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THE INFLUENCE OF WALL PROPERTIES ON THE THERMAL PERFORMANCE OF AUSTRALIAN HOUSING

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ABSTRACT

Over the past seven years, in collaboration with Think Brick Australia, researchers from the Centre for Energy at the University of Newcastle have been involved in a wide range of experimental and analytical activities studying the thermal performance of various walling systems commonly used in Australian housing. This collaboration between the Masonry Research Group in Civil engineering and researchers from Chemical Engineering has involved guarded hot box tests and the construction and extensive monitoring of the performance of four, full scale purpose built housing test modules incorporating typical walling systems - cavity brick, insulated brick veneer, insulated cavity brick and insulated lightweight construction. This paper is concerned with a critical examination of the wall thermal resistance (R value) and its impact on thermal performance. Twelve months of experimental results are presented and used to explore the difference in thermal behaviour of the modules incorporating the four walling types. It is shown that the wall thermal resistance is not the only factor influencing the thermal performance, indicating a potential deficiency in the current Australian building regulations which assume that the thermal resistance (R) value of the wall to be the principal design parameter influencing thermal performance.

KEYWORDS: thermal performance; housing; walling; energy.

INTRODUCTION

Energy efficiency in housing has become a major issue in Australia with a ‘star rating’ scheme being applicable for all new housing. Failure to meet minimum criteria requires changes to the building design or fabric. To provide input into this regulatory framework, the University of Newcastle, in conjunction with Think Brick Australia and the Australian Research Council (ARC) has embarked on an extensive research program to study the thermal performance of various forms of masonry construction under Australian climatic conditions [1-3].

The project is in its eighth year and consists of: the construction of a guarded hot box apparatus (GHB) to determine the thermal resistance (R-value) of full-scale wall assemblies; the construction and instrumentation of four purpose built housing modules to study thermal performance; and the development of simulation software to model the thermal performance of buildings, with the experimental data collected from the modules being used for validation purposes. Secondary aspects of the program also involve the study of the thermal performance of various roofing systems and the development of strategies for the most effective use of thermal mass.

This paper focuses on a study of the thermal comfort achieved within each of the experimental housing modules constructed from four different walling systems having a range of R-values and thermal mass: cavity brick; insulated brick veneer; insulated cavity brick and insulated 'lightweight' construction. The analysis focuses on the observed internal air space temperature under 'free-floating' conditions, with the buildings assumed to be comfortable when the internal air space temperature lies in the 18-24ºC range. Whilst it is recognised that thermal comfort is also influenced by other factors such as humidity, radiant energy, air speed and individual preferences [4], these variables have not been considered in this study of the relative performance of the four modules under real world conditions. The results clearly show that the R-value of the walling system is only one of the factors governing thermal performance, as different performance was observed for modules with similar R-values but different walling systems. It is also demonstrated that wall systems incorporating thermal mass and insulation can improve the thermal comfort within a 'passive' structure.

OVERVIEW OF EXPERIMENTAL INVESTIGATION

The investigation involved the study of the performance of various walling systems commonly used in Australian housing. The strategy was to determine the thermal resistance (R-value) of each walling system as an isolated element using an in-house Guarded Hot Box Apparatus, and then to incorporate that walling into a representative housing module to allow its performance in a complete building system to be studied.

Walling Systems

Four walling systems typical of Australian housing were investigated:

Conventional Cavity Brick (CB): 110mm external brickwork skin; 50mm air cavity; 110mm internal skin finished with 10mm internal render.

Insulated Brick Veneer (Ins.BV): 110mm external brickwork skin; 50mm air cavity with wall-wrap membrane and pine frame/10mm plasterboard internal skin.; R1.5 bulk insulation batts incorporated between the studs of the internal skin on the cavity side of the plasterboard.

Insulated Cavity Brick (Ins.CB): 110mm external brickwork skin; 50mm air cavity with R1 rigid polystyrene insulation fixed to the interior surface of the internal masonry skin within the cavity.; internal brickwork skin finished with 10mm cement render.

Insulated Lightweight construction (LW): external skin of polymer render over 7mm fibro-cement sheeting fixed to an internal pine stud frame; 10mm plasterboard on the internal surface of the frame; breathable membrane fixed onto the pine stud frame immediately behind the external sheeting, with R1.5 bulk insulation batts incorporated between the studs.

