IMPACT OF INSULATION ON THE THERMAL PERFORMANCE OF HEAVY WALLING SYSTEMS SUBJECTED TO DYNAMIC TEMPERATURE CYCLES

Dariusz Alterman[1], Adrian W. Page[2], Behdad Moghtaderi[3] and Jared Robinson[4]
[1] Research Fellow, The University of Newcastle, Priority Research Centre For Energy, NSW, 2308, Australia
dariusz.alterman@newcastle.edu.au
[2] Professor Emeritus, The University of Newcastle, Priority Research Centre For Energy, NSW, 2308, Australia
adrian.page@newcastle.edu.au
[3] Professor, The University of Newcastle, Priority Research Centre For Energy, NSW, 2308, Australia
behdad.moghtaderi@newcastle.edu.au
[4] Undergraduate Student, The University of Newcastle, Discipline of Civil Engineering , NSW, 2308, Australia
jared.robinson@uon.edu.au

ABSTRACT
This paper describes an experimental investigation of the heat flow mechanisms for plain and insulated heavy walling systems exposed to dynamic heating and cooling cycles. Current Australian housing thermal design practice emphasizes the importance of thermal resistance (R-value) and thermal conductivity. However, these are only steady-state parameters and inadequate as the sole descriptors of the thermal performance of walling systems under changing conditions throughout a day, month or seasons.

A novel method for the testing of building materials under dynamic conditions is under development at the University of Newcastle to overcome a shortage of data on the performance of various materials when exposed to dynamic heating and cooling cycles, and in particular, to obtain the optimum combination of thermal resistance and thermal mass in a walling system. This paper describes preliminary tests performed on plain and insulated heavy walling panels to provide more realistic data on the response of wall components when exposed to typical temperature fluctuations. For convenience in the initial tests, plain concrete panels with varying degrees of insulation were used as an extreme example of heavy walling. These are being followed by a series of tests on masonry walls with varying combinations of thermal resistance and thermal mass. The three construction combinations tested as part of the preliminary study were a plain concrete panel, and a concrete panel with internal and then external insulation. A modified Guarded Hot Box Apparatus was used to expose the three wall configurations to sinusoidal temperature cycles, representing a typical moderate Australian climate, with temperature changes and heat flux profiles monitored across each wall. The findings directly relate to masonry construction and indicate that energy demands for moderate weather conditions are more efficient if an appropriate combination of both thermal mass and thermal resistance is used, especially if passive solar design principles can be utilized.

KEYWORDS: thermal performance, thermal mass, thermal resistance, passive solar design principles, housing

INTRODUCTION

In building design, the material selection has a major influence on the potential performance and energy consumption over its life cycle. The increasing emphasis on energy efficiency and the need to reduce carbon emissions is increasing the focus on novel design solutions for all buildings. Designing for energy conservation requires consideration of all of the factors that affect energy consumption and presents major challenges for builders and architects to deliver designs that are functional whilst also energy efficient. Over the years Australian houses have also become larger with increased numbers of appliances and reliance on artificial means of heating and cooling to create comfortable interior conditions with the little emphasis on energy efficiency and environmental impact.

A minimum standard for energy efficiency of new dwellings in Australia was included in the Building Code Australia (BCA) in 2003. Since then, numerous computer software packages have been developed to assess the energy efficiency of dwellings such as the Nation Wide House Rating Scheme (NatHERS), AccuRate and FirstRate. The energy efficiency rating takes into account building location, climate, surrounding environment, materials used in construction, natural lighting, passive heating and cooling to determine the suitability of a building. The accuracy of these computer models is directly dependant on experimental data collected from in-situ testing and the assumptions used in defining the thermal steady-state material parameters.

