions. This facilitated the study of the combined contribution of the individual wall properties previously determined in the larger dynamic hot box. Several of the larger hot box tests were repeated to confirm the compatibility of the results from the two facilities.

This chapter has focused on a study of the ability of walls to ameliorate internal room temperatures by reducing the amplitudes of the external temperature profiles. Comparative studies based on the test results for a solid brick wall with and without the attachment of polystyrene insulation board on either the external or internal face under a selected dynamic cycle. The study has revealed the following:

i. The study confirmed the premise that the wall R-value alone (a steady-state parameter) cannot represent the actual dynamic performance of a building. The current emphasis on the thermal performance of buildings is on their performance under static thermal conditions, with the thermal resistance (R-value) of the various building components being the principal parameter considered. This does not represent the real situation which involves dynamic external and internal temperature environments. Work is proceeding on the detailed development of a method which takes into account wall performance under a dynamic temperature cycle with an appropriate measure and an accompanying standard test for its evaluation for various walling systems. This chapter has described the first series of tests in this process which has focussed on a high thermal mass walling systems with and without insulation.

ii. The tests have shown that through effective design and correct implementation of thermal mass it is possible to minimise internal air temperature variations, i.e. reducing the need for heating and cooling, during sections of a diurnal temperature cycle. The thermal mass acts

as a temperature regulator producing interior fluctuations less than the exterior environment. Thermal mass can therefore be utilised in conjunction with a sound passive design principles to obtain the best results. The addition of insulation produced more desirable interior temperatures than the non-insulated wall whilst effectively moderating interior temperature changes. Both internal and external insulation setups, replicating insulated brick veneer and insulated reverse brick veneer walling systems respectively, had the same steady-state R-value but the tests clearly illustrated how their performance varied considerably. The best thermal performance was achieved for the panel with an external insulation layer. This is consistent with the relative performance of full scale insulated brick veneer and reverse brick veneer modules which forms part of our study (as reported in Chapter 2).

5. Dynamic Temperature Response Concept For Walls (T-Values)

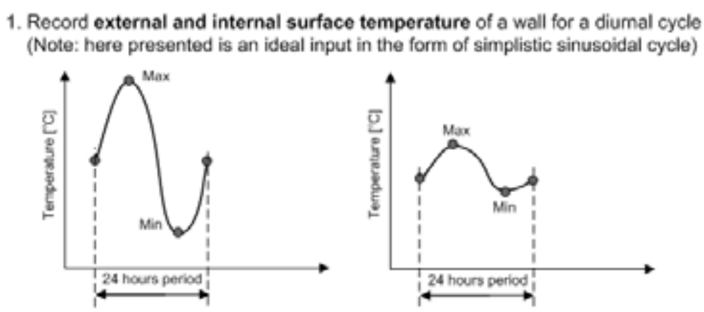
5.1 Overview

It is clear that a more representative parameter than R-value is required to fully capture the dynamic thermal behaviour of a walling system. A relatively simple metric which encapsulates the contribution of all physical parameters influencing the thermal performance is required. An analysis by energy balance equations yields more accurate predictions, but this is complicated by the fact that the heat transfer does not occur uniformly over the whole area of the wall. The key feature of the method proposed here is that it deals with the temperature profiles of a wall from the measured external surface temperatures (influenced by external weather variables such as ambient temperature, solar radiation, wind speed) and the response of the internal side of the wall (with the internal surface temperature reflecting the influence and response of the wall profile). The extensive testing program in this investigation, involving both individual wall elements and housing modules has provided the necessary data for the development and verification of such a concept.

The basic idea for the concept was derived from an "automatic reasoning" paradigm, which says that the greatest component of the response variation (output) can be sufficiently described by a factor that combines just a few of the key input parameters. Here the concept is manifest within a metric that recognises the thermal performance of a walling system from the relationship between the external (inputs) and internal (outputs) surface temperatures of a wall (a barrier). Thus, the method does not come from the main physical principles and is a similar analogy to that used traditionally for several mechanical properties of materials (e.g. Young's Modulus or crack opening displacement) which are also evaluated from profiles in the relevant figure (i.e. load-displacement or stress-strain curves). A brief overview of the concept can be found in references (8,9). The metric takes into account all parameters involved in the heat transfer of a wall or building such as thermal mass, thermal resistance as well as diurnal temperature swings, ambient temperature, solar radiation and wind effects. The concept uses a parameter (temperature) which is easy to measure and encapsulates how well the internal side of a wall responds to a diurnal temperature cycle with the external surface exposed to normal environmental conditions. The temperature on the internal surface of the wall (i.e. on the out-put side) represents how the temperature has been changed due to energy transfer. This approach therefore includes the interactions of all of the wall components under all weather parameters, giving an accurate view of wall thermal performance and a picture of the whole mechanism involved. Ultimately a metric of this type has the potential to be used to characterise the interior thermal behaviour of a building that results from the entire wall system moderating external environmental changes.

5.2 Fundamentals of the concept

The key feature of the proposed concept is that it deals with the dynamic temperature profiles of a wall across the external and internal surface temperatures as shown in Figure 5.1.



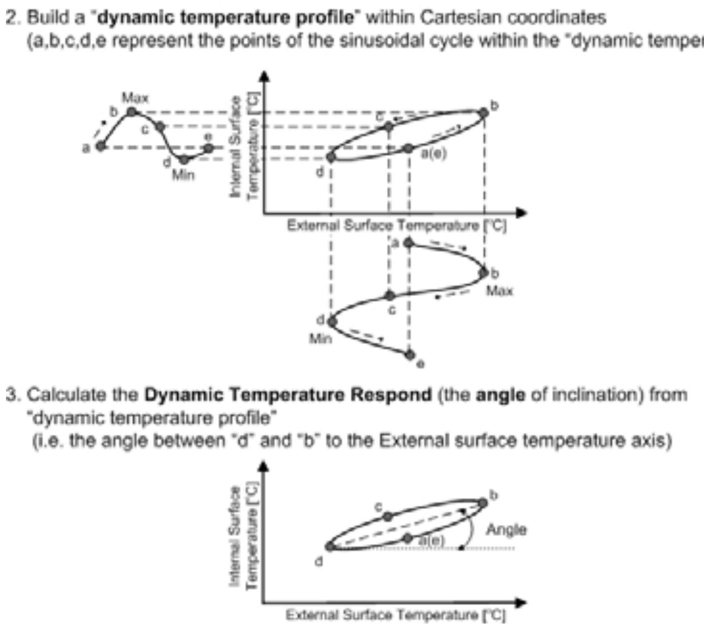


Figure. 5.1. Development of the dynamic temperature profile and calculation of the angle representing the Dynamic Temperature Response.

For idealised "pure" wall material cases where only the thermal resistance of the material is considered, a linear plot of the cyclic diurnal variation in wall temperature of an exposed side against that of the unexposed side (i.e. the internal side of a wall), is represented schematically by a straight line as shown in Figure. 5.2.

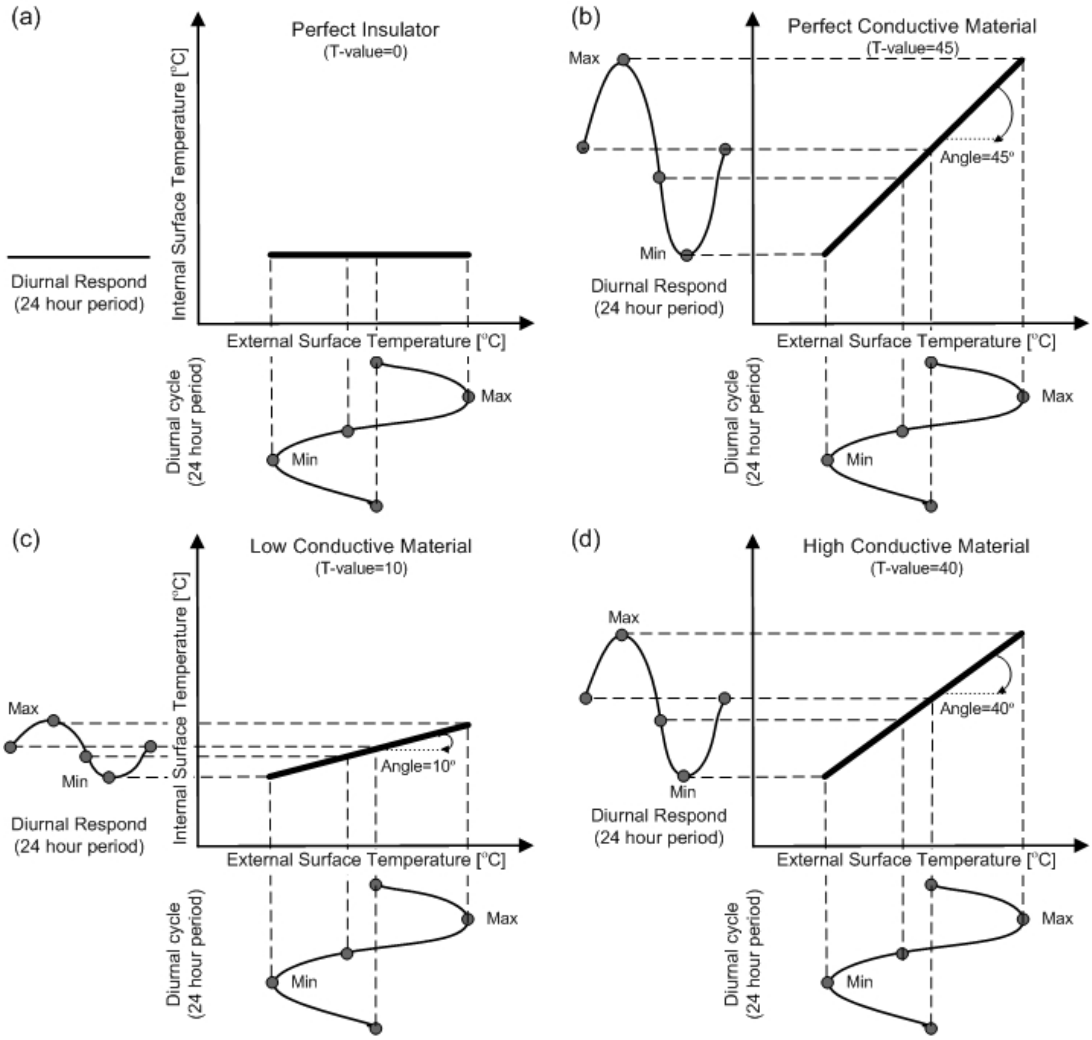


Figure. 5.2. Schematic dynamic temperature response concept of a wall for one diurnal cycle for: (a) perfect insulator, (b) perfect conductive material, (c) low conductive material and (d) highly conductive material.

Thus for given external conditions, the expected response on the internal side of the walling system will be represented by a different slope of the line, depending on the dynamic thermal resistance of the wall (note that this is different parameter to R-value). The angle of inclination of the line, defined for these idealised cases, is referred to here as the “Dynamic Temperature Response” (DTR in degrees or T-value as a non-dimensional parameter). Two extreme examples of these idealised cases are:

i. a wall behaves as a perfect insulator and consequently the internal temperature is not influenced by variations of the external environment (see Figure. 5.2 (a)). The thermal response is hypothetically represented as a horizontal line at a constant interior temperature level (i.e. a Dynamic Temperature Response of zero degrees or a T-value of zero),

ii. a wall behaves as a highly conductive material (i.e. a very poor insulator) in Figure 5.2 (d). The thermal response of the internal surface is hypothetically represented as a straight line inclined at 45 degrees indicating that the internal surface responds directly to changes in temperature on the external side (corresponding to “zero insulation ability” – i.e. a Dynamic Temperature Response of 45 degrees or a T-value of 45).

The effective thermal resistance of an idealised wall with intermediate values of thermal resistance is hypothetically located somewhere between these two extremes ($0 \leq$ T-value ≤ 45), presented in Figure 5.2. Each line is defined by the Dynamic Temperature Response parameter, (or T-value), corresponding to the angle of inclination to the horizontal axis.

Thus, if the angle of inclination (T-value) is small (say close to zero), energy transference to an internal surface would be limited through a wall regardless of the external dynamic conditions (thus it performs as an effective insulator – note that this is a different property to the intrinsic R-value). In contrast, a wall performs poorly if the angle of inclination is high (ie approaching 45 degrees) and the energy provided to the external surface is almost completely transferred to the internal surface (this means, both temperatures on external and internal surface will be equal), see Figure 5.2 (b).

For real walls, which are normally constructed with ordered layers of materials having differing insulation and thermal mass properties, the plot of internal versus external surface temperatures traces an irregular hysteresis loop for a typical diurnal cycle that can be approximated by an elliptical shape rather than a line (see Figure 5.3). In practice, the regularity of the hysteresis shape and the accuracy of approximation by an ellipse will depend on the exact form of the diurnal input cycle. However, even if the temperature hysteresis is irregular, an elliptical representation determined from a Principal Component Analysis (PCA) of the external and internal temperature variations will still be a reasonable summary of how the internal and external temperature measurements behave principally with respect to each other. The size and orientation of the principal axis of the ellipse to the horizontal will depend on the combination of material properties of the wall layers and the order of these layers within the wall. This will be particularly influenced by the presence of thermal mass on the internal side of the wall relative to the external and internal environments (this will be further discussed in the “Treatment of irregular profiles” section).

The wall material layer combinations determine the response of the interior environment to the external environmental perturbations. The trace plot of internal and external surface temperatures provides a picture of the thermal processes occurring through a cross-section of a wall. Thus, it determines the orientation of the major axis of the ellipse to the horizontal axis as well as the lengths of the major and minor axes of each curve. Note that the angle of the major axis is only discussed in this chapter; however, it is likely that various thermal properties of the walls and their physical meaning can potentially be determined from the ellipse geometry. Note that in practice, in some cases it is possible that the angle of inclination of the principal axis can be less than zero (i.e. the internal side of a heavy wall may be much warmer than the external side e.g. during a cloudy or rainy day, following a hot day), or greater than 45 degrees (i.e. if the internal side of a wall is exposed to direct solar radiation through a window, resulting in sometimes higher temperature).

5.3 Interpretation of elliptical shapes

The above concept of the Dynamic Temperature Response has been validated through preliminary investigations of temperature profiles for walls from the real test modules on our existing data base. A consistent pattern for the dynamic response of walls for different construction types was observed. As

described above, for the "real" walls in the modules, due to the delay in heat transfer between internal and external surfaces, the response to a diurnal cycle of temperature traces approximately elliptical-shaped curves as shown in Figure. 5.3.

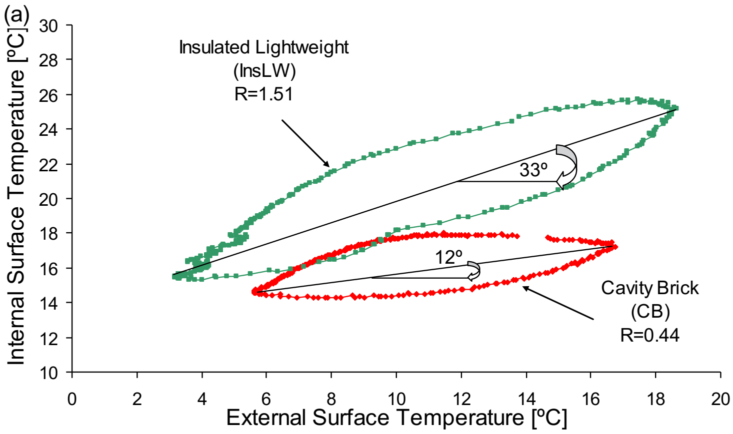


Figure. 5.3. Example of hysteresis loops for a diurnal temperature cycle for two module southern walls with widely different combinations of thermal mass and insulation properties.

The elliptical shapes vary depending on the thermal properties of the wall, and the insulation and thermal mass properties of its components. However, the angle between the principal axis of the ellipse and the horizontal axis is the most important parameter for the current discussion. While this angle can be approximated analytically using the lower and upper extreme positions of the points on the curve for each direction, the angle of the principal axis of a fitted ellipse also correctly encapsulates the overall pattern of relative temperature variations.

For the examples presented in Figure 5.3, a cavity brick wall construction exhibits a low angle of inclination of the major axis to the horizontal (i.e. T-value=12) and exhibits a relatively small variation in temperature in the direction of the minor axis (internal surface temperature). That is, for a relatively broad change in external temperature, there is minimal change in the internal temperature axis direction. In contrast, the insulated lightweight wall construction exhibited a large angle of inclination to the horizontal (i.e. T-value=33). This indicates that large temperature changes on the internal surface almost linearly follow the external temperature variations. Note from Figure 5.3 that both walling system were exposed to the same weather cycles (air temperature). The insulated lightweight external wall almost followed the air temperature cycle; however the cavity brick wall departed from the air temperature cycle due to the effects of its thermal mass. This confirms that the difference in T-value is consistent with the behaviour of the walls under real weather conditions, where the module with CB walls having lower thermal resistance but higher thermal mass performed better than its lightweight counterpart, despite the steady-state parameter (R-value) of the CB wall being almost 3.4 times lower than for the InsLW wall (R=0.44 for the CB wall; 1.51 for the InsLW wall).

It is also significant to note that because of the different material in the external layer of the InsLW and CB walling systems, the external surface temperature variations were different under the same dynamic weather conditions. This can be observed from the dynamic temperature profiles for the temperature ranges on the "External Surface Temperature" axis in Figure 5.3. The external surface temperatures ranged between 5.5ºC to 16.5ºC for the CB wall compared to 3ºC to 18.5ºC for the InsLW wall. The same effect can be also observed for the walling systems presented on the dynamic temperature profiles in the later figures.

5.4 Dynamic thermal response theory applied to the assessment of walling systems in laboratory testing

5.4.1 Introduction

In the systematic study of the dynamic temperature response of wall elements with and without insulation, a range of types have been considered, from a solid brick wall (with maximum thermal mass) to a polystyrene panel (with low thermal mass), with a range of masonry walling types in between (see Table 5.1). As summarised in Table 5.1, a series of static and dynamic tests were performed on a wide range of wall panel

types with varying combinations of thermal mass and resistance. The static tests were used to determine the steady state R-value; the dynamic tests were used to determine the dynamic T-value (based on surface to surface temperatures) and the S-value (based on the temperature of the surrounding air on the "external" and "internal" sides). In each case, after determining the static R-value in the standard manner, the test panel was subjected to simulated Brisbane and Melbourne temperature cycles and a combined cycle capturing the maximum and minimum temperature extremes (see Figure 4.2).