Guarded Hot Box Apparatus

The guarded hot box facility (GHB) measures the thermal resistance (R-value) or conductance of walling elements by establishing a steady-state temperature gradient across the wall whilst measuring the energy flow through the wall. An in-house facility conforming to ASTM C 1363–97 ‘Standard Method for Steady-State Thermal Performance of Building Assemblies by Means of a Hot Box’ [5] was developed and used to obtain the R value of each of the four wall types used 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 (expressed in SI units) obtained for an Δ18ºC temperature differential (air to air across each wall thickness) are shown in Table 1.

Table 1: R-values of Module Walling Systems

Walling System	R-value m^2K/W (surface to surface)	R-value m^2K/W (air to air) *
Cavity brick	0.44	0.62
Insulated brick veneer	1.58	1.72
Insulated cavity brick	1.30	1.48
Insulated Lightweight	1.51	1.69

* air film values from AS4859.1 [6]: 0.04 external; 0.14 internal

Housing Modules

The principal aim of the tests on the Thermal Test Modules was to provide qualitative and quantitative data on the thermal performance of various walling systems under local climatic conditions. The modules were comparable in size to other buildings used in similar studies overseas [7,8]. Four modules were constructed. The modules had a square floor plan of 6 m x 6 m and were spaced 7 m apart to avoid shading and minimise wind obstruction. With the exception of the walls and roof, the buildings were of identical construction, being built on a concrete slab-on-ground and aligned in a manner so that the north wall of the building was perpendicular to astronomical north. The modules are located on the University of Newcastle campus in suburban Newcastle (Newcastle is on the east coast of Australia, latitude 33 degrees south).

Timber trusses were used to support the roof which consisted of tiles or metal sheeting material placed over a layer of sarking. The buildings had ceiling height of 2450 mm. The ceiling consisted of 10mm thick plasterboard with glasswool insulation bats (R 3.5 $m^2.K.W^{-1}$) placed between the rafters to minimise the “through-ceiling” heat flow. The response of the modules was observed with the interior being either in a ‘free-floating’ state (where the response of the module was influenced by the weather conditions and the recent thermal history), or with the module heated or cooled to maintain the interior temperature within the range of 18^0C to 24^0C. In this case, the heating/cooling energy requirements for the module were measured.

The initial series of tests were performed on windowless modules with the emphasis on the performance of the walling systems themselves. Subsequent tests included the insertion of a major opening on the northern wall of each module, as well as the inclusion of some internal walls and floor coverings to more accurately reflect the situation in an actual dwelling. An adjustable curtain was also fitted to the opening in each module to allow this effect also to be studied. The modules are shown in Figure 1. The tests reported here include the effects of the major opening, with each module contained a north-facing 3-panel sliding door assembly, 2050 mm high x 2840 mm wide, representing ≈20% of the floor area which is typical of a living room window/floor area ratio. The door consisted of clear, 6.38 mm laminated glass, set in a light coloured aluminium frame. The purpose of the opening was to allow solar ingress to the modules. The opening was also used for ventilation purposes in some cases.

Internal Walls

The initial module tests were performed with external walls only. Subsequently, to assess the influence of internal walls on the system performance, internal walls were provided to each module consistent with the form of construction. In each case the internal walls consisted of two "L" shaped walls in plan, 2m x 1m long x 2.3m high located centrally in each module. For the cavity brick and insulated cavity brick modules, these walls were constructed from conventional 110 mm thick brick masonry; for the insulated brick veneer and lightweight modules, the walls were constructed as typical 90 mm internal timber-plasterboard stud walls. The relative proportion of internal to external walls for all modules was therefore consistent.

Venting and Other Effects

The bulk of the tests for each module were performed with the window and access door shut. However, to assess the effects of artificially venting the structure, for some limited periods of time the window and access door were opened to allow the free ingress of external air. Most of this ventilation was carried out at night in the warmer periods to facilitate the removal of heat from the heavy walls and slabs. Ventilation, during day and night, was also used on short occasions. Prior to the end of the period reported in this paper, carpet was also laid on the floor of each module to more realistically represent the influence of slab thermal mass and the heat flows that would occur into and out of the floor. The periods for which venting occurred and when the carpet was present are shown in Table 2. It is important to note that identical procedures were used at the same time for all four modules, thus allowing direct comparison of their performance for any given module set up.

INSTRUMENTATION OF MODULES

The 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. In total, 105 data channels were scanned and logged every 5 minutes for each of the modules all year round. 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. These sensors were ultra-thin and measure 100x100mm. Thermocouples were placed on the surface of the slab at various locations between the window and the centre of the room. For the window, three net radiation sensors were placed at different heights along the glass panel to assess the incoming/outgoing radiation. These sensors were suspended 100 mm away from the glass surface and had a spectral range of λ=0.3 to 20 μm. The surface temperature of the glass was recorded and additional heat flux sensors were placed on the aluminium frame to assess the influence of the frame itself. Internal air space temperatures were monitored at three heights, 600, 1200 and 1800 mm with the relative humidity and globe temperatures being measured at mid-height.