The current regulatory climate now requires all housing to be assessed for energy performance. There is thus a need to establish the thermal characteristics of the typical walling systems in the range of Australian climates under all seasonal conditions. In this context, researchers at the University of Newcastle, in collaboration with Think Brick Australia, are involved in a major study of the thermal performance of Australian housing with a view to utilising more effectively the benefits of thermal mass which is inherent in masonry heavy walling systems. This 10 year study has involved the testing of a range of walling systems in a guarded hot box apparatus to obtain their thermal resistance (R-value), as well as the continuous monitoring of the thermal performance of four full scale housing test modules on the University of Newcastle campus incorporating a range of walling systems. A detailed report of the first eight years of the study has been published recently [1]. One of the key conclusions from the study was that for all walling types (cavity brick, brick veneer, reverse brick veneer and lightweight construction) the thermal performance of the modules did not correlate directly with the wall R-value, with the thermal mass and thermal resistance both playing a significant role.

As a result of the above findings, the study has now been extended in a major new project aimed at developing a suitable parameter (or parameters) which will more realistically define the contribution of walls with various combinations of thermal mass and thermal resistance to the performance of buildings subjected to a dynamic temperature environment. Based on the earlier data, some initial postulates have been produced [2], and the current research involves the more formal development of that theory. In the initial stages, a series of tests on walls with varying combinations of thermal mass and resistance subjected to a varying temperature cycle are being performed in a modified hot box apparatus. As an extreme example of thermal mass, a solid concrete panel has been used in the first tests, with varying amounts of insulation (a polystyrene sheet) being used on the internal or external face. These tests are then being extended to include various masonry insulation combinations. A series of temperature cycles are being used to cover a range of summer and winter conditions. The detailed performance of the concrete panels under a typical summer cycle is presented in this paper, together with the design implications for various types of masonry walling systems.

OVERVIEW OF THERMAL MASS AND PASSIVE SOLAR DESIGN PRINCIPLES

Thermal mass is the ability of a particular material to absorb and store thermal energy. Through effective design, heat energy can be stored using the thermal mass of the material. This stored energy can then be released appropriately to assist in the heating or cooling of the building, under both hot and cold weather conditions

The use of thermal mass is not a recent innovation. For example, studies have shown that the Ancient Romans utilized the thermal mass concept in the design of their buildings and heating systems. Ancient astronomers observed and tracked the path of the sun and this information was implemented into building design to effectively use the energy provided from it. Structures built from stone, earth, clay bricks, mud brick and logs all have good thermal mass and are common in early home construction around the world. With the advent of electricity and cheap sources of energy from burning fossil fuels, less emphasis was placed on utilizing the thermal mass of materials for heating and cooling. As the cost of traditional housing materials and construction increased, cheaper construction methods also emerged. These included the use of lightweight insulated structures where the expense of artificial heating or cooling was placed on the occupant. With the recent increase in energy costs and emphasis on sustainable design, there is now a renewed emphasis on the design of energy efficient structures that utilise thermal mass and reduce energy consumption whilst maintaining a desired level of performance.

Through correct design and implementation of passive solar design into a structure it is possible to stabilize the interior air temperature with lower fluctuations compared to the exterior. This is illustrated in Figure 1 which shows typical temperature fluctuations for housing modules constructed from heavy (masonry) and lightweight materials when subject to a dynamic heat and cooling temperature cycle [1]. It can be seen from Figure 1 that with increased thermal mass the interior temperature fluctuations reduce significantly. Reducing the fluctuations within a comfortable level may reduce the need for heating and cooling. The graph also shows how the peak of the internal temperature of the high thermal mass material occurs after the peak of the external temperature (illustrating the concept of “thermal lag”).