5.4.2 Results

Cyclic testing under laboratory conditions provided information on the heat energy transfer mechanisms through each of the walling panels. The first panel studied was the solid brickwork panel with and without insulation (as described in Chapter 4). This preliminary study, applying the dynamic external conditions for the brickwork panel with/without an insulation layer, provided information on how heavy walling systems such as masonry respond to cyclic weather conditions, absorbing and releasing heat. The typical temperature response curves obtained for the solid brick panel with and without insulation are shown in Figure 5.4 as an example. Similar curves for each of the other wall types are contained in Appendix A. In each case, the relevant graphical representations of the temperature profiles were analysed to determine the surface to surface (T-value) and the air to air (S-value). The results of the tests are summarized in Table 5.1.

		Thickness [mm]	Weight [kg/m²]	Cp [kJ/kg·K]	Thermal mass [kJ/k·m²]	T-value (surface)			S-value (air)			R-value (surface)			R-value (air)		
						No Insulation	Internal insulation	External insulation	No Insulation	Internal insulation	External insulation	No Insulation	Internal insulation	External insulation	No Insulation	Internal insulation	External insulation
Concrete panel	Solid	110	260	0.835	217	39.5	16.6	-0.3	0.7	-1.8	-0.6	0.09	0.8	0.8	0.44	1.14	1.14
Dry-pressed brick	Solid	110	223	0.835	186	36.3	15.4	-0.4	1.9	-2.1	-0.9	0.11	0.79	0.79	0.42	1.12	1.12
Extruded bricks	28% coring	110	163	0.835	136	31.4	11.8	-0.3	0.3	-2.4	-0.8	0.14	0.82	0.82	0.45	1.17	1.17
	40% coring	110	138	0.835	115	29.6	10.5	-0.5	1.6	-2.3	-0.9	0.16	0.84	0.83	0.48	1.19	1.18
	Solid	70	137	0.835	115	38.5	16.7	2	7.8	-0.9	0.2	0.1	0.8	0.82	0.41	1.15	1.16
	19% coring	70	105	0.835	88	39.8	20.9	1.4	11.9	1.7	0.1	0.1	0.79	0.8	0.4	1.13	1.13
	30% coring	70	103	0.835	86	40	17.7	0.9	7.9	-1.1	-0.8	0.09	0.81	0.83	0.42	1.18	1.17
Concrete Block	27% coring	90	118	0.837	99	30.8	11.8	0	6.2	0.9	-1	0.21	0.93	0.97	0.54	1.26	1.3
Styrofoam Panel	Solid	25	6.9	1.4	9.66	28			19.4			0.68			1.04		

Table 5.1 Summary of wall panels used in the dynamic and steady-state tests

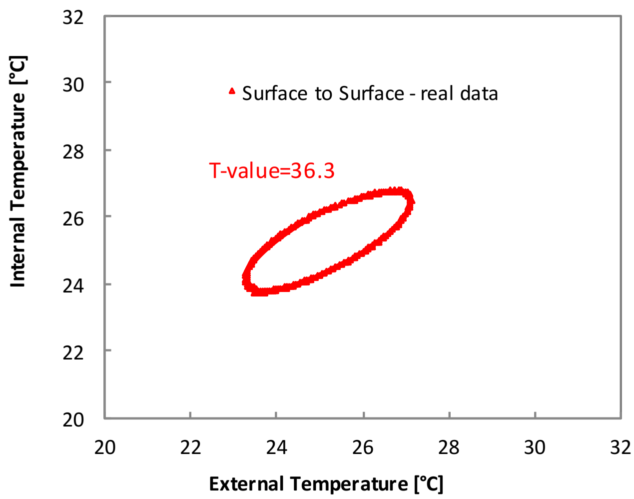
Wall type	Perforation volume	Thickness [mm]	Weight [kg/m²]	Photo of masonry unit	Insulation
Polystyrene board	Solid	25	0.6	-	-
Concrete panel	Solid	110	260	-	No
					Yes (Internally)
					Yes (Externally)
Dry-pressed brick	Solid	110	223		No
					Yes (Internally)
					Yes (Externally)
Extruded brick	28%	110	163		No
					Yes (Internally)
					Yes (Externally)
	40%	110	138		No
					Yes (Internally)
					Yes (Externally)
	Solid	70	137		No
					Yes (Internally)
					Yes (Externally)
	19%	70	105		No
					Yes (Internally)
					Yes (Externally)
	30%	70	103		No
					Yes (Internally)
					Yes (Externally)
Concrete Block	27%	90	118		No
					Yes (Internally)
					Yes (Externally)

Table 5.2. Test results for all panels in laboratory testing

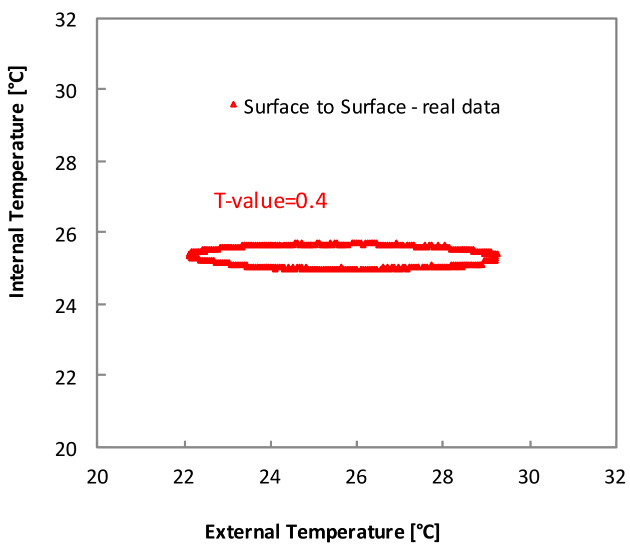
As for all the wall panel types, the thermal behaviour of the solid brick panel was studied alone or with an internal or external insulation layer. Typical summer and winter temperature cycle were applied in tests involving the plain panel, the panel with the insulation on the outer face and the panel with the insulation on the inner face (note that the R-value of the brick panel with internal and external insulation will be the same). The temperature response curves are shown in Figure 5.4.

With the layer of insulation on the interior face of the wall, the exterior brick surface reacts in a similar manner to the non-insulated panel, as there is the same exposure to the summer cycle (resulting in a T-value of 15.4). In this case, the interior insulation decreases the internal air fluctuation range and would improve the thermal performance. This behaviour would also be similar to the external heavy leaf of the InsBV wall system. This compares to a T-value of 36.3 for the non-insulated wall, indicating it still provides some resistance to the exterior environment even though it has a low R-value. In this case, the energy that was stored in the mass was also continuously released into the interior air.

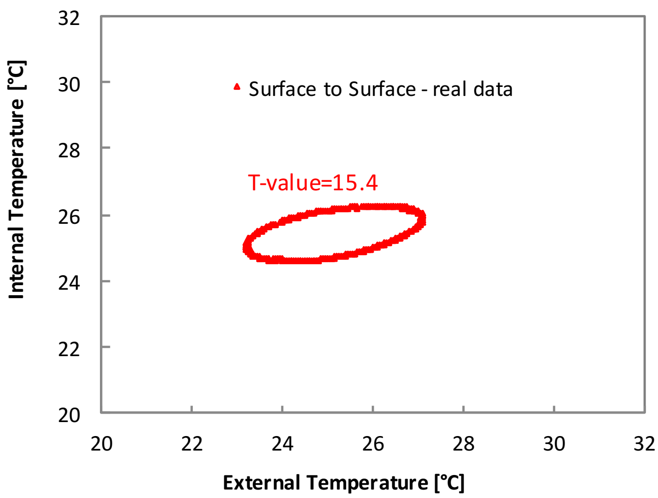
The insulation layer on the "external" face of the wall will approximate the behaviour of an InsRBV wall, (representing the heavy internal leaf located inside the wall insulation). In this case, the T-value had the lowest value of 0.4, compared to 36.3 for the non-insulated case and 15.4 for the "internally" insulated. Thus, the exterior insulation arrangement was the most efficient in reducing the interior temperature fluctuation. This is a result of the high resistivity of the insulation on the exterior face. The insulating panel prevents the majority of energy from reaching the thermal mass and penetrating through to the interior. To increase the temperature of the thermal mass a large amount of energy is required, and the insulation is essentially blocking this from occurring.



(a) No insulation



(b) External insulation



(c) Internal insulation

Figure 5.4 Dynamic Temperature Response plots for non-insulated (T-value=36.3), internally insulated (T-value=15.4), externally insulated (T-value=0.4) brickwork panels under dynamically simulated laboratory conditions.

5.5 Significance of external temperature cycles in laboratory dynamic tests

As indicated earlier, a range of input temperature cycles was developed to reflect typical cycles from different Australian climate zones. Originally, a more extensive range of temperature cycles was envisaged to represent each of the eight Australian climate zones. However, preliminary tests revealed that the T- and S- values were an inherent property of the wall and independent of the input temperature cycle. This is shown in Figure 5.5 for dynamic tests on the solid brickwork wall for Brisbane and Melbourne summer and winter cycles. It can be seen from Figure 5.5 that T-value is independent of external temperature cycle with the inclined angle of the principle axis for each of relevant ellipses being the same. Further discussion of this aspect is contained in Section 8.1.2.

5.6 Thermal performance of walls in the building test modules

The study of the thermal performance of the housing modules described in Chapter 2 has involved data collection since 2001 under a wide range of external weather conditions. The modules have incorporated various walling systems, and for part of the observation period have incorporated a north facing window. This large body of data, together with laboratory results from the guarded hot box tests for individual walls is being analysed to further develop and refine the theory outlined above.

To evaluate and verify that the proposed Dynamic Temperature Response concept can be applied to building enclosures as well as individual walls, studies were carried out for cavity brick, insulated cavity brick, insulated light weight, and insulated brick veneer walling systems from the modules with identical north facing windows. The study has been performed on a south facing wall from each module for typical winter and summer conditions to illustrate how the principles of the Dynamic Temperature Response concept can be applied. A typical set of temperature response curves for winter conditions obtained from a preliminary analysis of the existing data from four full-scale test modules but constructed from four different walling systems are summarised in Figure 5.6. For each module under given external conditions, the T-value parameters were calculated analytically, using extreme positions of the points on the hysteresis loops.

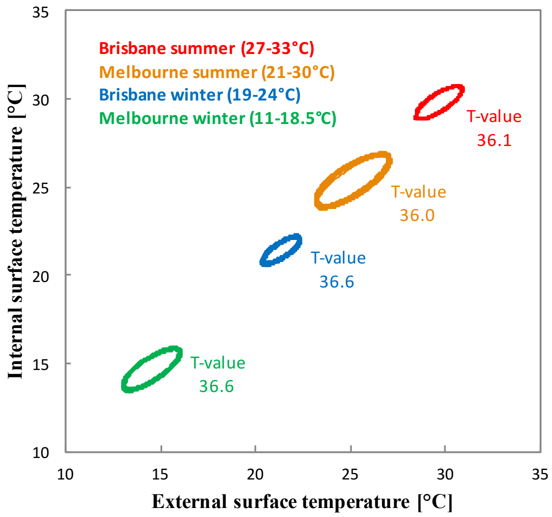


Figure 5.5 T-values for various temperature cycles for a solid brickwork wall

As has been previously demonstrated in Chapter 2, using the internal module air temperature as a measure of thermal comfort, the modules with lower thermal mass (e.g. InsLW and InsBV) generally do not perform well. This is also evidenced here by the high inclination angles (InsLW: T-value = 32 and InsBV: T-value = 35.8), corresponding to poor thermal performance. In contrast, the presence of more thermal mass in the walls (for the CB and InsCB modules), lowers the angle of inclination of the principal axis to the horizontal for better thermal performance of these two modules. Note also that the curve for the CB module is displaced downward from that of its InsCB counterpart, illustrating how the cavity insulation plays a significant role in influencing the module performance.

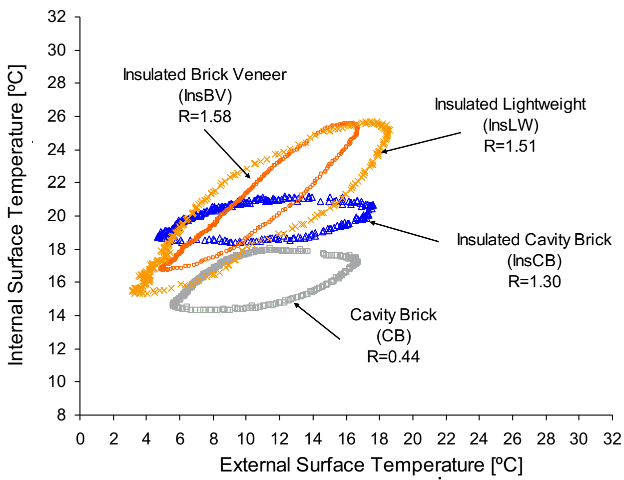


Figure 5.6 Dynamic Temperature Response profiles for southern walls of full-scale test house modules constructed from InsLW, InsBV, InsCB, and CB walling systems with T-values equal to 32, 35.8, 8.4 and 12.8 respectively for a typical diurnal cycle for winter conditions.

Data from the test modules under the same external conditions were used to calculate the T-value parameters for each walling type (see Table 5.3). As reported in Chapter 2, from the detailed observation of the performance of the modules, it was found that the modules with lower thermal mass (e.g. InsLW and InsBV) did not perform very well even though they had high thermal resistance (with R-values of 1.51 and 1.58 respectively). This poor thermal performance was captured by the DTR concept which yielded high angles of inclination of 32 for the InsLW module and 35.8 for the InsBV module, compared to much lower values for the CB and InsCB walls (12.8 and 8.4 respectively). This also illustrates that the location of thermal mass within the walls significantly lowers the angle of inclination and can improve the thermal performance, with the better thermal performance of the InsCB and CB modules being partly the result the high thermal mass of the internal skins (see Table 5.3).

For the summer period, the response of walling systems to the cyclic variation in external air temperature was very similar and indeed consistent with those for the winter period, i.e. significantly lower angles for heavy walling systems (see Figure. 5.7). However, since the modules were exposed to different (summer) weather conditions, the response of the walls was different to that for the winter. The T-value parameters for the walls with lower thermal mass were found to be 13 and 12.3 for the InsBV and InsLW modules respectively. The heavy modules (InsCB and CB) had T-value parameter of 0.6 and 1.6 respectively; again the trend for the Dynamic Temperature Response (T-value) for the heavy and lightweight modules for the summer period directly corresponds to that for the winter period.

Wall Type	T-Value (winter)	T-Value (summer)	R-Value [m^2K/W]	Comments
Cavity brick	12.8	1.6	0.44	Good thermal performance
Insulated cavity brick	8.4	0.6	1.30	Good thermal performance
Insulated Brick Veneer	35.8	13.0	1.58	Poor thermal performance
Insulated Lightweight	32	12.3	1.51	Poor thermal performance

Table 5.3 Summary of T and R- values for four module wall types

Interestingly, the presence of wall insulation in the module with a window appears to raise the position of the corresponding curve in the direction of internal temperature axis without changing the angle of inclination or the T-value parameter (compare the InsCB and CB cases in Figure 5.6 and Figure 5.7). The results certainly provide useful information on the heat flow attenuation and thermal lag of each individual wall element on a comparative basis for each wall type and demonstrate how different wall systems perform under the influence of a dynamic input.

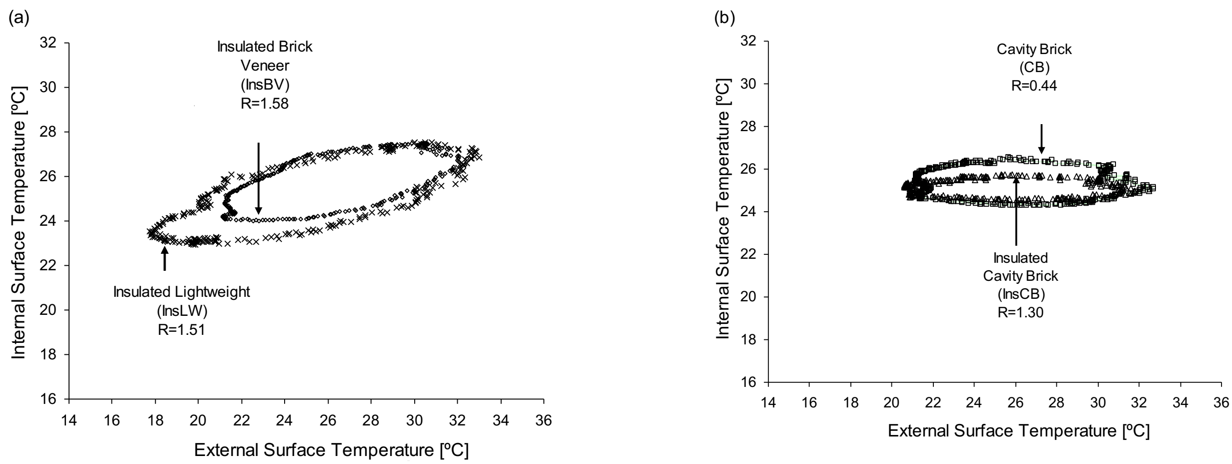


Figure 5.7. Dynamic Temperature Response profiles for the southern walls of full-scale test house modules for a typical diurnal cycle, for summer conditions (a) InsLW and InsBV modules with T-values 12.3 and 13 respectively, (b) InsCB and CB modules with T-values 0.6 and 1.6 respectively.

5.7 Conclusions

This chapter has described the development of the "Dynamic Thermal Response" or DTR concept for walling systems both in isolation in laboratory simulations and in building enclosures. The method considers

the dynamic temperature profiles from the measured external temperatures, both surface or air, (influenced by external weather variables such as ambient temperature, solar radiation, and wind speed) and the response of the internal surface and air temperatures. The following are the key conclusions:

i. When the resulting dynamic temperature profiles are plotted for a diurnal dynamic cycle, the data takes the form of an ellipsoidal shape, with the slope of the principal axis being the main variation of performance between the various walling systems. This angle is taken as the DTR (or T-) value for the wall or building enclosure and correlates directly with its thermal performance under dynamic external weather conditions.

ii. The principles of the concept have been confirmed using data obtained from observations of the thermal performance of existing lightweight and heavy walling housing test modules subjected to a wide range of seasonal conditions. When the DTR concept is applied to the observed external and internal wall surface temperatures, the T-value for the individual wall is obtained. When the concept is applied to the observedexternal temperature and the internal air temperatures of a building enclosure, the S-value of the overall enclosure results (this concept is explained in detail in Chapter 6).

iii. The current emphasis on the thermal performance of buildings is on their performance under static thermal conditions, with the thermal resistance (R-value) of the various building components being the principal parameter considered. This does not represent the real situation which involves dynamic external and internal temperature environments. A DTR measure has been proposed that will define the behaviour of walls both in isolation and incorporated in the housing test modules. The measure takes into account the dynamic nature of the environmental conditions, the wall response to the environmental changes and more importantly, facilitates the assessment of the thermal performance of the whole building envelope.

iv. The tests have shown that through effective design and correct implementation of thermal mass it is possible to minimise internal air temperature variations, thus reducing the need for heating and cooling during parts of a diurnal temperature cycle. The thermal mass acts as a temperature regulator producing interior fluctuations less than the exterior environment. Thermal mass can therefore be utilised in conjunction with sound passive design principles to obtain the best results. The addition of insulation moderated interior temperature changes and produced more desirable interior temperatures.

v. Work is proceeding on the detailed development of the measure and an accompanying standard test for its evaluation for various walling systems. Once fully developed, such a comprehensive metric has the potential to improve the accuracy and effectiveness of current energy efficiency measures and ultimately lead to more thermally efficient house designs as well as the assessment of the effectiveness of the retrofitting of existing housing stock. In the on-going study, various wall configurations and types are being considered, including the type of masonry units (i.e. solid and hollow) and the optimum location of an insulation layer for a masonry walling system. Comparison of the curves obtained for the internal and external air temperatures from the modified hot-box apparatus will allow the best wall configuration for the Australian climate to be determined, depending on the location.

vi. The dynamic testing method presented also has the potential to form the basis of a standard testing procedure to predict the dynamic thermal response of walling systems which will reflect the influence of both the thermal resistance and the thermal mass of its components.