Figure 1: Housing Test Modules (with opening in north wall), (a) Insulated Brick Veneer (b) Insulated Cavity Brick (c) Cavity Brick and (d) Insulated Lightweight

TESTING PROGRAM

The testing program for the modules has had several phases, with a range of variables such as wall type, roof type, major window openings, internal floor coverings, internal walls and ventilation being considered. Some results have already been reported [1-3]. The data discussed and analysed in this paper relates to the tests performed on the four modules with the major opening in the northern wall and with the internal walls in each module in place. For purposes of comparison, data for a period between 16th of May 2007 to 17th of May 2008 has been selected. This period encompassed 'free floating' conditions with and without ventilation as well as all seasonal conditions. Table 2 summarises the range and conditions for the tests included in the present analysis.

ANALYSIS OF RESULTS

As previously described, readings from 105 data points for each module were recorded every 5 minutes, 24 hours per day all year round. The data was downloaded on a weekly basis and imported into MS-Excel. Due to the large volume of data and transient nature of the external

Table 2: Chronology of Tests

Date	Test	Comments*
17/05/07 – 25/05/07	Free Floating	
26/05/07 – 12/08/07	Free-floating	Curtains open 6am, close 5pm
13/08/07 – 25/10/07	Controlled	Curtains open 6am, close 5pm
26/10/07 – 13/11/07	Free-floating	
13/11/07 – 19/11/07	Free-floating with night-time venting	Doors and curtains closed 8am,Door and curtains opened 5pm
19/11/07 – 30/01/08	Free-floating	Curtains and doors closed
30/01/08 – 11/02/08	Free-floating with night-time venting	Doors and curtains closed 8am,Door and curtains opened 5pm
11/02/08 – 22/02/08	Free-floating	Curtains Closed
22/02/08 – 14/03/08	Free-floating with night-time venting	Doors and curtains closed 8am,Door and curtains opened 5pm
16/03/08 – 4/04/08	Controlled - daytime only	A/C running during the day with natural night-time venting
4/04/08 – 7/04/08	Free-floating & venting	Doors and curtains left open all weekend
1804/08 – 21/04/08	Free-floating	Daytime Venting
22/04/08 – 29/04/08	Free-floating	
6/05/08 – 16/05/08	Free-floating	Carpet and underlay installed

**Note: (1) Curtains open unless otherwise stated.; (2) Opening in northern wall in all cases.*

weather conditions it was necessary to import the data into a statistical analysis package for easier manipulation and comparison against 'independent' variables. The Statistical Support Services of the Faculty of Science and Information Technology at the University were employed to provide advice on the processing of the data. The JMP statistical package was selected due to its user friendliness and graphical interface for data representation (http://www.jmp.com/software/). Initially, procedures were developed for importing the MS-Excel data, identifying outliers and subsequently, scripts were generated to provide daily summaries which included:

- classifying daily average wind speed into low, medium and high
- summing daily global radiation and comparing it against theoretical maxima
- external air temperature- frequency distributions, mean, maximum & minimum
- internal temperatures- frequency distributions, mean, maximum, minimum and 'degree hour' above and below comfort zone.

Further interrogation of the database is under way to investigate the trends in other sensors, especially heat flux, and the flux integration over time to yield the magnitude and direction of energy flow through the various components of the building envelope.

RESULTS AND DISCUSSION

As already mentioned the results presented below focus on the observed internal air space temperature under 'free-floating' conditions using the assumption that the buildings were comfortable when the internal air space temperature was in the 18-24ºC range. The diurnal behaviour of the 'free-floating' modules is described for two time periods, in June and November 2007, to highlight 'typical' trends during cool and warm external temperature conditions. These two examples describe the behaviour of the modules in a totally passive sense, without any ventilation. The analysis then encompasses the year round behaviour by examining the relevant number of hours each of the modules sat within the comfort zone. This longer period encompasses periods with and without ventilation and various curtain and other configurations as outlined in Table 2. The number of hours and degree*hours above and below the comfort zone is also presented. This analysis of the 'free-floating' data involved excluding days where sensor or logger difficulties were encountered and periods when the interior of the buildings was being 'controlled'. This reduced the number of observation days from a maximum of 366 to 253.