Solar passive design principles are used to mobilise the contribution of thermal mass and thermal lag effectively. This requires consideration of a number of interacting factors such as climate (i.e. geographic location), sun and shade data, building layout and orientation, humidity, wind and the effective use of appropriate glazing and insulation. Think Brick Australia has recently produced a user-friendly web based design tool for this purpose called the “Climate Design Wizard” [3]

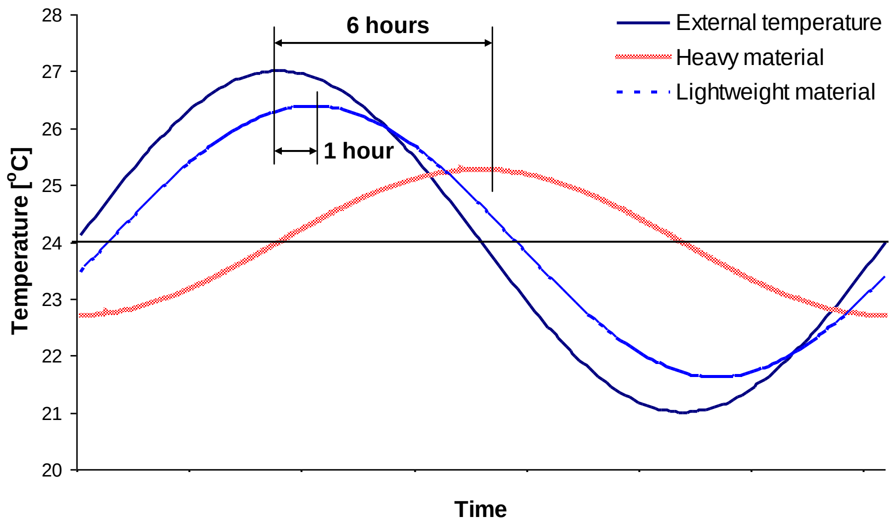

Figure 1: Thermal lag comparison and temperature fluctuations for a high and low thermal mass walling systems

A material property known as "heat capacity" or "thermal capacity" plays a vital role in the performance of the thermal mass. Heat capacity refers to the amount of energy required to raise the internal temperature of a material by one degree. For a material to have high thermal mass it must also have high density and thermal capacity combined with moderate conductivity. If the thermal conductivity is too high the material will expel all the energy quickly and there will be less benefit as the time lag will be shortened. On the other hand if the conductivity of the material is too low heat energy will be restricted from flowing through it. Masonry has a high thermal mass in comparison to many other modern day building materials. The density of material is a major factor affecting the thermal mass of solids. With increased density the kinetic vibrations can travel across the material delivering the heat energy to the opposite surface.

DYNAMIC VERSUS STEADY STATE CONDITIONS

Over the life cycle of a structure it will be exposed to a variety of climatic conditions. The extremities of the conditions will be heavily reliant on the location of the structure, the time of year and the surrounding environment. Due to the extensive variability of weather conditions in different locations around the world it is necessary to determine suitable building materials for the correct environment. Through cyclic, rather than steady state testing, it is possible to some extent to replicate different seasonal cycles applicable to a particular area and observe the performance of building materials when exposed to those cycles.

Steady-state testing in a guarded hot box is typically used to determine the thermal properties of a material or a walling system. A differential temperature is set across the wall to simulate external air to internal air and the energy supplied to the system is set to remain constant [4, 5]. The energy and temperature across the wall is observed for a set period (typically four hours). A constant heat flow gradient develops and thermal properties of the material and its R-value can be calculated. Extensive steady state testing has been completed for a range of walling systems at the University of Newcastle [1] and the R-values and thermal conductivity have been calculated. R-value is a numerical representation of how well a material will restrict heat energy flowing through it. The R-value in general is the ratio of the temperature difference across the material and the heat flux. 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 in a typical structure under a variable temperature environment.

Although a material may have a high R-value, this does not mean it will perform well when exposed to a dynamic temperature cycle. 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 be increased by adding insulation but it is the correct combination of insulation and wall material along with building layout that achieves better results. Lightweight types of walling systems (such as insulated brick veneer) with a high R-value have been shown to be more responsive to the external conditions resulting in larger interior temperature oscillations that a lower R-value heavy construction method (such as cavity brick) [1].