6. Laboratory Wall Testing

6.1 Overview

The assessment of the thermal performance of a building enclosure such as a house is critical for sustainable housing design and efficient retrofitting of existing stock. Such an analysis must consider the entire building as a system, taking into account the energy absorbed and released by the various building components under a continually changing dynamic environment. The contribution of the thermal resistance and thermal mass of the building components as well as the impact of glazing need to be properly recognised using a measure which correctly encapsulates the overall behaviour of a building enclosure which is subjected to a dynamic temperature environment.

Whilst there are obvious merits in pre-evaluating the performance of a building prior to construction, except for static temperature conditions, there is a lack of experimental data on the actual thermal performance of building materials and real buildings in various climate zones, including those relevant to Australia. To provide a more accurate estimate of building performance, further refinements in the modelling assumptions and techniques are also required. The choice of materials and the results of any thermal simulation for pre-evaluating the performance have direct implications on building cost, the embodied energy of the materials used in construction and on the thermal performance of the enclosure throughout its life. Therefore any benefits gained by more accurately estimating the thermal performance is important in the assessment of the impact of any structure in a sustainable environment.

Whilst measures such as the introduction of energy star rating programs for buildings are generally seen as a positive move towards reducing space heating and cooling energy use, the representative nature of tools with which the energy ratings are currently evaluated is questionable. As a result, the performance of the real building may not give the predicted energy savings. Most simulation models are relatively artificial as only one steady-state parameter (usually the R-Value) serves as the main driver. In reality, the performance of the building is complex, influenced by a range of factors, including the dynamic nature of the external environment.

A new measure, the "System Dynamic Temperature Response", (called SDTR or S-Value), is developed here which accounts for the contribution of all of the building components and their subsequent influence on the dynamic thermal performance of a building enclosure under diurnal temperature cycles. The derivation of this measure is an extension of study reported in Chapter 5 which developed a parameter for the thermal behaviour of individual walling systems called the "Dynamic Temperature Response" or "T-Value". As described in Chapter 5, the T-Value concept was verified from comparisons of external and internal surface temperatures of typical walling systems in full scale housing test modules under a range of seasonal conditions. Analysis of the database collected on the thermal performance of the full scale housing modules in the first eight years of our study confirmed the basic assumptions of the T-Value theory and indicated the potential for applying the concept to the assessment of the performance of full building enclosures by directly comparing external and internal air temperatures (rather than wall surface to surface temperatures).

6.2 Fundamentals of the concept applied to building enclosures

Generally, the T-Value concept analyses the dynamic temperature profile resulting from the relation between the external (inputs) and internal (outputs) surface temperature response of a barrier (a wall). The idea for the concept comes from an "automatic reasoning" paradigm, which states the response component (output) can be defined by the key input parameters (8.9). Temperature is the driving parameter of the concept. The dynamic temperature profiles characterise various walling systems, depending on the angle of the principal axis of the ellipse obtained by plotting the external versus the internal wall surface temperatures for a diurnal cycle (defined as the "T-Value"). Lower T-Values (that is, smaller inclination angles of the principal axis of the ellipse) have been shown to consistently correlate with better wall thermal performance. The detailed development of this concept has been described in Chapter 5.

Further investigations have shown that the T-Value concept for assessing the thermal performance of a walling system (based on external and internal wall surface temperatures) has the potential to be extended to also assess the overall thermal performance of a building enclosure, based on the observed external and internal air temperatures, rather than wall surface temperatures, (called here "the System Dynamic Temperature Response" (SDTR or S-Value). This has the potential to provide a convenient means of assessing the performance of a building enclosure using a simple parameter such as air temperature which, by default, takes into account the contribution of all of the building components.

The idealised relationship between the external and internal air temperatures for any building enclosure subjected to a diurnal temperature cycle is shown Figure 6.1. For any given external conditions, the response of the interior of the building will be different, depending on the combined effect of the properties and nature of the building (i.e. walling, roof and slab configurations, window size, temperature swings and surrounding environment). The angle of inclination of the linear curves is called the "System Dynamic Temperature Response" (SDTR or S-value), with the dynamic thermal behaviour of the enclosure being defined by this SDTR parameter. Various cases can be considered, for instance:

i. If a building behaves as a perfect system and is not at all sensitive to external conditions, the internal temperature is then not influenced by fluctuations of the external environment, and its response will be represented as a constant horizontal line (i.e. a System Dynamic Temperature Response (SDTR) of zero degrees or an S-value of zero), see Figure 6.1 (a).

ii. If a building has poor thermal performance (i.e. highly vulnerable to external conditions), its response will be represented by a linear curve with the internal surface temperature directly responding to the temperature changes on the external side as shown in Figure 6.1(b) (for a case of "zero insulation", this would correspond to a SDTR of 45 degrees or an S-value of 45).

Each such curve can be then classified by the SDTR (or S-Value) parameter which corresponds to the angle of the curve to the horizontal axis. The schematic presentation in Figure 6.1 demonstrates the principles behind the SDTR concept. The effective thermal response of real systems/buildings will have an intermediate SDTR falling between the two extreme cases, depending on the thermal efficiency of the enclosure.

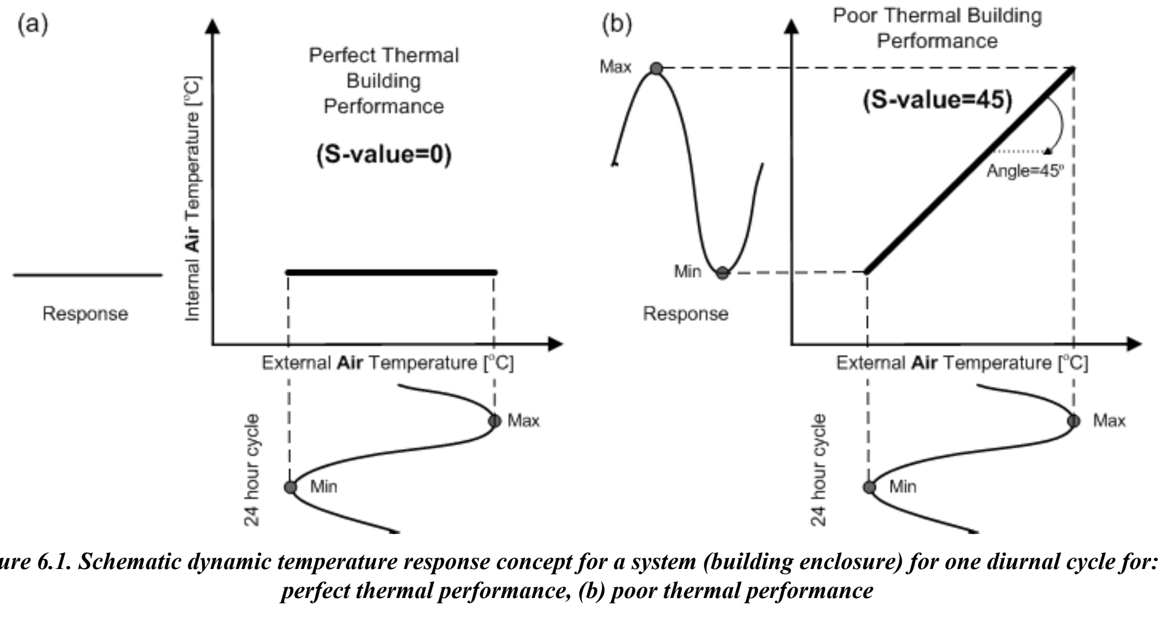


Figure 6.1. Schematic dynamic temperature response concept for a system (building enclosure) for one diurnal cycle for: (a) perfect thermal performance, (b) poor thermal performance

If the angle of inclination (SDTR) is small (say close to zero), energy transference to the interior of the enclosure would be limited regardless of the external dynamic conditions (corresponding to a near perfect thermal performance). In contrast, an enclosure with poor thermal performance will have a high angle, approaching even 45 degrees for buildings with little insulation (that is, performing in a manner similar to a "tent").

In the observed actual performance, the interaction curves are not straight lines but elongated elliptical shapes rotated and inclined at an angle to the external temperature axis. Nevertheless, each ellipse can

be simplified by considering the major axis (i.e. transverse diameter) which indicates the largest distance between antipodal points. This axis creates an angle with the horizontal axis of the Cartesian coordinate system and this is the most representative parameter (the SDTR or S-value).

The SDTR acts as an index for the dynamic thermal response of room temperatures relative to external temperatures measured at small time increments over a 24 hour period. While SDTRs are expected to be typically in the range of 0-45, it is possible for values to occur outside this range depending on factors such as the immediate thermal history of the building, changes in the weather and how such changes are being accommodated by the building design and materials. The shape of the ellipse is not used as a variable in this aspect of the study.

A typical example for winter conditions for the experimental cavity brick housing module is shown in Figure 6.2. The curve is based on measured data (288 points for a diurnal cycle, sampled at 5 minute intervals). The overall system dynamic response which is approximated by an ellipse was evaluated using the previously described Principal Component Analysis (PCA).

If the dynamic external versus internal temperature plots for several enclosures are combined in the one figure, the dynamic temperature profiles for each enclosure can be directly compared and the differences in the response of the modules highlighted giving a direct indication of their relative performance.

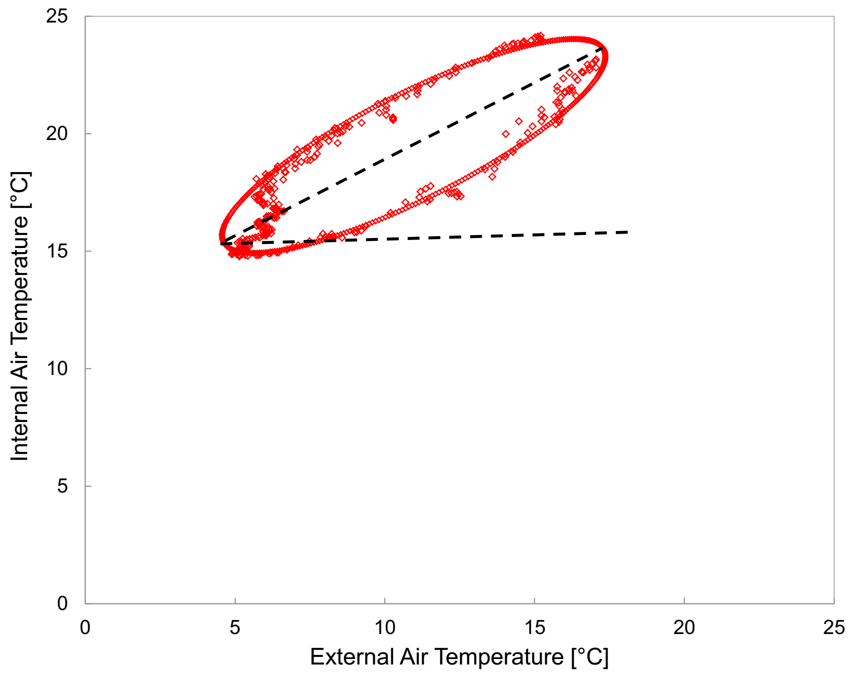


Figure 6.2: Dynamic temperature plot for a typical winter diurnal cycle for a cavity brick module. Note: Data points show the actual measurements (288 points for one cycle) and an ellipse evaluated using PCA.

6.3 S-value concept applied to the housing test modules

To evaluate and verify the proposed SDTR concept, detailed studies were carried out on the housing module data base for modules constructed from cavity brick (CB), insulated cavity brick (InsCB), insulated reverse brick veneer (InsRBV), and insulated brick veneer (InsBV) walling systems, all with identical north facing windows, roof and slab. The study has been performed for all seasons. Typical sets of temperature response curves for summer and winter conditions are shown in Figures 6.3 and 6.4 respectively. In all cases the use of the Principal Component Analysis resulted in ellipses which fitted the 288 observed data points from the one diurnal cycle.

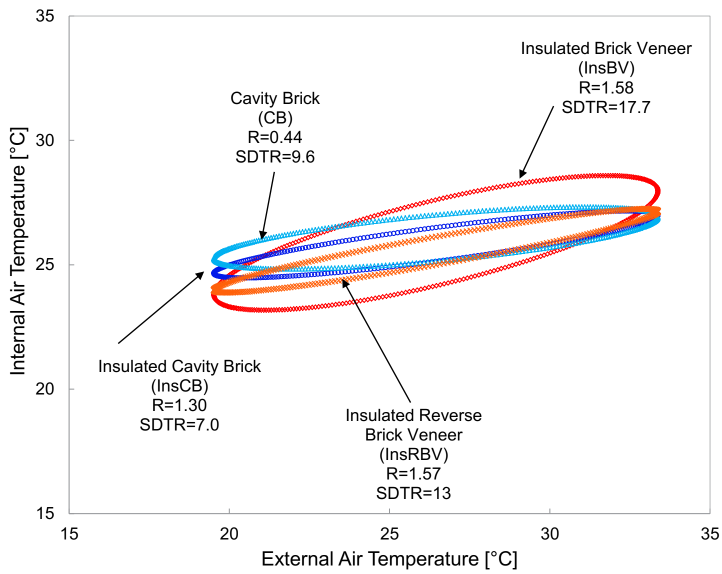


Figure 6.3: Dynamic plots of full-scale test house modules constructed from InsRBV, InsBV, InsCB, and CB walling systems for a typical diurnal cycle for summer conditions.

The elliptical shapes vary depending on the thermal properties of the module, its insulation properties and its thermal mass.For summer conditions, (Figure 6.3) , the ellipse for the InsCB module exhibits a low angle of inclination of the major axis to the horizontal (a low SDTR of 13) and exhibits a relatively small variation in temperature in the direction of the minor axis (internal surface temperature). That is, for a relatively broad change in external temperature, there is minimal change in the internal temperature axis direction. In contrast, the InsBV module, with no internal thermal mass, exhibited a larger angle of inclination to the horizontal (a higher SDTR of 17.7). This is consistent with the behaviour of the modules under real weather conditions exposed to the same weather cycles, where the modules with walls having lower thermal resistance but higher thermal mass performed better than their lightweight counterparts, despite the steady-state parameter (R-Value) being almost 3.4 times less [1].

For the winter conditions presented in Figure 6.4, the modules were exposed to different temperature cycles and the response of the walls was therefore different to that for summer conditions. The InsBV module exhibited the highest angle of inclination (SDTR = 34) compared to the CB module with a small angle of inclination (SDTR = 19). This is despite the fact that the steady-state performance, based on R-Value, would suggest the opposite performance since the R-Value of the InsBV wall was almost 3.5 times greater. Thus, despite the walls having higher thermal resistances (R-Values), the corresponding modules exhibit high S-Values. This corresponds with the overall findings of the 10 year module study and was confirmed through analysis of the data, which found that the R-Value was not the sole predictor of the behaviour of the various walling systems, with other parameters such as the thermal mass, the composition of the layers of the walling envelope etc. also playing an important role.

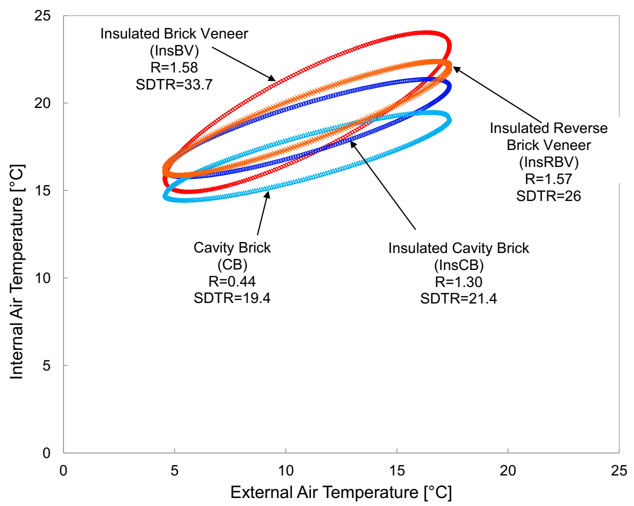


Figure 6.4: Dynamic plots of full-scale test house modules constructed from InsRBV, InsBV, InsCB, and CB walling systems for a typical diurnal cycle for winter conditions.

The same principles can be applied for the comparison of the thermal performance of complete building enclosures across all four seasons, since the interaction of all components of a building (such as walls, slab, ceiling, internal walls and window) and their influence on overall thermal performance of the building is inherently included in the SDTR parameter. The plots illustrate how the modules respond to external air temperature and thus determine the trace of the internal air temperature against external air temperature across each season. As can be seen, the relative performance was similar, regardless of season. This also indicates that at least for an enclosure with a north facing window, increasing the wall R-value results in an increased mean internal air temperature without the SDTR parameter being affected.

The overall summary plots shown in Figure 6.5, confirm that the S-values characterise the thermal performance of the housing enclosures as the trend for every module is similar, although the values differed between seasons as the external weather conditions (external air temperature) changed. In addition, both winter and summer seasons define the extremes with the spring and autumn values lying between them. This suggests that any dynamic laboratory tests should at least incorporate the winter and summer external temperature variations.