Cool Weather Conditions, June 2007

The internal air space temperature of the four modules without ventilation together with the external air temperature is shown in Figure 4 over a three day period in early June 2007. The lower (18ºC) and upper (24ºC) boundaries of the comfort zone have also been included. It can be seen that the internal air space temperatures of the four modules exhibited similar behaviour, with the diurnal swing being attenuated and the mean temperature being increased. The Ins. LW module had periods above the comfort zone during the day and the CB module had periods below the zone at night. The net increase in mean temperature by 7-10ºC for all of the modules demonstrated the mini-greenhouse effect provided by the building envelope and the large solar gain entering via the window.

Warm Weather Conditions, November 2007

Figure 5 shows the response of the modules for a three day period in November 2007. The mean internal air space temperatures of the modules have increased, with the mean values close to the external mean temperature and coinciding with the upper level of comfort temperature. In terms of comparing the influence of wall R-value on thermal comfort it can be seen that both buildings with internal mass, CB (R0.62) and Ins. CB (R1.48), now develop similar maxima and minima. The main difference is the tendency for the CB module to remain warmer during the evening and at night-time from heat released by the west facing wall into the room air.

Combined Results for May 2007 – May 2008

The results presented above provide an indication of the behaviour of the walling systems for specific periods. In order to obtain a representation of the year-round performance use was made of the JMP database to extract the number of hours and degree*hours for each of the modules between May 16th of 2007 and May 17th 2008. As previously mentioned the data was filtered to remove periods of 'controlled' internal air space conditions or when maintenance was being carried out on the logger system. The following discussion summarizes the year-round thermal performance over 253 days. Note that in all periods under consideration each module had an identical configuration and was subjected to the same external conditions. The data is summarised in Tables 3 and 4.

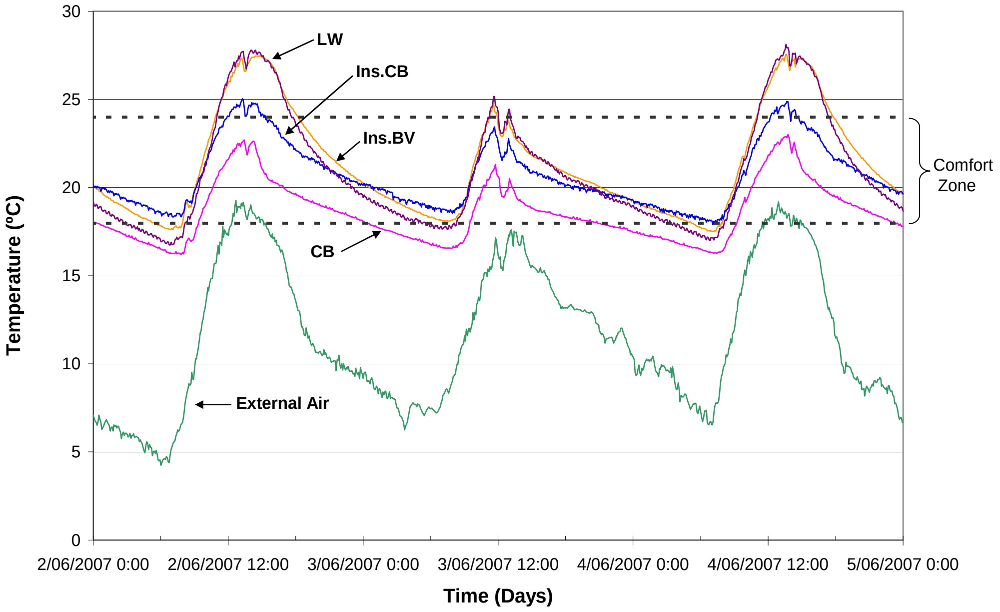

Figure 4: Internal Air Space and External Temperatures, winter conditions, June 2-5, 2007.