Dynamic cyclic tests performed on walling systems have the potential to provide a more realistic picture of how various materials perform when exposed to the typical temperature fluctuations. By monitoring the temperature and energy flow at various points through the wall information of heat flow and thermal lag can be observed. Cyclic tests will also demonstrate the ability of the material to attenuate the heat flow whilst storing and emitting heat after the exterior temperature begins to reduce. The changing nature of the dynamic cycles does not allow a constant heat flow mechanism to develop in the structure, and it is much more difficult define the performance with a single parameter [2].

The thermal lag is the difference in time between the peak of the external heat cycle and the interior peak temperature. This is illustrated clearly in Figure 1 for high thermal mass and low thermal mass walling systems. The material with high thermal mass (red curve) shows that the interior surface temperature does not peak until 6 hours after the peak of the exterior temperature. This high thermal mass is the typical response of masonry wall construction. 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 low thermal mass construction (blue curve) on the other hand has only a time lag of 1 hour. This is a typical representation of a light weight insulated wall construction (e.g. brick veneer walls). The light weight material has less thermal mass and therefore requires less energy to raise the core temperature. As a result the interior surface temperature of the light weight construction material will be greater than the high thermal mass when exposed to the same external temperature cycle. The response of the low thermal mass construction is more immediate and it adjusts quickly to the exterior heat cycle. By increasing the thermal mass it is possible to decrease the amplitude of the response and reduce the need for heating and cooling of the structure.

DYNAMIC THERMAL RESPONSE TESTING PROCEDURE

An ASTM standard guarded hot box [4] was developed as part of the original investigation [1] to quantify the steady-state thermal behaviour of individual walling systems together with the evaluation of the thermal resistance (R-value). Once the heat transfer resistance metrics were fully established from the guarded hot box tests, the rig was modified to develop a standard laboratory based test for cyclic temperature testing to simulate the dynamic temperature effects in a real structure. This also allowed heat flux attenuation studies to be performed under cyclic (transient) temperature conditions which mimicked day-night temperature variations The modified hot box apparatus is shown schematically in Figure 2a. .

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 as close as possible to the actual conditions, see Figure 2b. Both summer and winter cycles have a minimum to maximum temperature difference of 15°C. Whilst the combined cycle has a minimum to maximum temperature difference of 25°C. The temperature values are the average day/night temperatures experienced in Newcastle, NSW for that particular season whilst the combined cycle incorporates the minimum and maximum from each. The system is also capable of simulating any of the seven Australian climate zones. Only the summer cycle results are reported here.

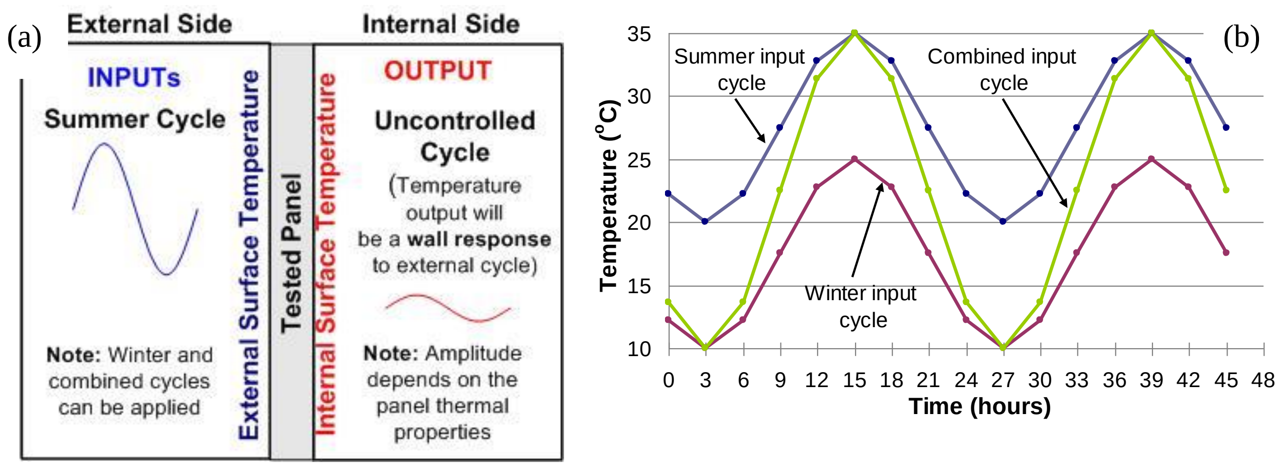

Figure 2: Idealised hot box tests for dynamic thermal performance (a) Adjusted Temperature Cycles (b)