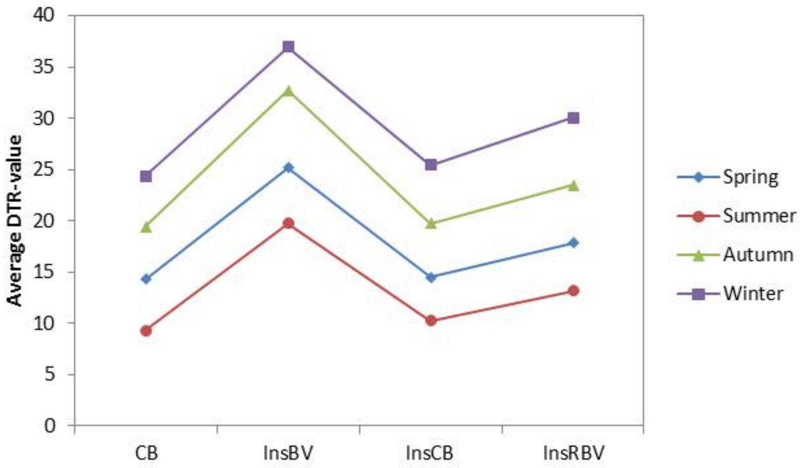


Figure 6.5: Comparison of the System Dynamic Temperature Response for various modules across the whole year.

Interestingly, the presence of wall insulation in a building with a window appears to raise the position of the corresponding curve in the direction of internal temperature axis without changing the angle of inclination or the DTRS parameters. This is an indication that at least in buildings with a window, increasing the R-value raises the internal air temperature (comparing thermal performance of both modules), significantly affecting the DTR parameter.

6.4 S-value concept applied to the assessment of the contribution of carpet to the housing module performance

6.4.1 Introduction

Internal and external temperature variations within a 24 hour cycle are predominantly driven by diurnal and seasonal solar cycles but are also influenced by the weather and the immediate thermal history of the building. The time based relationship between the internal and external temperatures is variable, due to the seasonal cycles, differential solar ingress and uncontrolled weather variations. It is also impacted by the building design and the thermal properties of the construction materials. Complex, dynamically varying heat transfer patterns exist between internal and external environments resulting in varying time lags observed between the diurnal cycles of internal and external air temperatures.

6.4.2 Carpet impact

As a result of the lagged temperatures, when internal air temperature is plotted against external temperature over separate 24 hour periods, elongated hysteresis patterns are observed. Examples are shown in Figure 6.6. The elongation of the pattern is due to the external temperature exhibiting greater diurnal variation compared to the internal temperature. These hysteresis patterns, which are effectively daily thermal summaries, vary from day to day, season to season and module to module. The pattern differences between modules reflect

the different thermal performances of the modules. In particular, the angle of inclination of the elongated hysteresis axis to the external temperature axis is a daily summary of the apparent sensitivity of internal temperature to external temperature variation. The use of this angle as the empirical thermal response index (S-value) facilitates the statistical comparisons of the relative thermal performances of the modules. While Figure 6.6 is used here mainly to illustrate how ellipses are used to summarise temperature patterns, it also illustrates for the InsLW, InsBV, InsCB and CB modules the different effects that the inclusion of carpet has on temperature patterns

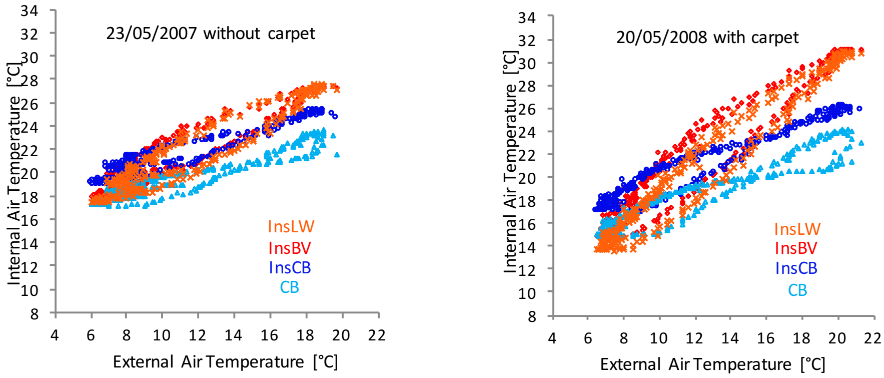


Figure 6.6: Actual elliptical representations of the thermal response of interior air temperature to a Diurnal Temperature Cycle. The graphs are for two similar days in each year and compare the effects with and without carpet for the InsLW, InsBV, InsCB and CB modules.

Module	Predicted S-value		Difference (carpet – no carpet)	
	With carpet	No carpet		%
InsBV	42.7	30	12.7	42
CB	24.8	19.2	5.6	29
InsCB	26.1	20.5	5.7	28
InsLW	46.3	31.9	14.5	45

Table 6.1: Observed S-values

In addition, the observed S-values for modules with and without carpet are shown in Table 6.1. The inclusion of the carpet increased the S-values for all test modules (by about 30% for the heavy internal walling systems (InsCB and CB) and by more than 40% for the lightweight modules (InsBV and InsLW)).

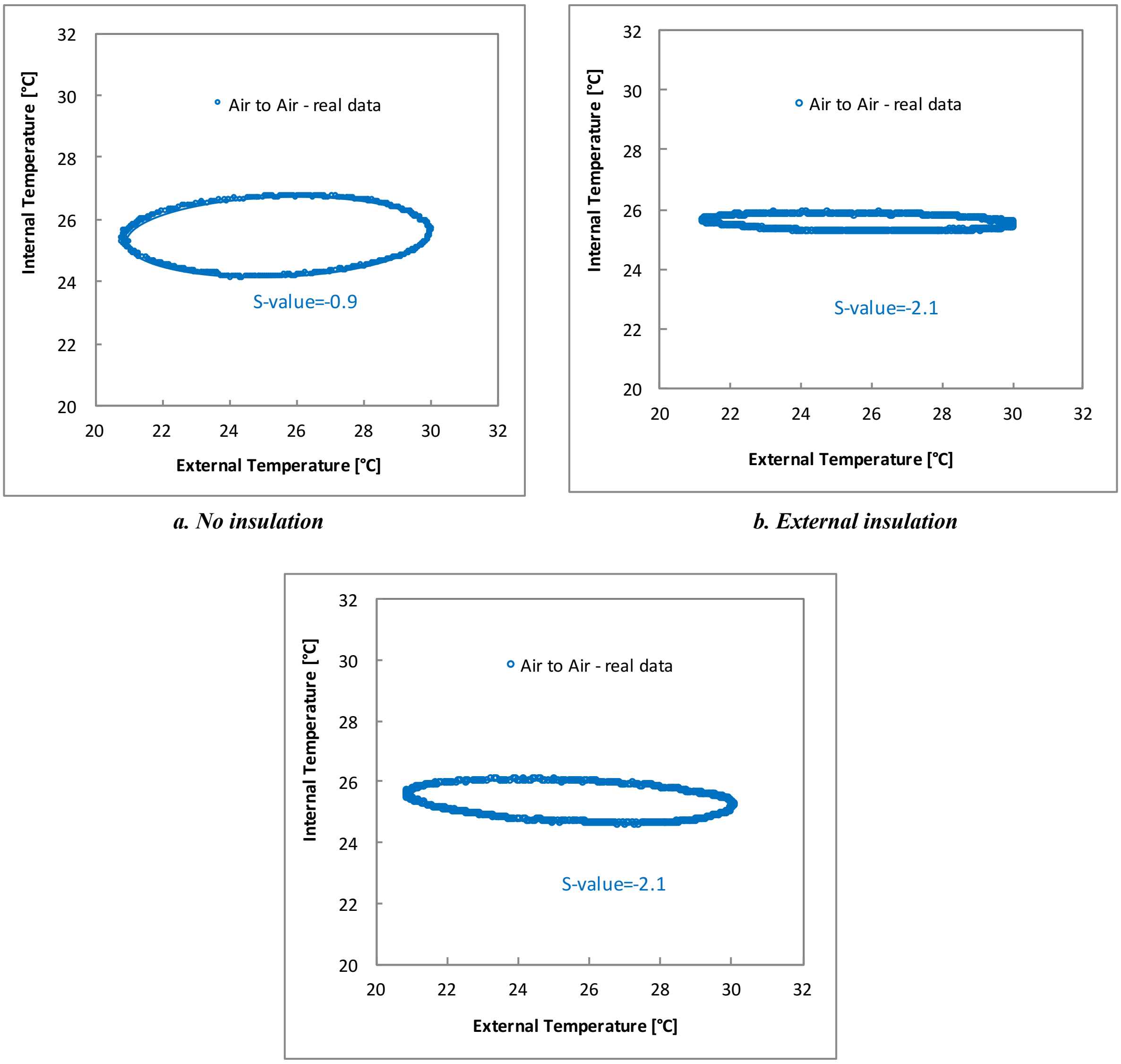
6.4.3 Summary of carpet effects

The modules with the least response to external temperature changes (i.e. lower S-values) were those with cavity brick walling systems because they had exposed thermal mass surfaces forming the interior walls (in addition to the concrete floor slab). The study also illustrated how a metric such as the S-value enables comparisons of performance to be carried out by a statistical analysis of available data from the same days in each year but without necessarily the same weather conditions. The use of the S-value as a response metric to measure the influence of carpet on the performance of the different buildings is illustrated in Figure 6.6 and Table 6.1. It can be seen that the influence of carpet was significant, particularly for the InsBv and InsLW, modules where the concrete floor slab was the main contributor to the internal thermal mass.

6.5 S-value concept applied to laboratory wall tests

As previously described, the dynamic temperature response of a range of wall panels (from a solid brick panel with high thermal mass to a polystyrene panel with low thermal mass) has been studied, This study also included a range of masonry walling types with varying ratios of thermal mass and thermal resistance. As described in Chapter 5, in evaluating the T-value for any particular wall, the external to internal wall surface temperatures have been used. Since the air temperatures from the controlled "external" and "internal" spaces of the testing rig are also available, they can be used to also potentially develop an S-value for each panel. The S-values obtained for each of the wall panels is included with the T-value results in Table 5.2.

The concept is illustrated here for tests on solid brick panel with and without insulation, as described in Chapter 4. The typical air to air temperature curves are shown in Figure 6.7. Each curve is based on measured data (288 points for a diurnal cycle, sampled at 5 minute intervals). All three cases (without insulation, with internal and with external insulation) exhibit a low angle of inclination of the major axis to the horizontal (a low S-Value of about 1), and exhibits a relatively small variation in temperature in the direction of the minor axis (internal air temperature).



a. No insulation *b. External insulation*

c. Internal insulation

Figure 6.7 Dynamic Temperature Response plots for non-insulated (S-value=1.9), internally insulated (S-value=-0.9), externally insulated (S-value=-2.1) brick panels under dynamically simulated laboratory conditions.

6.6 Conclusions

This chapter has described the development of the "System Dynamic Temperature Response" concept (or S-value) for building enclosures as an extension of the previously reported T-Value concept for individual walls in Chapter 5. The method deals with the dynamic temperature profiles from the measured external air temperatures (influenced by external weather variables such as ambient temperature, solar radiation, and wind speed) and the response of the internal air temperature of a building enclosure. When the resulting dynamic temperature profiles are plotted for a diurnal dynamic cycle, the data takes the form of an ellipsoidal shape, with the slope of the principal axis of the ellipse being the distinguishing feature between the performance of modules constructed from the various walling systems. This angle is taken as the SDTR value (or S-value) for the building enclosure. and correlates directly with its thermal performance under dynamic external weather conditions. The main outcomes of this part of the study are:

i. The SDTR measure has the potential to define the behaviour of all modules (both heavy and lightweight) under the cyclic nature of the environmental conditions, the wall response to environmental changes and more importantly, facilitate the assessment of the thermal performance of the whole building envelope.

ii. The SDTR value correlates directly with the thermal performance of the enclosure under dynamic external weather conditions. It is therefore a promising first step in the development of a convenient representative measure of the thermal performance of a building under dynamic conditions encapsulating inherently the contribution of all of the building components.

iii. Once fully developed, such a comprehensive metric has the potential to improve the accuracy and effectiveness of current energy efficiency assessment measures and ultimately lead to more thermally efficient house designs. It also provides a convenient measure to assess the performance of retrofitted existing housing stock by providing a means of direct comparison of the performance through the DTRS values before and after the retrofit.

7. Application of T and S-Value Concepts to the Assessment of Housing Thermal Performance

7.1 Introduction

This report has presented the results of extensive testing of the thermal performance of individual wall and wall combinations as well as the performance of housing modules constructed from typical Australian walling systems. This has resulted in the development of the T and S-value concepts which directly reflect the thermal performance of individual walls and building enclosures. The T-value is evaluated from the surface temperatures of the "external" and "internal" wall surfaces when the wall is subjected to temperature variations simulating a diurnal temperature cycle. The S-value is evaluated from the "external" and "internal" air temperatures of the enclosure, again under a diurnal temperature cycle. Both these parameters are represented by the inclination of the principal axis of the resulting elliptical curves. The key feature of both measures is that they each reflect the combined contribution of both the thermal mass and thermal resistance in the one parameter.

The S-values have been derived from observations of the performance of the housing test modules and directly reflect the influence of the external conditions and all of the building components, not just the properties of the walls. This concept can be extended to the study of the performance of a complete multi-roomed house provided a representative internal air temperature (from an appropriate room in the house) can be selected and observed. By determining the S-value before and after a retrofit on an existing house to improve its thermal performance, this approach could also be particularly useful in assessing the effectiveness of a given retrofitting strategy. The T- and S-value approach therefore has the potential to become a key design parameter in future building design regulations.

7.2 Application of the T-value concept

Since the T-value is evaluated from the surface to surface wall temperatures, it provides a direct measure of wall performance under dynamic conditions taking into account both thermal resistance and thermal mass. It inherently incorporates the contribution of each component of a walling system, including any insulation which may be present. As has been shown in Chapters 4 and 5, the location of each of the wall components (including the insulation) within the overall walling system has a direct influence of the thermal behaviour of the wall. For example, in a composite wall system, if the insulation layer is located on the outside of a layer with a high thermal mass (such as a brickwork skin), it not only limits the amount of heat transmitted through the wall to the interior, but also allows the thermal mass of this layer to be mobilised and used to advantage in storing and releasing heat to the interior of the building.

The T-value for a particular walling system directly reflects this effect. For example, as can be seen from Table 5.2, a 110mm single skin, solid brickwork wall with no insulation has a T-value of 36.3; with insulation on the "inner" face a T-value of 15.4; and with insulation on the "outer" face, a value of 0.40 (the reasons for this response have already been discussed in Section 5.4.2). Depending on the design circumstances and required wall response, knowledge of this nature can be used to advantage (particularly in solar-passive design), to maximise the contribution of the walling system and minimise energy consumption to obtain the most efficient thermal design of a building.

7.3 Application of the S-value concept

The System Dynamic Temperature Response parameter (S-value) developed here provides a measure of the thermal performance of a building enclosure under a full diurnal temperature cycle, and in doing so, inherently considers all of the physical parameters influencing thermal performance. As mentioned above, it will be of particular value in comparing the relative thermal performance of various forms of house construction, for new or retrofitted buildings.

7.3.1 Application of S-value to the assessment of thermal comfort

The System Dynamic Temperature Response profiles can also be used to assess the thermal comfort of a system (building) by specifying the amount of time a system spends within an acceptable temperature range

for its occupants as shown in Figure 7.1. Thermal comfort is influenced by a range of factors, but since temperature is one of the main contributors, it is used here for illustrative purposes. Using this approach, the optimum thermal performance is represented by an idealised module B in Figure 7.1, exhibiting a small variation on the Y-axis and remaining within the "comfort range" for the entire diurnal cycle. In contrast, the idealised poor module thermal performance is shown for Module A in Figure 7.1 which exhibits wider variations in internal temperature and much less time within the thermal comfort level (or in the worst case, lying predominantly outside the thermal comfort range). Note that the DTRS profiles are season dependent (see for example, Figure 6.5), and this would have to be taken into consideration when choosing the most effective walling system). The concept could also potentially be extended to a larger structure such as a house provided a representative internal space (such as the living area) is selected as an appropriate location to provide a "representative" internal air temperature

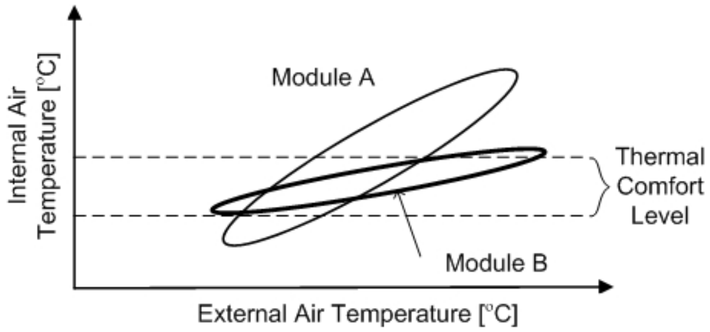


Figure 7.1: An idealised example of temperature profile curves with typical temperature comfort level

The SDTR (S-value) also has the potential to be applied to the assessment of various retrofitting schemes for enhancing the energy efficiency of existing housing by comparing the predicted temperatures for each scheme using appropriate thermal modelling software, or after the event, by monitoring simultaneously the internal and external air temperatures.

Interestingly, as observed in the module tests, the presence of wall insulation in an enclosure with a north facing window results in increased internal temperatures and the upward displacement of the corresponding response curve without changing the angle of inclination or the SDTR parameter (compare the curves obtained for InsCB and CB in Figure 7.2. The InsCB module, although having an R-Value almost three times higher than the CB module, has a similar S-value, but with its ellipse displaced upward). This may or may not be an advantage in terms of internal thermal comfort, depending on the range of internal temperatures that each ellipse covers during the diurnal cycle.

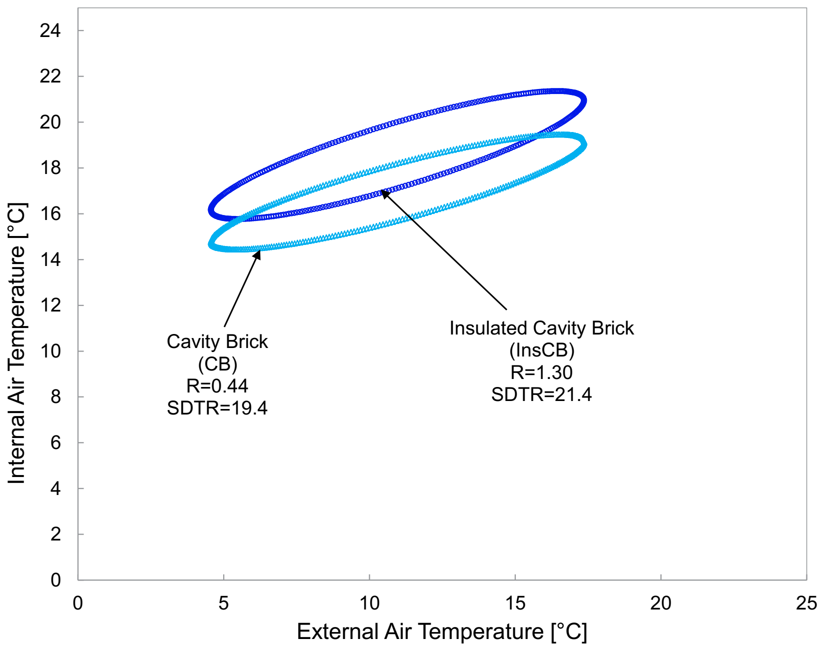


Figure 7.2: Thermal comfort level for the InsCB and CB modules for a typical winter day.