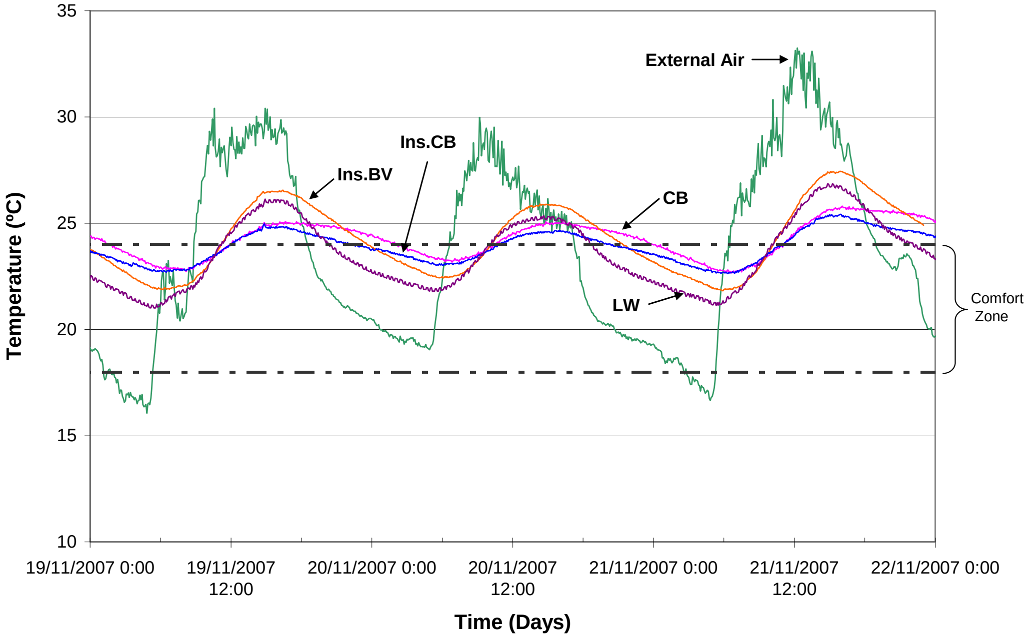

Figure 5: Thermal response of Modules, November 2-5, 2007.

It can be seen from Table 3 that there is no clear trend between R-value and the percentage of time in the comfort zone. For example, comparing CB to Ins.LW, a 2.7 times increase in R-value results in only a 3.5% improvement in the number of hours spent in the comfort zone. Similarly, an increase in R-value of 2.4 times from CB to Ins.CB results in a 10.2% increase.

Further insight into the influence of wall R-value on thermal performance can be gained by examining Table 4 which shows the degree*hours above and below the comfort zone. This data confirms the previous observations. For example, improving the R-value of the CB walling system to that of Ins.CB (a 2.4 times increase) reduces the degree*hours below the comfort zone by 50%. However, the difference in R-value between the Ins.CB and Ins.BV has no apparent influence below the comfort zone. It seems that the presence of the exterior brickwork and cavity contributes to improve cold weather performance of Ins.BV since this is the only structural difference between it and LW construction.

Table 3: Comparison of R-value and Number of Hours in the Comfort Zone

Wall Type	R-value (m^2K/W)	No. Hours in Comfort Zone (18-24°C)	% Time In Comfort (18-24°C)	Normalized to Ins.CB
Ins.CB	1.48	3756	61.8	1
CB	0.62	3135	51.6	0.83
Ins.BV	1.72	3278	54.0	0.87
Ins.LW	1.69	3345	55.1	0.89
External Air	n/a	1900	31.3	n/a

Table 4: Degree*Hours above and below the Comfort Zone

Wall Type	R-value (m^2K/W)	Degree.Hours below 18°C	Normalized to Ins.CB	Degree.Hours above 24°C	Normalized to Ins.CB
Ins.CB	1.48	2005	1.0	987	1.0
CB	0.62	4079	2.0	1118	1.1
Ins.BV	1.72	1908	1.0	2609	2.6
Ins.LW	1.69	2540	1.3	2180	2.2

In terms of degree*hours above the comfort zone it would appear that the influence of R-value is not significant as the increase in performance between CB and Ins.CB is marginal. The two walling systems with high R-value and no internal mass however are poor performers indicating that thermal mass rather than R-value is of major importance for thermal performance at warmer temperatures.

The year-round observations are consistent with those shown above for the June and November periods. Therefore, it would appear that under ‘free-floating’ conditions internal thermal mass or the combination of thermal mass with insulation work more effectively than walling systems which depend solely on high R-value for their thermal performance. This raises the question whether R-value on its own is an appropriate measure of thermal performance for walling systems used in domestic construction.

CONCLUSIONS

It is clear from the results that the R-value of a walling system, although a useful measure of the thermal resistance of the wall itself, is not necessarily a good predictor of the thermal performance of the complete building as there are a number of other factors at play. To obtain a true indication of thermal performance, account must be taken of the performance of the whole building as a system rather than simply considering the thermal resistance of the walls alone. The interaction with the other components of the building is critical, particularly those with thermal mass. In combination with external walls with an appropriate R-value, internal thermal mass can therefore be used to advantage to improve and maintain internal comfort levels. Deemed to satisfy building regulations expressed solely in terms of the R-value of the external walls will therefore not accurately reflect the true thermal performance of a building.

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