The cyclic results provide useful information on the heat flow attenuation and thermal lag of each individual wall element on a comparative basis for any wall type and demonstrate how the systems perform under the influence of a dynamic input. The previous steady-state results illustrate the ability of a wall to attenuate heat flow and provide information on the nature of the temperature gradients established within each wall. 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.

As the first stage of a systematic set of tests to encompass the various combinations of thermal resistance and thermal mass in a range of walling systems, a solid concrete panel with and without insulation was tested. The panel was 110mm thick solid concrete, 2.4 metres square (with high thermal mass; a mass of 2000kg). The R-value of the panel was 0.09 Km^2/W. A 25mm thick low thermal mass polystyrene panel (with a mass of 4kg) and an R-value of 0.67 Km^2/W was used in the tests to provide insulation as appropriate. The summer temperature cycle shown in Figure 2b was then 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.

Cyclic testing provided feedback on the heat energy transfer through each wall system. Through analysis of results the presence of thermal lag, the influence of thermal mass and effect of insulation can be observed. Relevant graphical representations of the temperature fluctuations were analysed to compare how each construction method performed when exposed to the different temperature cycles. In interpreting the results, for convenience, the internal comfort level has been assumed to lie in the 18 – 24 ^{o} C range. The results shown in Figures 3, 4 and 5 below are for a period approaching the end of the summer cycle.

NON INSULATED WALL

As can be seen from Figure 3, for the plain concrete wall the exterior surface of the concrete reaches a maximum temperature of 29ºC occurring 3.5 hours after the peak exterior temperature of the cycle. The peak temperature of the interior surface is 28.1ºC and this does not occur until 5.5 hours after the peak of the exterior temperature. The peak of the interior surface temperature occurs at exactly the same time that the exterior air temperature drops below the concrete interior surface temperature. The interior air temperature also peaks at this time usually around 27ºC. At 7:30pm the exterior surface temperature of the wall drops below the interior surface temperature. At this point we would expect heat to flow in the reverse direction but is not the case. Heat energy is flowing back towards the exterior but at the same time a small amount is still flowing towards the interior. Because the heat flux does not completely reverse, the heat energy that is being expelled on the exterior is merely energy that has been stored in the concrete mass. The heat energy that has been stored in the mass is released in both directions.