These hysteresis patterns, which are effectively daily thermal summaries, vary from day to day, season to season and module to module, with the pattern differences between modules reflecting their different thermal performance. In particular, the angle of inclination of the elongated hysteresis axis to the external temperature axis is a manifestation of the sensitivity of internal temperature variations to external temperature variations. The behaviour will not be consistent over all seasons, as the wall insulation layer may enhance the thermal performance during winter, but not necessarily be an advantage over the summer when thermal mass may be more important. In terms of selecting the most effective wall design, a comparison of system behaviour (and S-values) for a given thermal comfort level could be performed for every season to obtain an optimum combination of thermal mass and insulation for that particular building in that location.

7.4 Summary

This chapter has illustrated how the T- and S-value concepts can be potentially applied to the assessment of the thermal behaviour of both walls and building enclosures. By nominating the temperature range considered reasonable for internal thermal comfort, the location of the SDTR elliptical curves in relation to that range gives a direct indication of the thermal performance of the building enclosure, and at the same time taking into account all of the external and internal variables influencing the thermal performance. With sensible assumptions regarding the location of a representative internal temperature, the S-value concept also has the potential to be used for the assessment of the thermal performance of a complete structure such as a house.

The key feature of the proposed method is that it deals with the temperature profiles of external and internal air temperatures (influenced by external weather variables such as ambient temperature, solar radiation, and wind speed) to the response of the interior air temperature of the enclosure. The concept is based on easy to measure air temperatures and describes how the enclosure responds to a diurnal temperature cycle when it is exposed to external environment conditions. This inherently takes into account all parameters involved in the heat transfer of a building such as thermal mass, thermal resistance, diurnal temperature swings, ambient temperature, solar radiation and wind impact. Therefore, this approach encompasses the interactions among the building components, giving a realistic view of wall thermal performance and a picture of the whole mechanism involved.

8. T- And S- Values – The Way Forward

8.1 Relationships between elliptical response and thermal features

8.1.1 Introduction

The Dynamic Temperature Response concept uses external and internal temperatures as a driven parameter. The response of a system to a diurnal cycle of temperature creates elliptical-shaped curves as shown previously in Figures 5.3 and 5.4. The geometrical analysis of the elliptical curves yields the physical properties of either walling systems or entire enclosures. Two of the parameters, represented by the inclination of the principal axis were the T- or S-values, which reflect the combined contribution of the thermal mass and thermal resistance. Both approaches measure the thermal performance under dynamic conditions and also reflect the influence of the location of the wall components (including the insulation) within a walling system. This chapter provides a brief overview of other possible physical parameters which can be evaluated through geometrical analysis of the ellipses. These include the angle of the principal axes ("a" and "b") and the area and perimeter as shown in Figure 8.1. Such elliptical shapes take into account the energy absorbed and released by the various building components under a continually changing dynamic environment and inherently reflect their contribution to the performance of the entire walling system or building enclosure. The detailed analysis presented here is for the brick masonry constructed from brick units with 28% coring. Similar trends were observed for the other walling types.

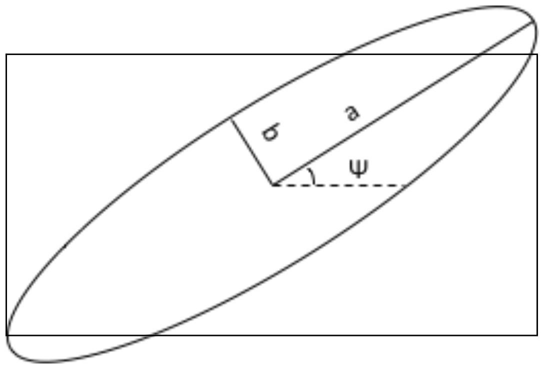


Figure 8.1: Elliptical shape.

8.1.2 Dependence on weather cycles

The daily 24 hour temperature cycles corresponding to Brisbane and Melbourne summer and winter conditions representing typical Australian hot and cold weather conditions were used to test the dynamic response of various walling system and building enclosures. These time and temperature relationships were important in assessing the dependence of the results on the seasonal temperature cycles. As shown in Figures 8.2 to 8.4, it was found that the variation of internal temperature to the external temperature was independent of the season throughout the T-and S-value analyses. It can be seen that the observed behaviour was consistent over all seasons for the uninsulated, internally insulated and externally insulated panels (with similar slopes of the principal axis of the ellipses in all cases). As shown in Figure 8.2, the different external temperature cycles resulted in the displacement of the elliptical responses in relation to the observed internal temperature, but significantly, the slopes of the ellipses remained constant. As shown in Figure 8.4, the wall insulation layer enhances the thermal performance during both winter than the summer compared to the uninsulated panel. Note, however, that both T-and S-values for each wall type still remain constant across all seasons. Therefore, since the T- and S- values are independent of location, only one cycle for a particular season is required to obtain an optimum combination of thermal mass and insulation for a particular building for all locations in Australia. Figure 8.3 also clearly illustrates the effectiveness of locating the insulation layer on the external rather than the internal face of the wall. Similar results for walls constructed from the other unit types are contained in Appendix B

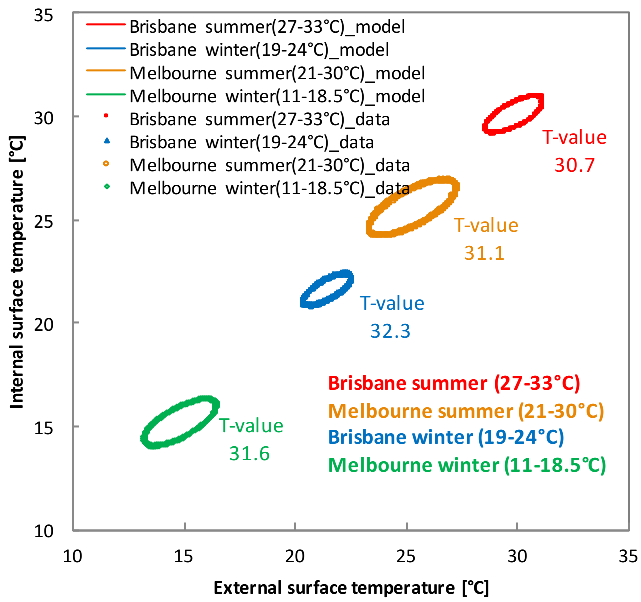


Figure 8.2: T-values for uninsulated brickwork panel for all analysed seasons (28% cored units)

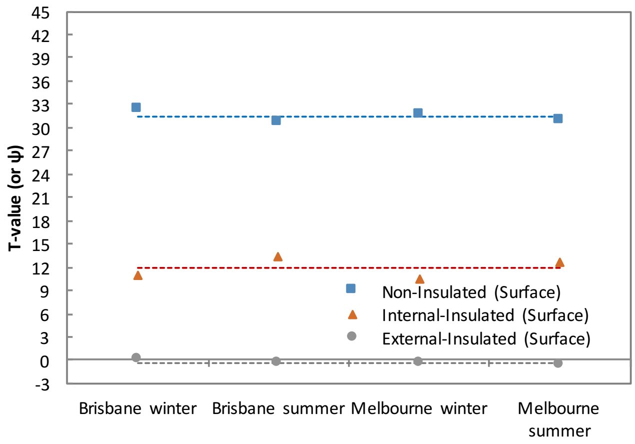


Figure 8.3: Comparison of T-values for various brickwork wall configurations for all analysed seasons (28% cored units)

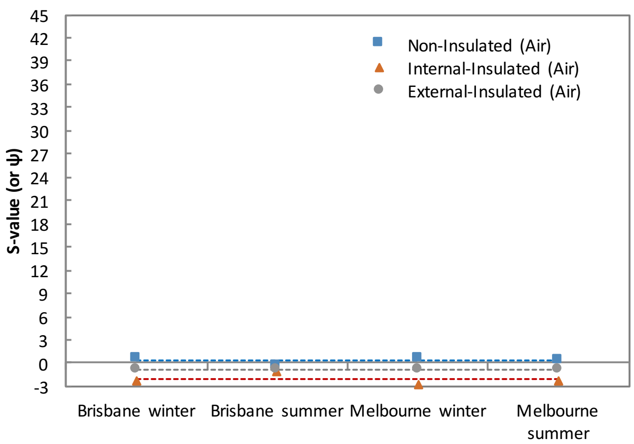


Figure 8.4: Comparison of test panel S-values for various brickwork wall configurations for all analysed seasons (28% cored units)

8.2 Relationship with thermal lag

The dynamic panel tests allowed the analysis of the complex heat transfer pattern between internal and external environments for both surface to surface (see Figure 8.5) and air to air (see Figure 8.6). This resulted in varying time lags for each panel configuration. As can be seen from Figures 8.5 and 8.6, the thermal lag for any particular wall configuration was not affected by seasonal variations. Similar results for walls constructed from the other unit types are contained in Appendix A5.

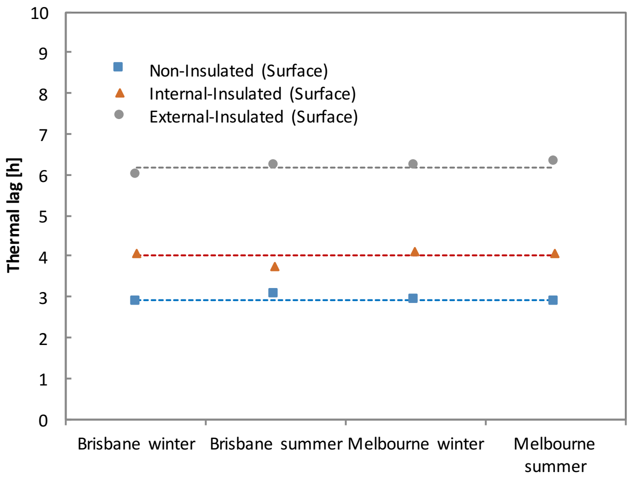


Figure 8.5: Surface to surface thermal lag comparisons for various brickwork wall configurations and analysed seasons (28% cored units)

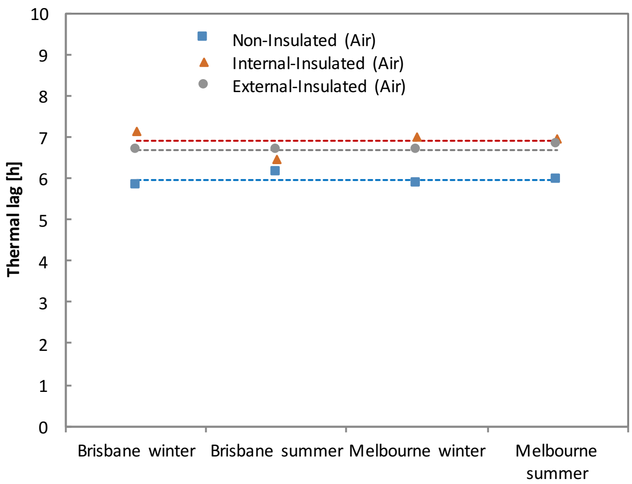


Figure 8.6: Air to air thermal lag comparison for various brickwork wall configurations and analysed seasons (28% cored units).

8.3 Dynamic thermal resistance

The thermal resistance (R-value) is a static parameter which does not reflect the ability of a wall to respond to a dynamic temperature cycle. In contrast, the elliptical hysteresis patterns observed in all of the dynamic wall tests in this investigation effectively summarise the daily thermal performance, and reflect what could be termed "the dynamic thermal resistance" of the wall. One potential version of this parameter which can be evaluated from the observed elliptical curves is based on the ratio of the square root of the area of the ellipse and the corresponding temperature variation. This concept is illustrated in Figure 8.7 for the brickwork wall with and without insulation for the air to air test panel S-values. Note that both the internally and externally insulated panels have the same "static" thermal resistance (R-values). A similar effect is observed here for this dynamic parameter, with a different value for the plain wall, but the same values for the externally and internally insulated wall. This is a very promising characteristic which, like the static R-value, is a

constant value for a particular wall configuration and is independent of season, but now also reflects the dynamic response of the wall including the combined effect of thermal mass and thermal resistance. Further development of this promising concept is still in progress.

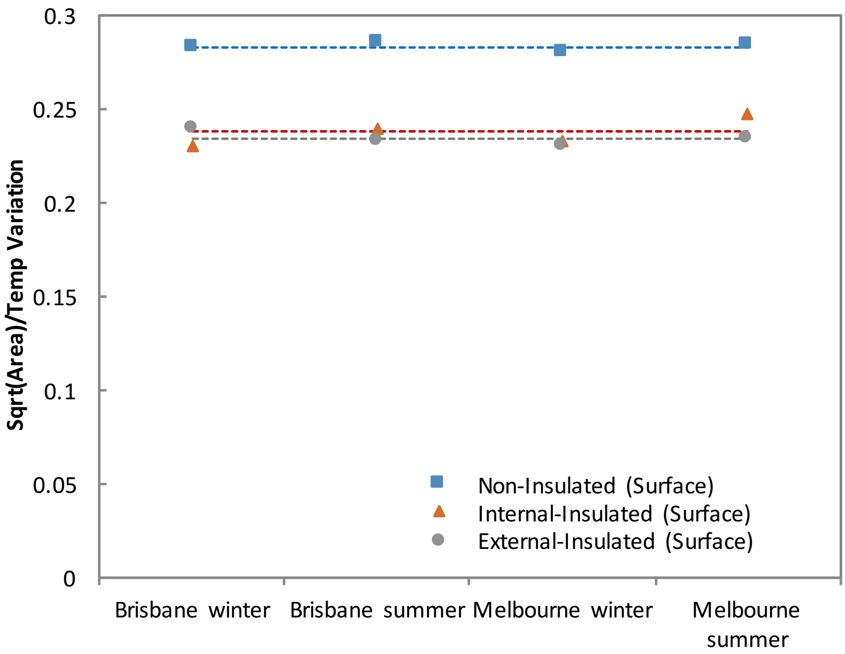


Figure 8.7: Comparison of test panel S-values for plain and insulated brickwork wall for all analysed seasons (28% cored units)

8.4 Shielding effect

The shielding effect of a brick skin located on the outside skin of a walling system for both the CB and InsCB modules is particularly important in illustrating the benefits of the masonry component. The heavy masonry component of a walling system limits the heat transferred through a wall to the interior as the heat is stored first in the thermal mass. Once external conditions change, much of this heat is radiated back to the external environment and only a small proportion of heat is passed through to the interior.

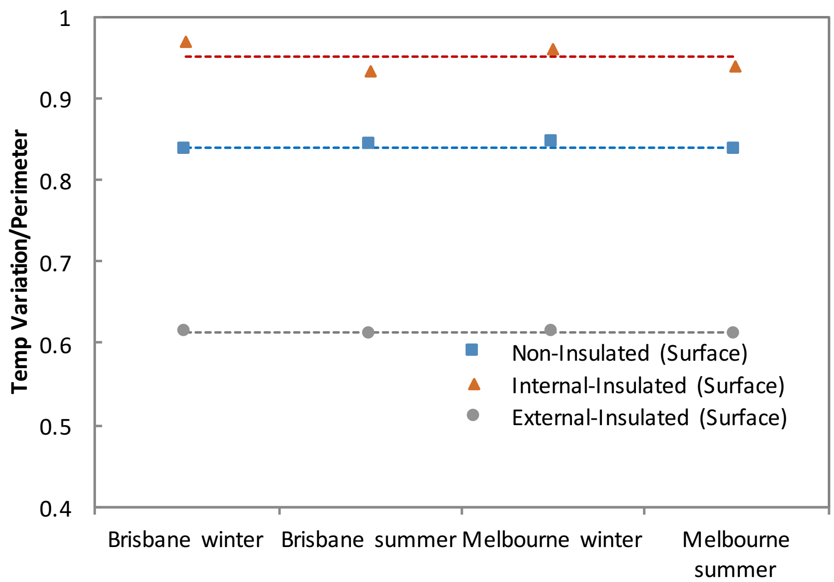


Figure 8.8: Ratio of Temperature Variation to Perimeter for all analysed seasons (surface to surface tests)

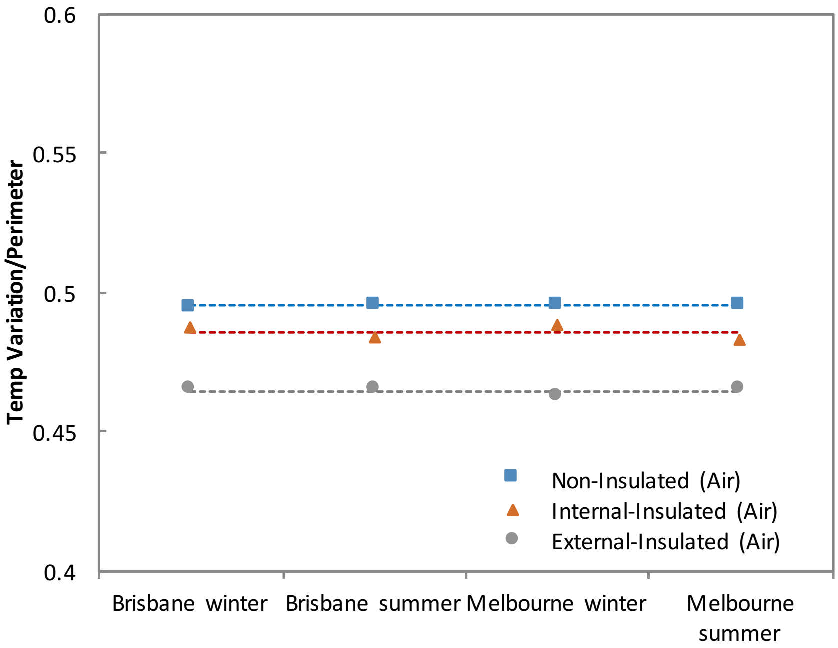


Figure 8.9: Ratio of Temperature Variation to Perimeter for all analysed seasons (air to air tests)

8.5 Other physical parameters

There are obviously a range of physical parameters which may have a useful relationship with the ellipse characteristics (for example, the ratio of the major to minus axis length). Relationships which could have the greatest potential for use in design are any parameters which are independent of seasonal effects and therefore more likely to represent an inherent characteristic of the wall in question. Some of the variables investigated in this context were:

i. Varying relationship with weather cycle for:

ii. Major axis of ellipse

iii. Minor axis of ellipse (b)

iv. Area of ellipse

v. Perimeter of ellipse

A summary of the study of these parameters (as shown in Figure 8.1) in relation to seasonal conditions for the brickwork wall with 28% coring is presented in Table 8.1.