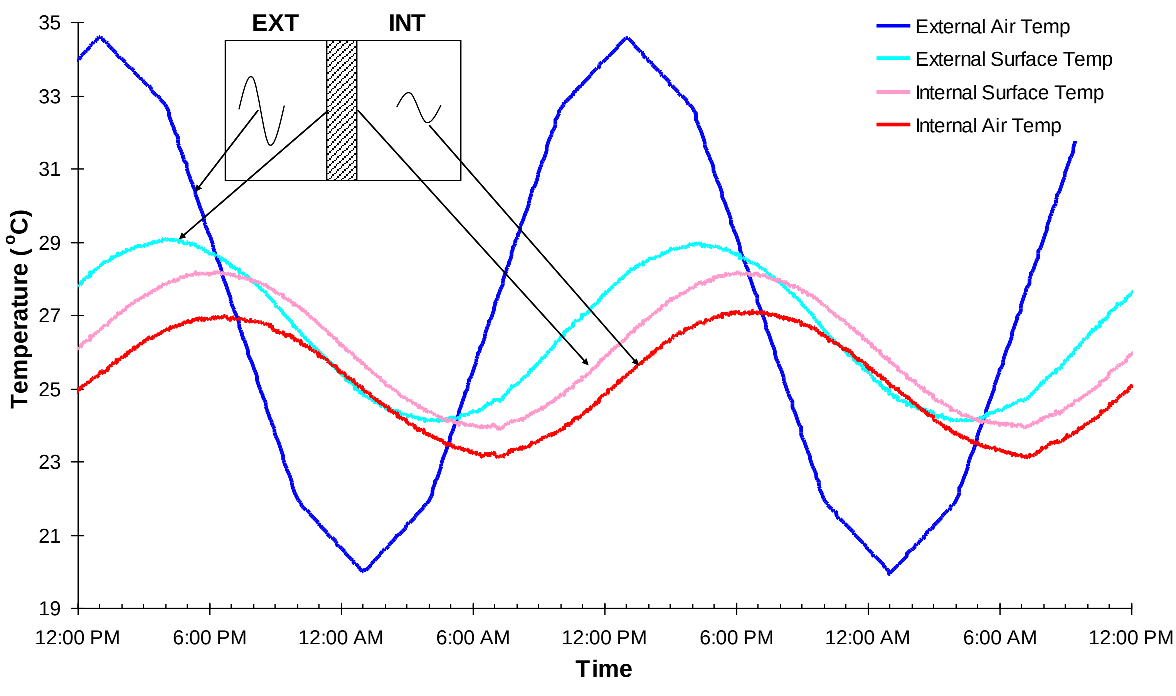

Figure 3: Non Insulated Wall Summer Cycle Temperature Profile

The non-insulated wall provided some resistance from the exterior environment. The exterior temperature had a peak to trough amplitude of 15ºC and the average interior air temperature was 25.1ºC. During the simulated summer cycle thermal mass provided some resistance to the exterior heat energy by absorbing energy and releasing it back to the external environment during the night. However energy that was stored in the mass was also continuously released into the interior air. This continuous flow forced the interior air temperature to remain high throughout the evening. The interior temperature was consistently above the comfortable temperature range for this season hence cooling would be required continuously during the day night cycle.

WALL WITH INTERNAL INSULATION

With the layer of insulation on the side corresponding to the interior face of the wall, the exterior concrete surface reacts in a similar manner to the non-insulated panel as there is the same exposure to the summer cycle. The external surface temperature peaks at 29.2ºC, 3.5 hours after the peak of the summer cycle. The peak temperature of the interior surface of the concrete wall is 28.7ºC occurring 5.5 hours after the peak of the exterior temperature cycle. There was only a 1-2mm gap between the interior concrete surface and the exterior insulation surface and temperature profiles of each therefore follow a similar trend. The outside of the insulation surface was slightly warmer than the adjacent concrete surface between 5:00pm and 8:00am.

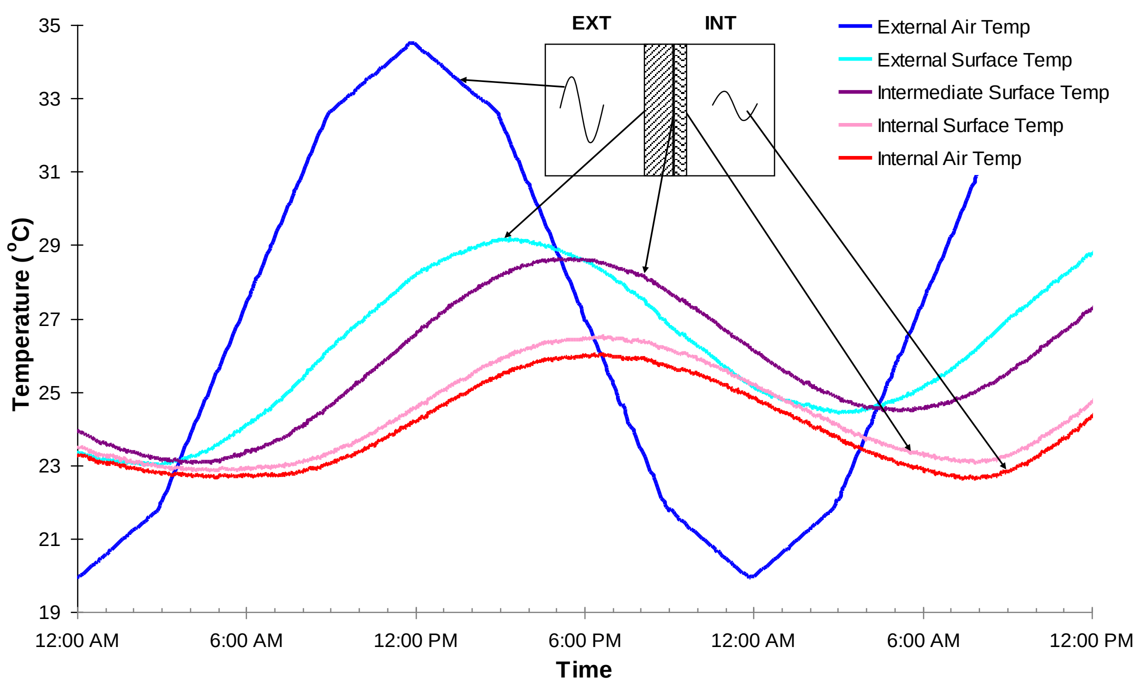

Figure 4: Internally Insulated Wall Summer Cycle Temperature Profile

The interior insulation decreases the internal air fluctuation range to 3.5ºC from minimum to maximum for the summer cycle. This is slightly less than for the non-insulated wall. This wall configuration was effective for the summer cycle as it allowed the thermal mass to expel heat during the night whilst receiving enough energy during the day to prevent the temperature dropping excessively. The average interior temperature was found to be 24.4ºC, which is slightly higher than the comfortable level. The early morning periods provided a temperature of 23ºC and during this period no cooling would be required. As the day progressed the increased external temperature began to heat the interior air. Artificial cooling would be necessary from lunch to midnight for this cycle to maintain a comfortable level. The interior insulation provided an average interior air temperature of 20.8ºC this is considered less than comfortable but is an increase on the average for the no-insulated wall. The internal air temperature naturally reaches 22.5ºC in the early evening.

WALL WITH EXTERNAL INSULATION

With the insulation layer on the "external" face of the wall, the exterior surface temperature of the insulation reaches a maximum temperature of 33.9ºC. Considering the exterior air temperature reached a maximum of 34.6ºC the surface of the insulation is extremely warm. The exterior surface of the insulation peaks 0.25 hours after the peak of the external temperature. The peak temperature on the interior surface of the insulation panel is 27ºC which occurs 0.5 hours after the peak of the external cycle. The insulation panel reduced the temperature by 6.9ºC. This temperature gradient across the insulation is significant but the panel has had little effect on the thermal lag to the interior surface. Since the concrete wall is receiving a reduced energy exposure from the external summer cycle, the temperature oscillation is between 24-25ºC.