		Brisbane summer	Brisbane winter	Melbourne summer	Melbourne winter	Average
Non-Insulated (Surface)	a	1.47	1.25	2.24	1.87	-
	b	0.56	0.45	0.82	0.68	-
	ψ	30.66	32.29	31.05	31.64	**31.41**
	Area [°C²]	2.58	1.77	5.79	4.03	-
	Perimeter	6.71	5.64	10.13	8.48	-
	Temp. Variation	5.65	4.72	8.47	7.16	-
	Thermal lag [h]	3.07	2.87	2.87	2.93	**2.93**
	a/b	2.64	2.76	2.72	2.74	**2.71**
	Sqrt(Area)	1.61	1.33	2.41	2.01	-
	Perimeter/Temp. Variation	1.19	1.19	1.20	1.18	1.19
	Sqrt(Area)/Temp. Variation	0.28	0.28	0.28	0.28	0.28
	a/Temp. Variation	0.26	0.26	0.26	0.26	0.26
	b/Temp. Variation	0.10	0.10	0.10	0.10	0.10
Internal-Insulated (Surface)	a	1.39	1.09	2.07	1.68	-
	b	0.42	0.33	0.70	**0.55**	-
	ψ	13.41	10.89	12.59	10.50	**11.85**
	Area [°C²]	1.85	1.13	4.57	2.73	-
	Perimeter	6.10	4.77	9.24	7.40	-
	Temp. Variation	5.68	4.63	8.67	7.09	-
	Thermal lag [h]	3.73	4.07	4.07	4.13	**4.00**
	a/b	3.27	3.27	2.94	3.06	**3.13**
	Sqrt(Area)	1.36	1.06	2.14	1.65	-
	Perimeter/Temp. Variation	1.07	1.03	1.07	1.04	1.05
	Sqrt(Area)/Temp. Variation	0.24	0.23	0.25	0.23	0.24
	a/Temp. Variation	0.24	0.23	0.24	0.24	0.24
	b/Temp. Variation	0.07	0.07	0.08	0.08	0.08
External-Insulated (Surface)	a	2.36	1.95	3.53	2.94	-
	b	0.25	0.22	0.38	0.31	-
	ψ	-0.30	0.03	-0.53	-0.27	**-0.27**
	Area [°C²]	1.86	1.35	4.22	2.84	-
	Perimeter	9.59	7.95	14.37	11.97	-
	Temp. Variation	5.86	4.87	8.78	7.34	-

Table 8.1: Summary of the study of parameters in relation to seasonal conditions for a brickwork wall (with 28% coring)

8.6 T- and S-value relationships between individual and combined systems

The bulk of the dynamic (T-value) tests performed in the laboratory hot box involved a single masonry (or concrete) skin, sometimes combined with either an internal or external insulation layer. From a practical perspective, a combined T-value representing the dynamic response of a walling system is desirable. In order to assess this effect, as described in Section 3.3, dynamic tests were performed in a smaller hot box on smaller samples of individual and combined wall components. The results of the tests on wall systems obtained by combining the single components (a brickwork skin, a timber framed wall and a 25 mm polystyrene insulation panel) and the relevant composite sytems made from these components (CB, InsCB, InsBV and InsRVB are shown in Table 8.2. The development of a potential method to combine the T-values of individual components to produce a value for a composite panel is still in progress.

Wall type	Insulation	Thickness [mm]	Weight [kg/m²]	T-value (surface)	S-value (air)	R-value (surface)	R-value (air)
Brick wall (28% coring)	No insulation	110	163	30.75	7.9	0.13	0.25
	Internal polystyrene insualtion	135	164	3.4	-4.6	0.72	0.85
	External polystyrene insulation	135	164	-0.75	-0.6	0.75	0.85
Timber framed wall	No insulation	110	23	32	22.6	0.4	0.26
	Glasswool insulation	110	25	18.4	15	0.73	0.82
25mm Polystyrene Panel	-	25	0.6	24	18		
InsBV	Glasswool insulation	260	188	8.5	0.81	1.43	1.57
CB	No insulation	270	326	-1.8	-3.5	0.42	0.56
InsRBV	Glasswool insulation	260	188	-1.3	-0.6	1.43	1.57
InsCB	Polystyrene insualtion	295	327	-3.9	-3.6	0.96	1.09

Table 8.2 Tests on walling systems and their components

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Appendices

Appendix A: Dynamic Wall Tests and Detailed T-value Results

A1: Surface to surface elliptical model (Non-insulated)

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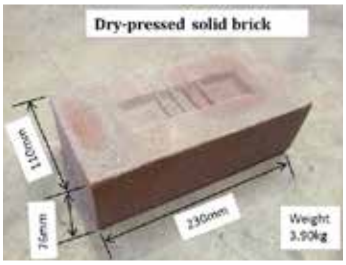
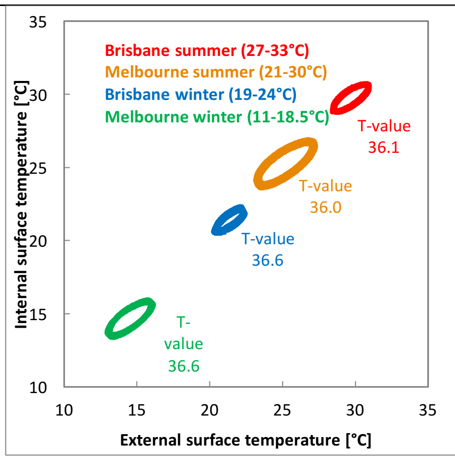
<tr><td rowspan="3">110mm</td><td>solid</td><td>
</td><td>
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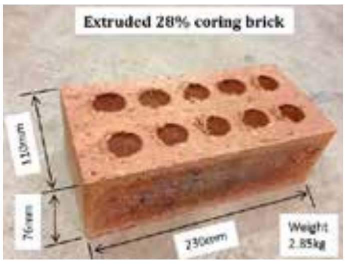
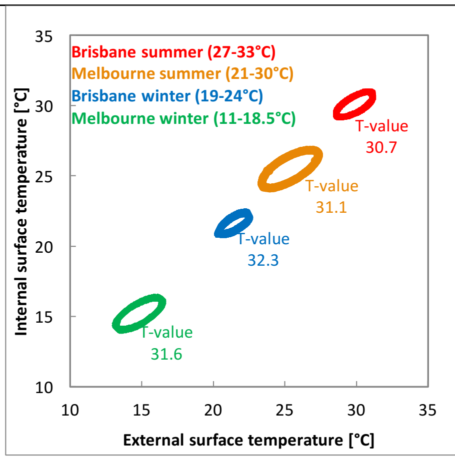
<tr><td>28%</td><td>
</td><td>
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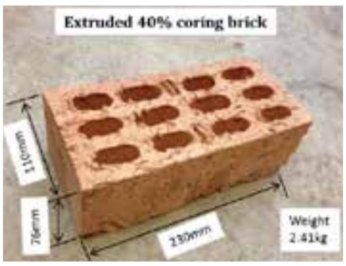
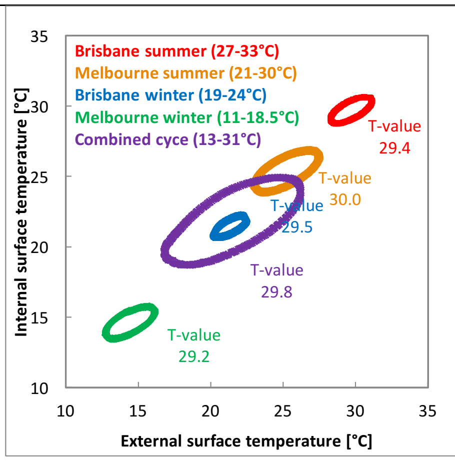
<tr><td>40%</td><td>
</td><td>
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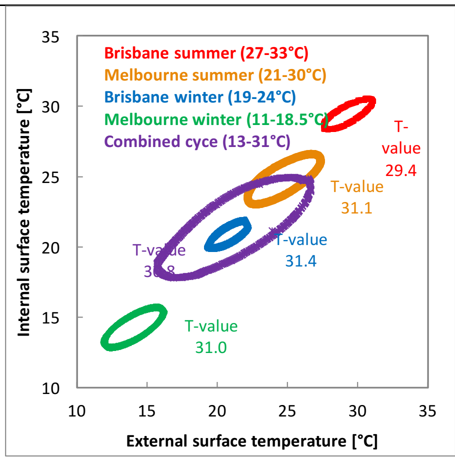
</td><td>
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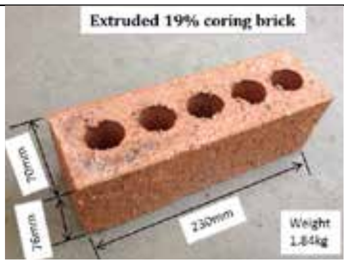
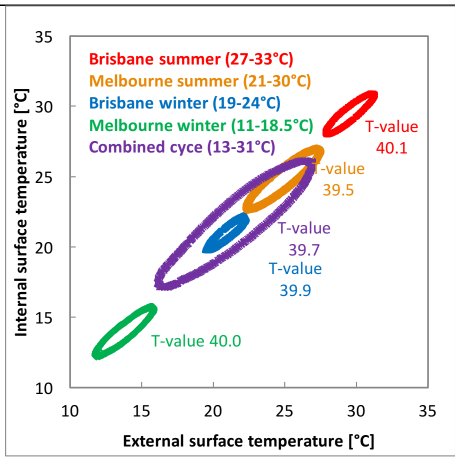
<tr><td>70mm</td><td>19%</td><td>
</td><td>
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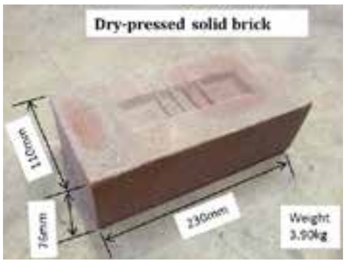

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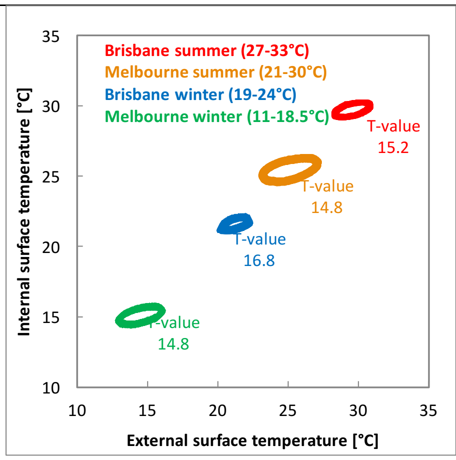

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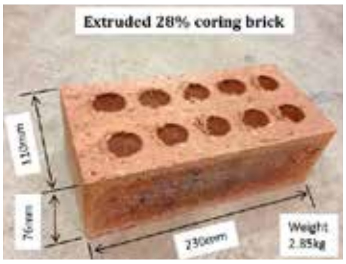

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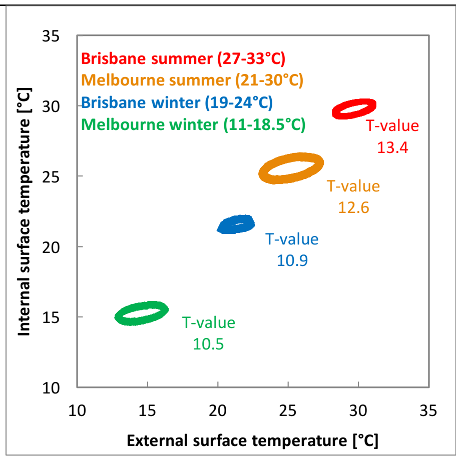

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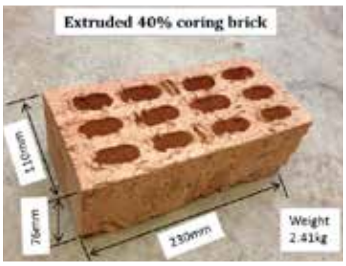

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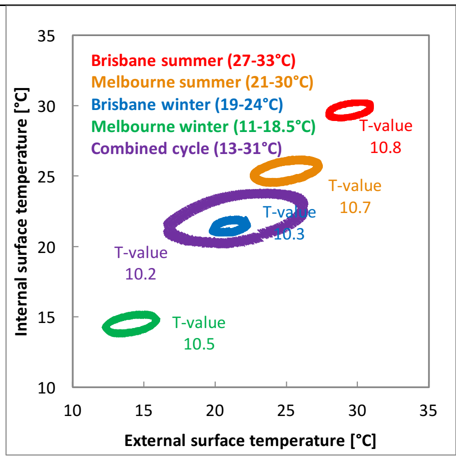

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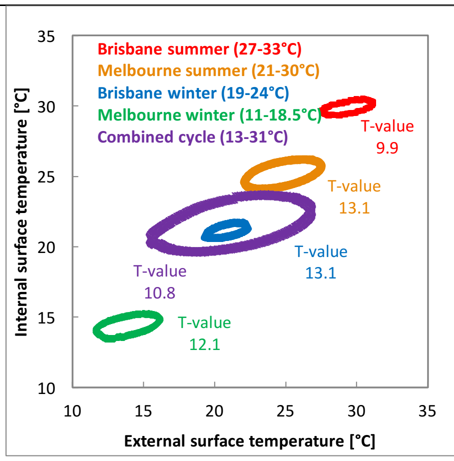
</td><td>
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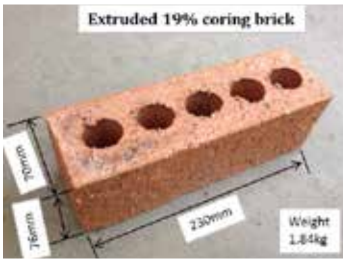
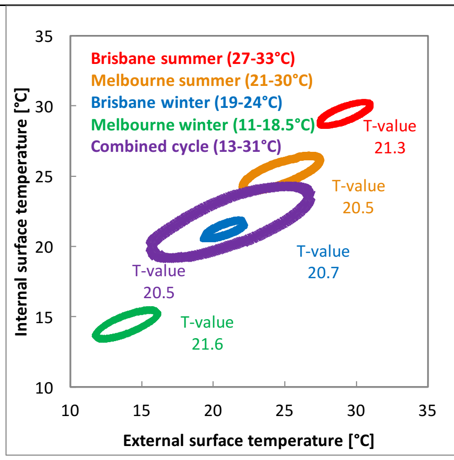
<tr><td rowspan="2">70mm</td><td>19%</td><td>
</td><td>
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A3: Surface to surface elliptical model (External insulation)

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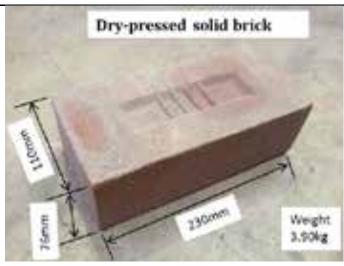
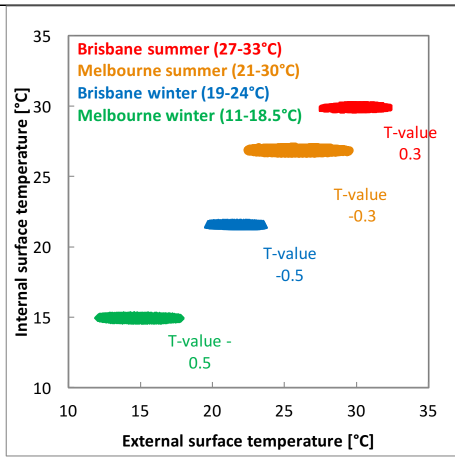
<tr><td>110mm</td><td>solid</td><td>
</td><td>
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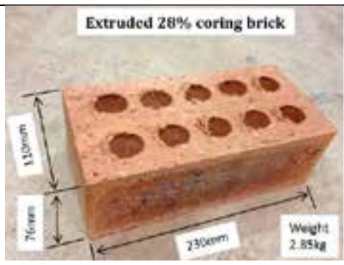
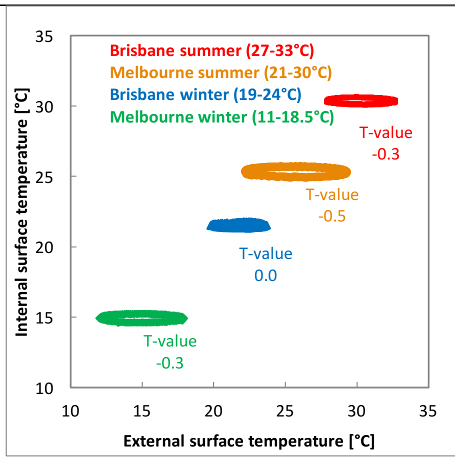
<tr><td></td><td>28%</td><td>
</td><td>
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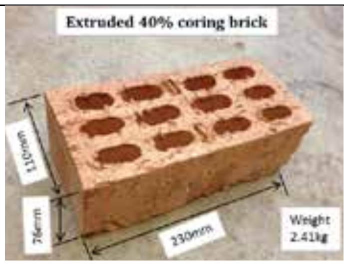
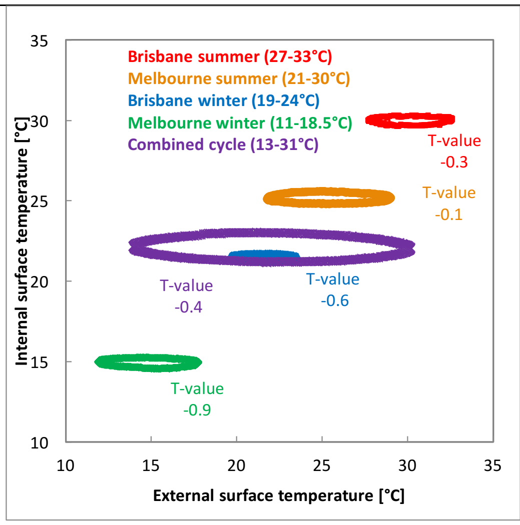
<tr><td></td><td>40%</td><td>
</td><td>
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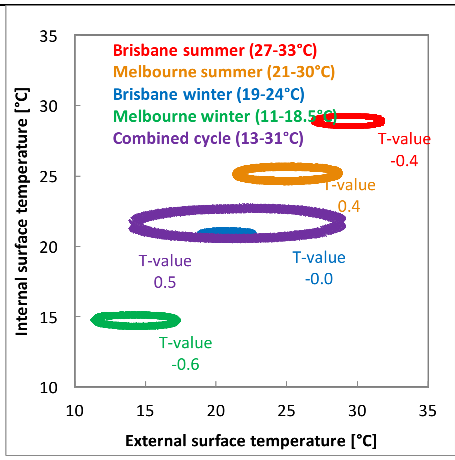
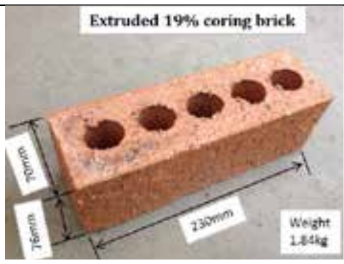
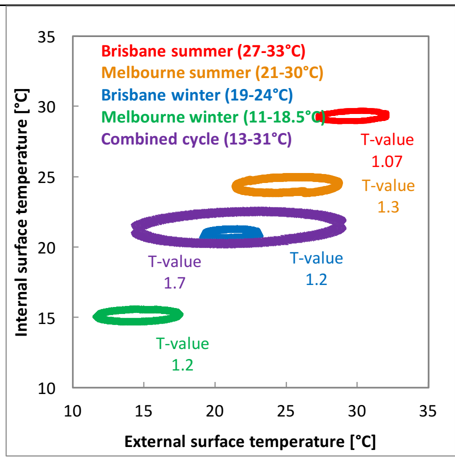
90mm	27%		
70mm	19%		