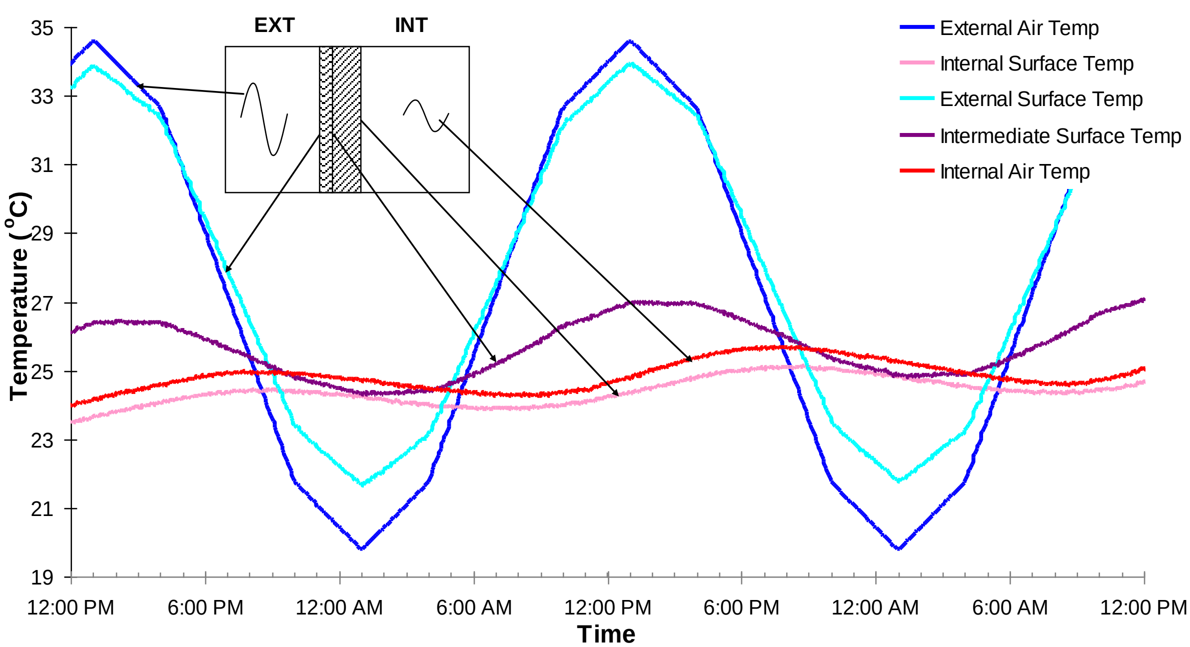

Figure 5: Externally Insulated Wall Summer Cycle Temperature Profile

The exterior insulation arrangement was the most efficient in reducing the interior temperature fluctuations. The interior air temperature fluctuation was only 1.5ºC for all cycles tested. 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 1ºC difference between the external temperature cycles. The average interior air temperature for the summer cycle is 24.1ºC which is slightly above the assumed comfort level.

IMPLICATIONS FOR MASONRY WALLING SYSTEMS

This preliminary study applying the dynamic external conditions for the concrete panel with/without insulation layer also provides information on how heavy walling systems such as masonry respond to cyclic weather conditions, absorbing and realising heat. The thermal behaviour of the concrete panel with an internal insulation layer will be similar to that of an insulated brick veneer walling system. The interior insulation slightly increased the thermal lag of the wall system. However, the heat energy penetrated through to the "interior" air and the insulation provided a barrier that made it hard for this energy flow to reverse and flow back to the exterior. It also indicates that for an insulated brick veneer house with a large proportion of the energy coming through the windows and raising the internal air temperature, further energy will 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 reverse brick veneer construction, 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 masonry.

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 (as presented here in Figure 3 for the concrete panel without insulation). The insulation layer attached to the heavy internal skin, as in Figure 5, 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.

A cavity brick walling system without insulation but with an air gap between two brick skins will also be tested but the overall thermal performance can be postulated from the mechanisms observed for the single layer concrete wall, shown in Figure 3. 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.

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 position of an insulation layer for the masonry walling systems. A 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. 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.

CONCLUSIONS

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 testing shown that performance of each varies. The best thermal performance was achieved for the panel with external insulation layer, the same as an insulated reverse brick veneer module what has been already observed for the real-scale test modules [1].

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. Once fully developed, such a comprehensive method (and further a metric, [5]) has the potential to improve the accuracy and effectiveness of current energy efficiency measures and ultimately lead to more thermally efficient house designs. This paper has described the first series of tests in this process which has focussed on a high thermal mass walling systems with and without insulation.

ACKNOWLEDGEMENTS
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