A4: Variation of T-value with Season

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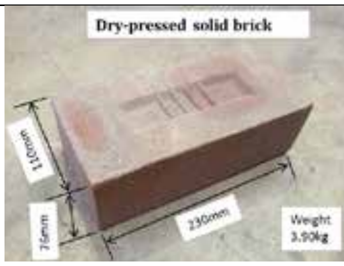
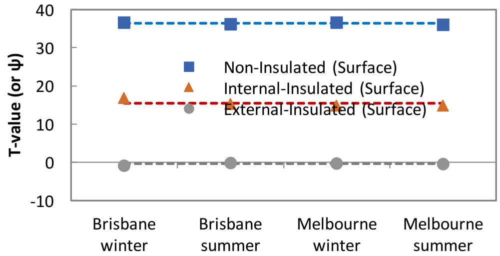
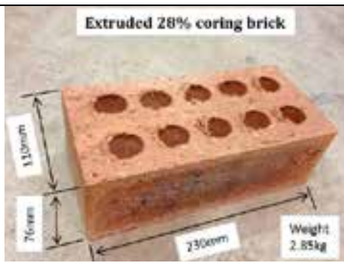
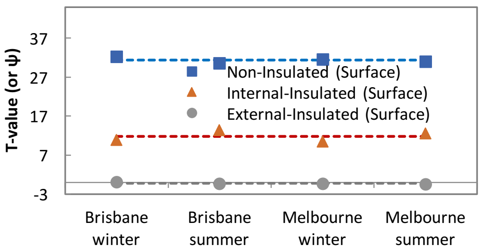
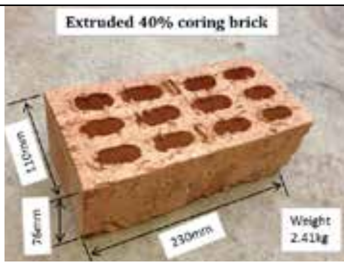
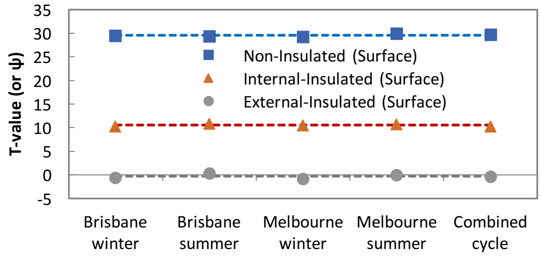
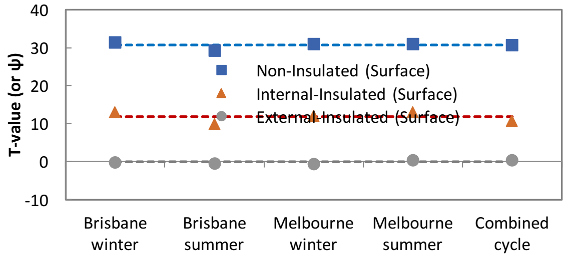
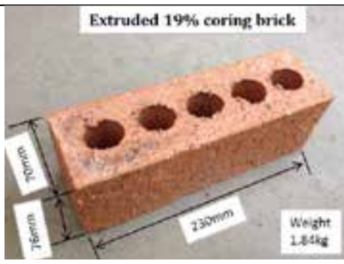
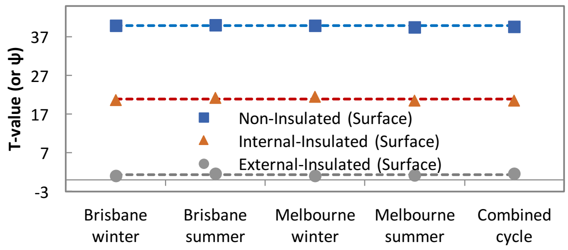
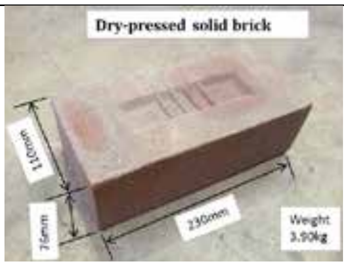
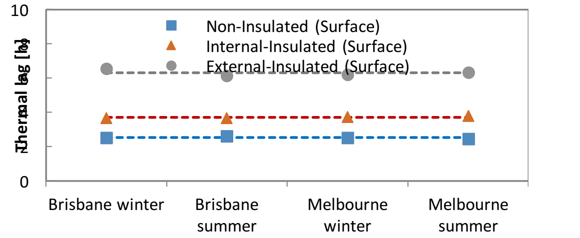
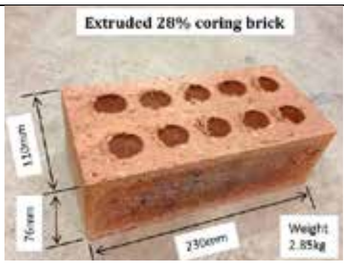
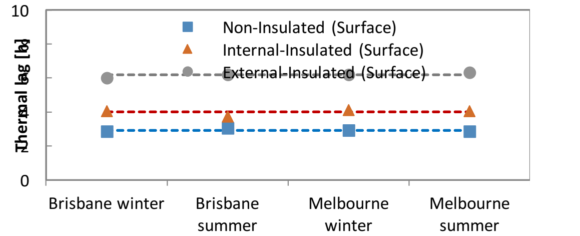
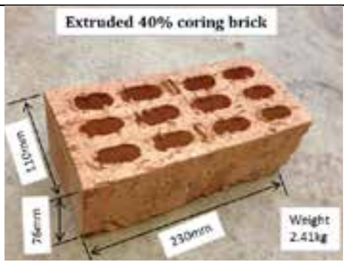
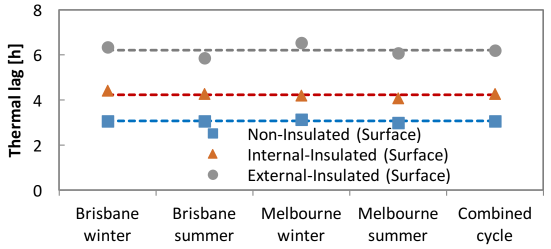
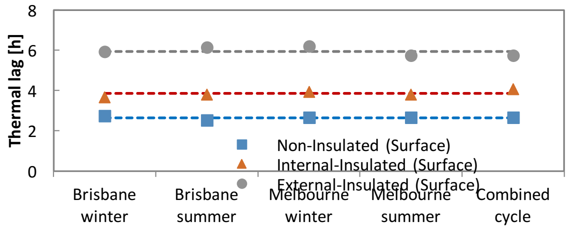
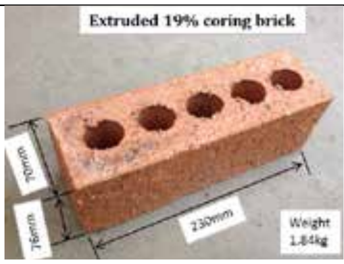
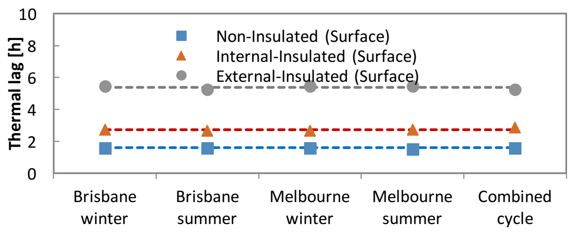
110mm	solid		
	28%		
	40%		
90mm	27%		
70mm	19%		

A5: Thermal Lag with Season

Thickness	Perforation	Detailed Photo	
110mm	solid		
	28%		
	40%		
90mm	27%		
70mm	19%		

Appendix B: Links Between The Dtr Ellipse Characteristics And The Thermal Performance

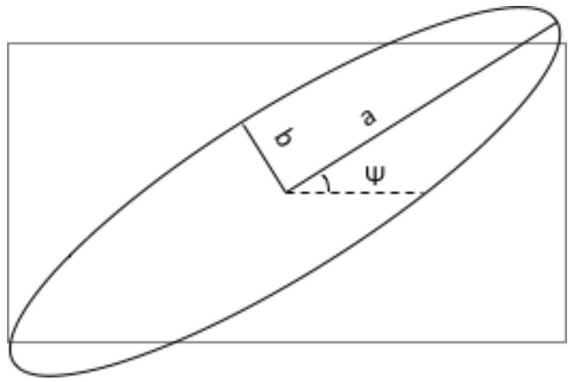
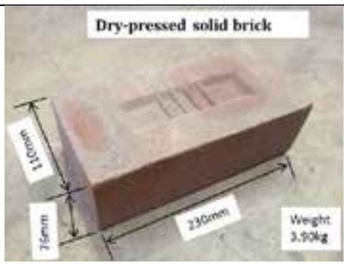
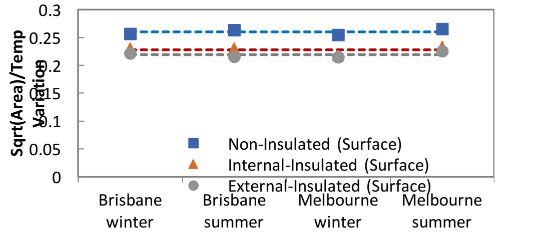
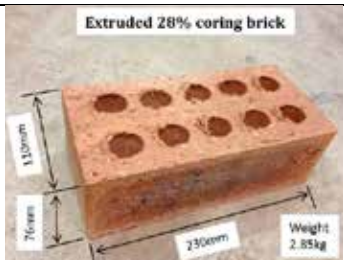
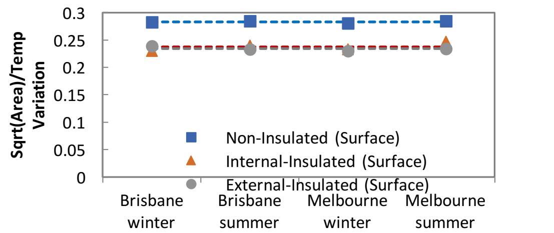
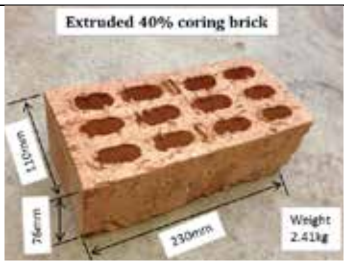
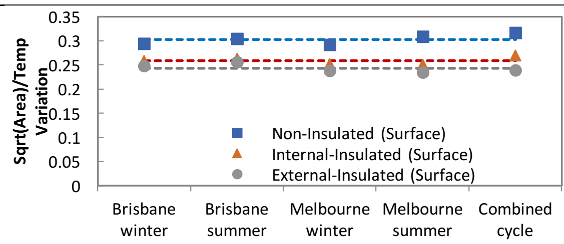
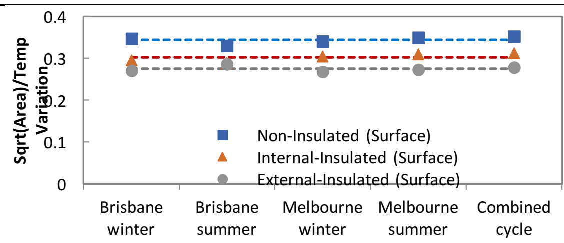
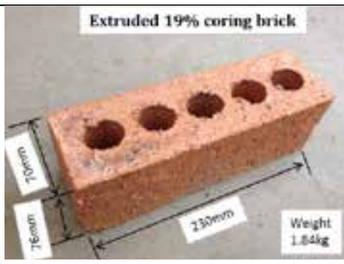
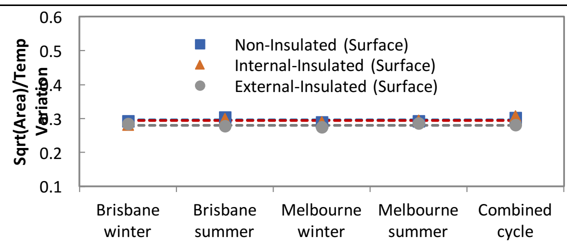


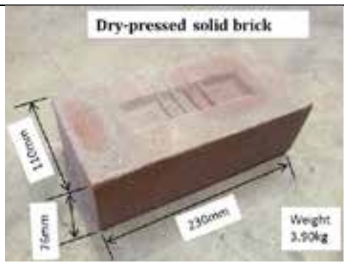
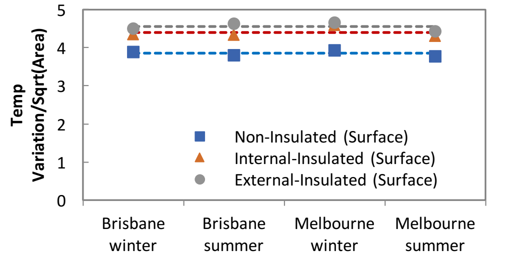
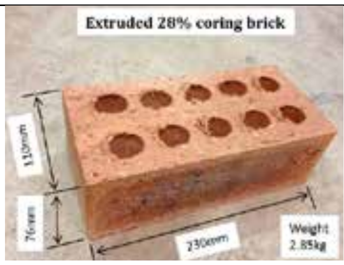
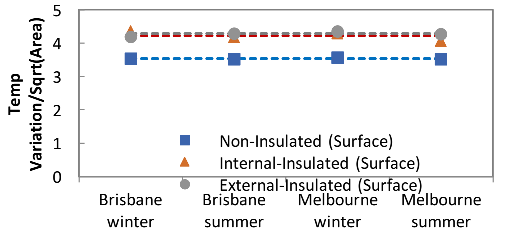
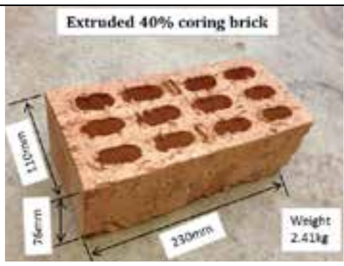
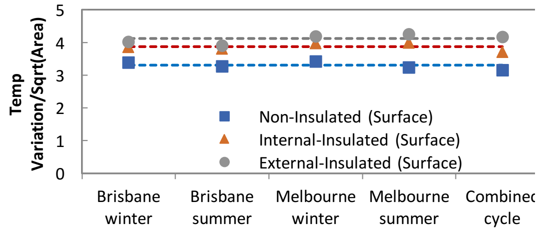
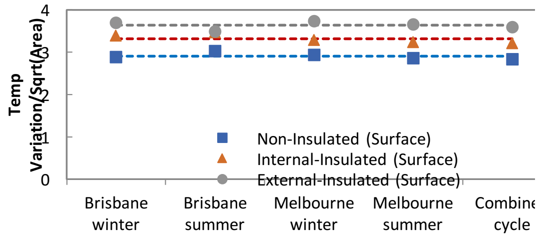
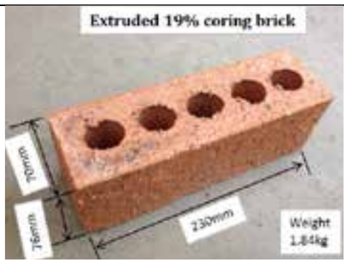
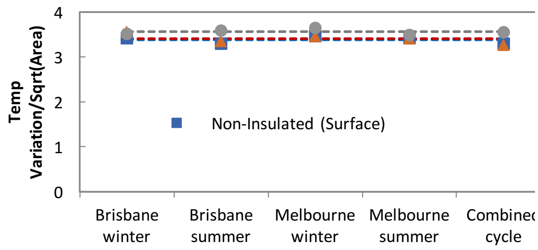
Figure B1: Elliptical shape.

As described in Chapter 8, the relationships between the thermal response ellipse and various observed thermal performance characteristics have been sought (the properties of the typical ellipse are described by the parameters shown in Figure B1). The following tables present the outcomes of that study for the various walling types.

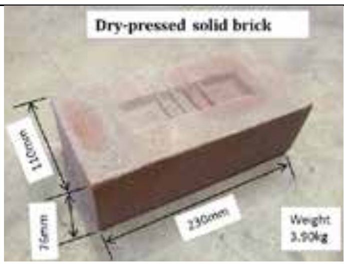
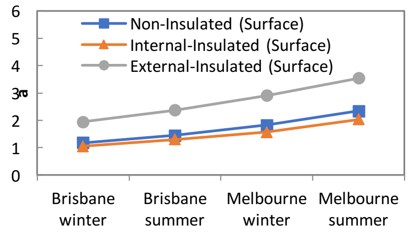
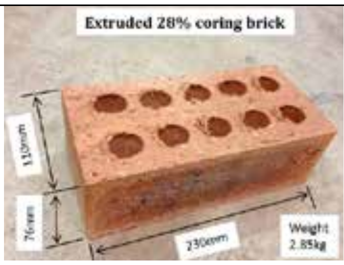
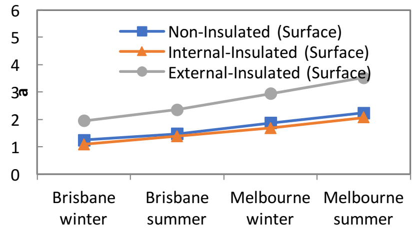
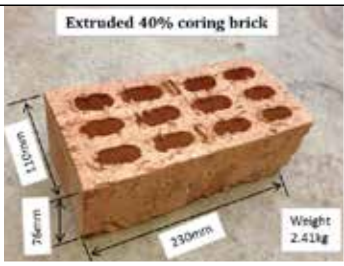
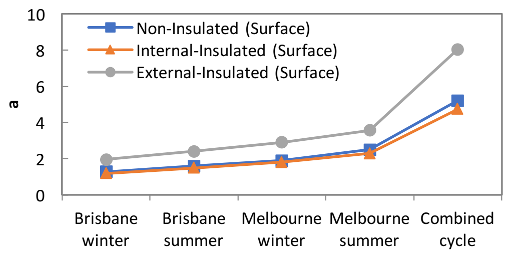
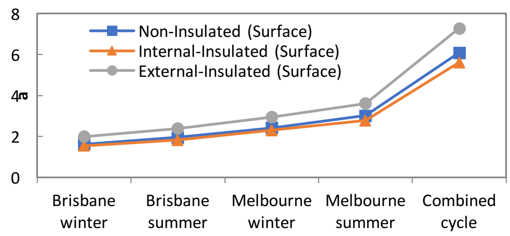
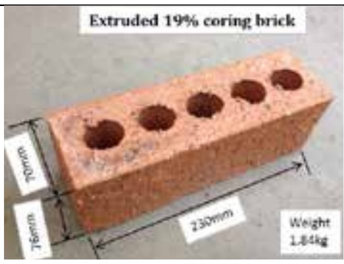
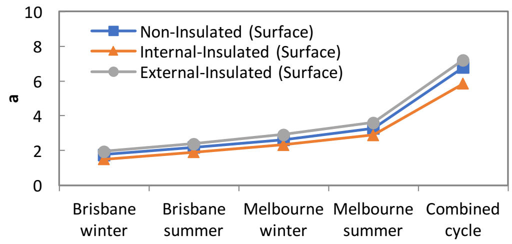
B1: Sqrt(Area)/external temperature variation (test cycles)

Thickness	Perforation	Detailed Photo	
110mm	solid		
	28%		
	40%		
90mm	27%		
70mm	19%		

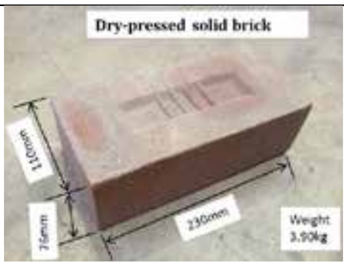
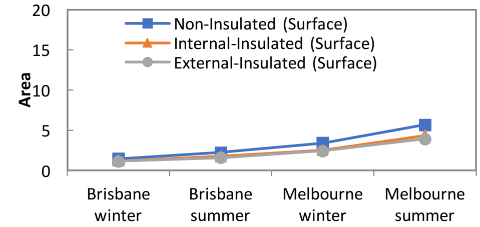
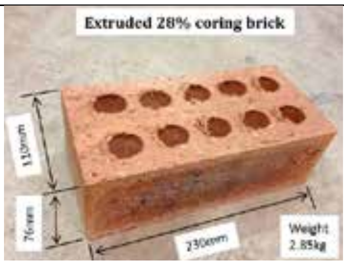
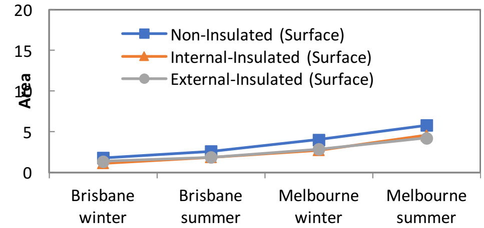
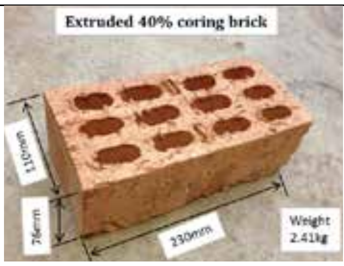
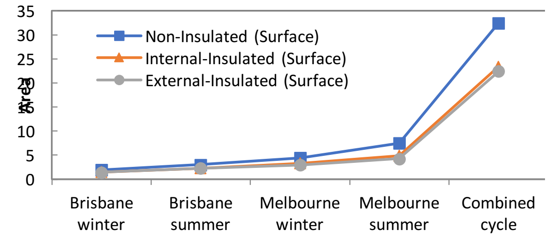
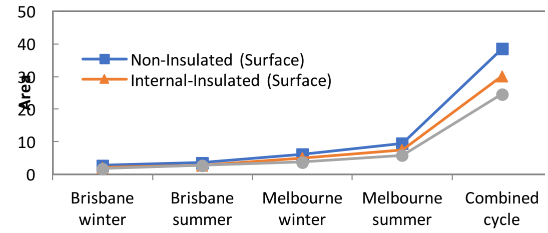
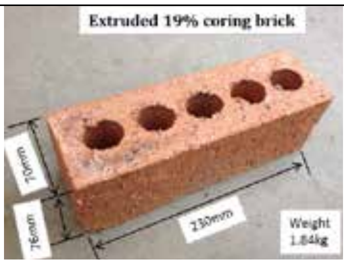
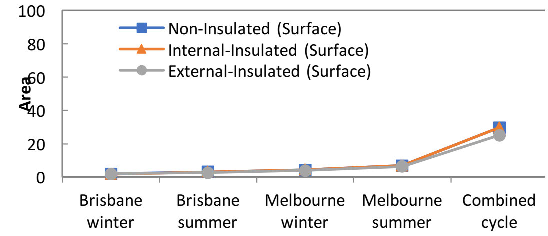
B2: External temperature variation (test cycles)/ Sqrt(Area)

Thickness	Perforation	Detailed Photo	
110mm	solid		
	28%		
	40%		
90m	27%		
70mm	19%		

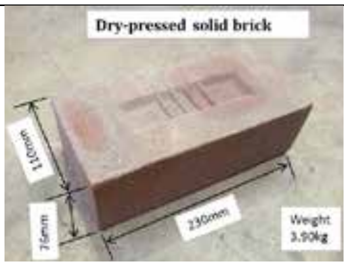
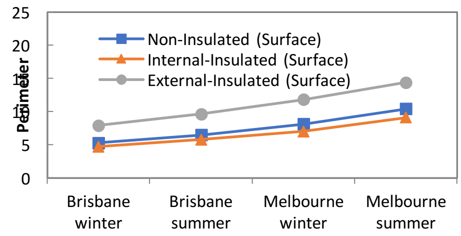
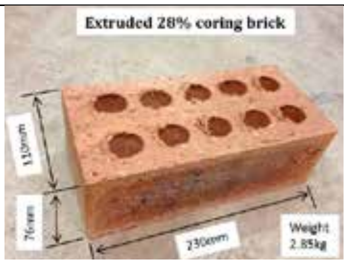
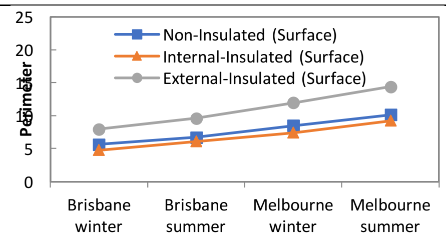
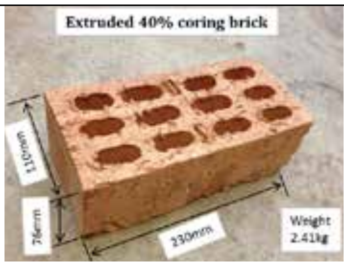
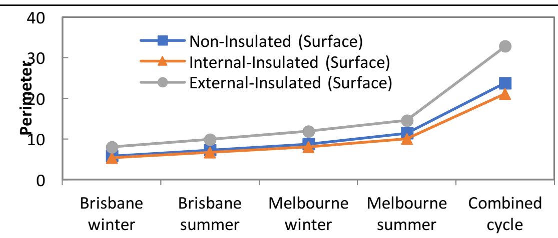
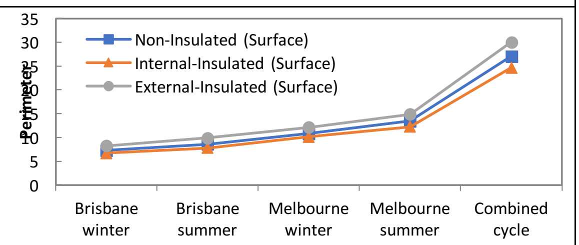
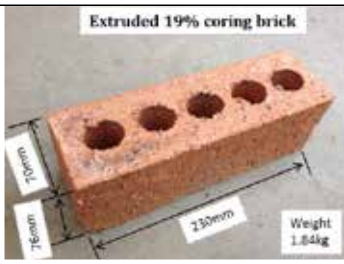
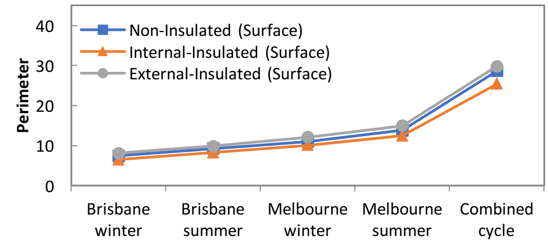
B3: Major axis a

Thickness	Perforation	Detailed Photo	Major axis a
110mm	solid		
	28%		
	40%		
90mm	27%		
70mm	19%		

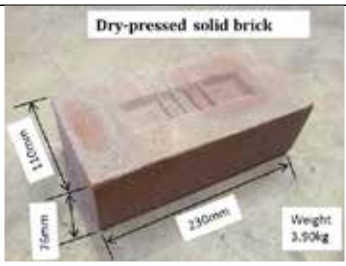
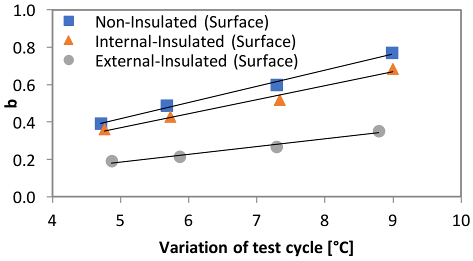
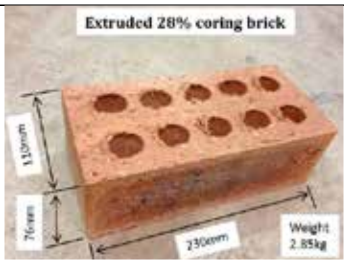
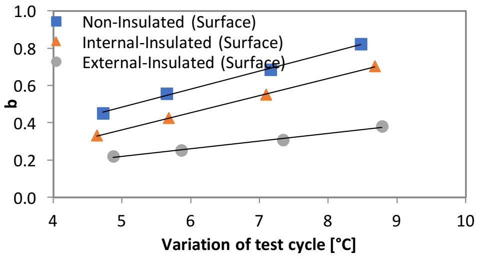
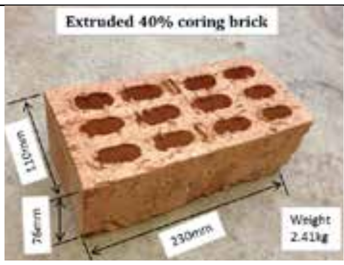
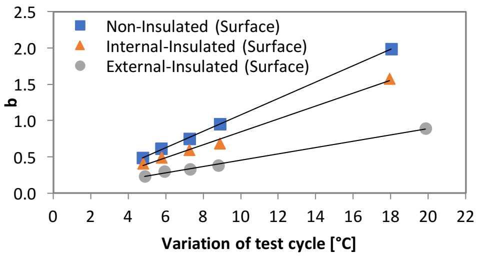
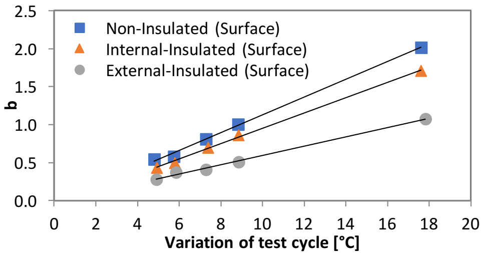
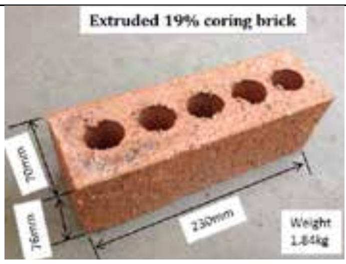
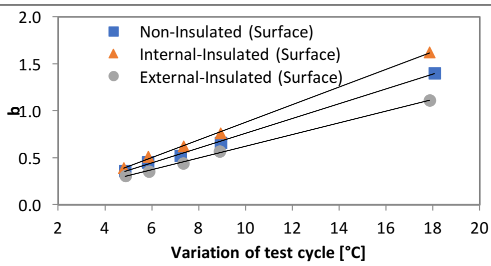
B4: Area

Thickness	Perforation	Detailed Photo	
110mm	solid		
	28%		
	40%		
90mm	27%		
70mm	19%		

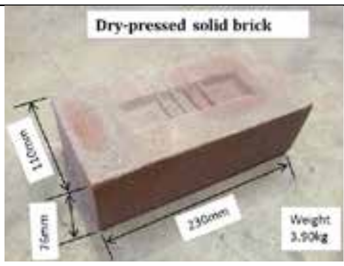
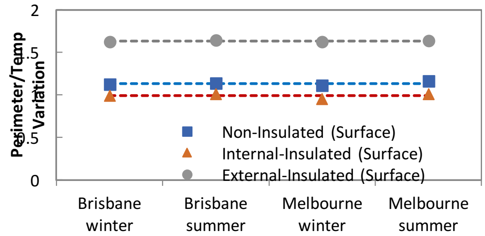
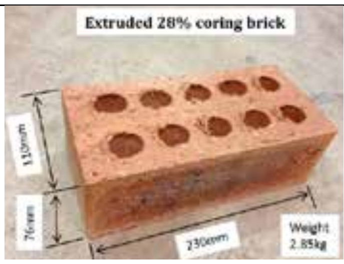
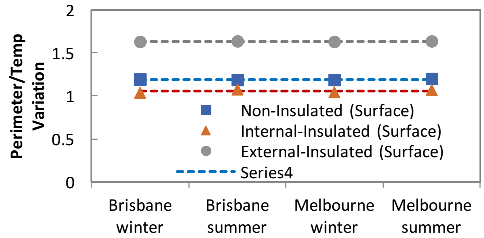
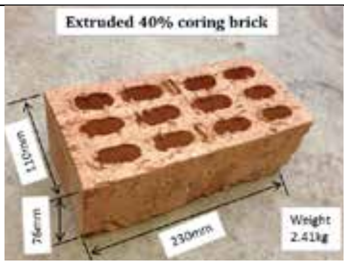
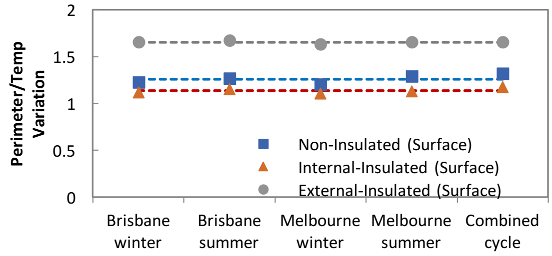
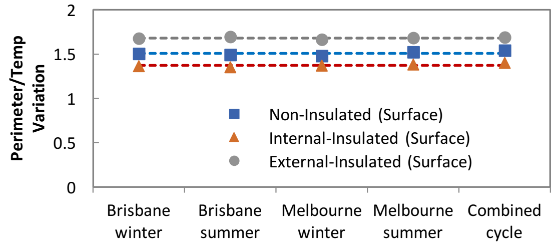
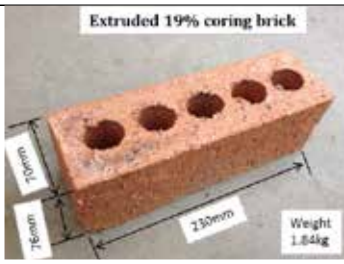
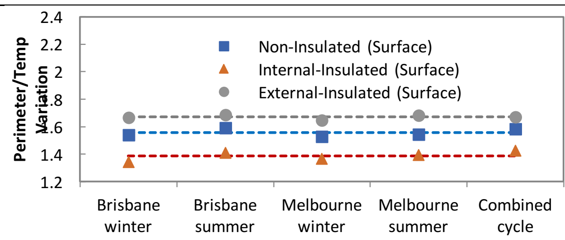
B5: Perimeter

Thickness	Perforation	Detailed Photo	
110mm	solid		
	28%		
	40%		
90mm	27%		
70mm	19%		

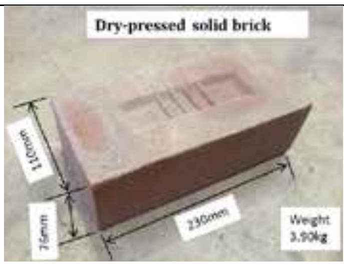
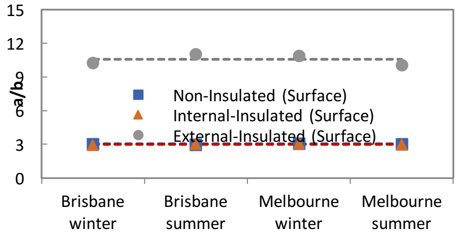
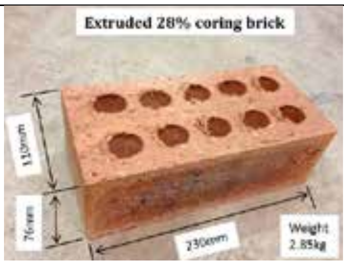
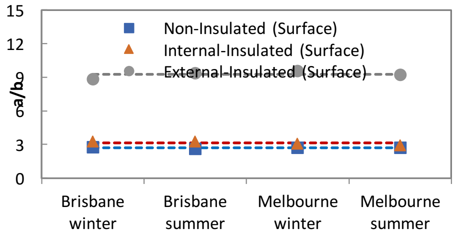
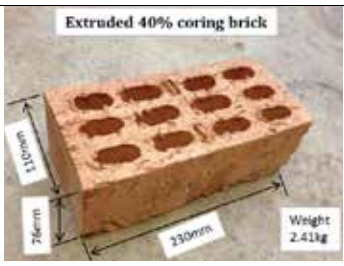
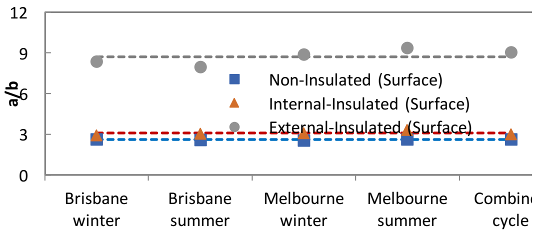
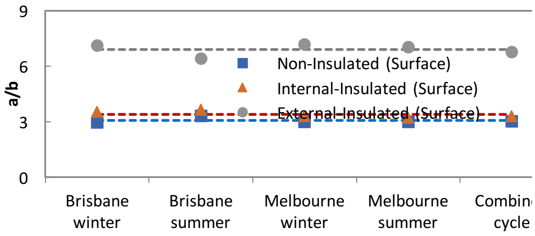
B6: Minor axis (b) vs. external temperature variation (test cycles)

Thickness	Perforation	Detailed Photo	
110mm	solid		
	28%		
	40%		
90mm	27%		
70mm	19%		

B7: Perimeter/external temperature variation (test cycles)

Thickness	Perforation	Detailed Photo	
110mm	solid		
	28%		
	40%		
90mm	27%		
70mm	19%		

B8: a/b

Thickness	Perforation	Detailed Photo	
110mm	solid		
	28%		
	40%		
90mm	27%		
70mm	19%