II

RESEARCH ARTICLES

USE OF DISSIMILAR WALLING SYSTEMS ON RESIDENTIAL BUILDING ENVELOPES FOR IMPROVING THEIR THERMAL PERFORMANCE

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ABSTRACT

This paper summarises the results of a combined numerical, statistical and experimental study concerned with the use of dissimilar walling systems on the external parts of a given building envelope. The rational behind this "hybrid wall" concept, as opposed to conventional approaches where identical walls are used in a building envelope, is to achieve a more effective distribution of thermal mass across the envelope and, hence, improve the overall thermal performance of the building. The effectiveness of the "hybrid wall" concept was investigated using a series of hypothetical building modules of common Australian residential constructions, namely Light Weight (LW), Brick Veneer (BV), Reverse Brick Veneer (RBV) and Cavity Brick (CB). These designs were examined numerically using a commercial energy rating tool known as "AccuRate", statistically using JMP software and experimentally using a novel bench-scale setup developed as part of this study. The performance of each design was evaluated by its energy consumption. The numerical predictions and experimental data highlighted that the east and west walls have the most impact on the energy consumption under Australian climatic conditions. It was found that considerable reductions in the energy consumption could be achieved in cases where the hybrid wall concept was implemented through the use of high thermal mass insulated walls on the east and west sides of the building envelope.

KEYWORDS

thermal mass, hybrid walling systems, energy efficiency, sustainable building

INTRODUCTION

A significant proportion of the electricity used in Australia is for space heating and cooling. Recent data indicate that space heating and cooling accounts for about 39% of total residential operational energy consumption in Australia [1]. Hence, new and innovative residential housing designs need to be investigated for the reduction of energy used for heating and cooling [1-11].

In a building, the effective use of thermal mass can significantly reduce the diurnal temperature swings making the conditions within the building more comfortable. Thermal mass, which is a function of material density (ρ) and specific heat (C_p), is a measure of the heat storage capacity of a material. When exposed to external heating, materials with high thermal mass (i.e. heavier and denser materials) can store more heat than their low thermal mass counterparts. It will also take longer for materials with high thermal mass to release their heat content once the heat source is removed.

Thermal mass is therefore an essential element of passive solar design, primarily because of the need to store the solar energy received by the building during the day and then to gradually release it overnight. This can be achieved through the smart use of appropriate building materials. By focusing on the orientation of a building and the placement of particular walling constructions, thermal mass can be utilised.

Whilst there are obvious merits in employing the passive solar design approach in Australia, there is a general lack of understanding about the thermal performance of high thermal mass construction

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materials in a variety of climates where the major population centres are located. In addition, much of the available data originates from studies on conventional Cavity Brick (CB) and Brick Veneer (BV) walling systems [10, 11] without much attention being given to more innovative designs.

Currently the common practice is to build residential buildings using identical walling systems for the entire external envelope of the building. Hybrid wall concept challenges this idea and essentially combines different walling constructions on different parts of the external envelope to attain a distributed thermal mass and increase thermal performance.

For example, it is known from experiments conducted within the Thermal Group at the University of Newcastle, that BV walls with their relatively small thermal mass perform better than CB under air-conditioned settings [3-5]. Although, BV walls cause the building to overheat quickly in summer and become cold in winter if the building is not air-conditioned. A proper ventilation design may partly resolve the overheating problem.

However, a more permanent solution for both summer and winter seasons can be realised only if optimum thermal mass is employed in the design of the building envelope. One way of achieving this goal is to construct part of the boundary walls using heavier CB with the remainder from the lighter BV. Some critics may argue that such hybridisation will increase the complexity and cost of constructions. However, if reasonable gains are attained by hybridisation of walling systems, the added cost and complexity will be well justified.

To establish the practicality of the hybrid wall concept, the cooperative interaction among different walls and wall types will need to be examined. During research and experimentation, moving the positioning of the walls will allow for the examination of the influence of building orientation, ground topology, and window placement. The hybrid wall concept is a novel idea and hence there is limited information and existing research on the concept.

The hybrid wall concept was developed at the University of Newcastle, and is part of a much larger combined experimental and analytical research program specifically designed to address the shortcomings of uniform walling systems by studying the thermal performance of a mix of conventional and unconventional masonry wall designs and light weight constructions in hybrid configurations [6, 7]. The present paper provides a comparative study of four different walling systems typically used in Australian residential buildings (CB, BV, RBV, and LW, constructions with and without insulation) in terms of energy efficiency. Numerical comparisons were made using the AccuRate energy star rating tool. Statistical analysis was carried out by a software package known as JMP. The predictions were compared with experimental measurements from a bench-scale setup.

The key objective is to develop methods for the smarter use of thermal mass through the implementation of hybrid wall concept into residential buildings.

NUMERICAL STUDIES

AccuRate Software

AccuRate is an energy rating tool developed by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO). The main purpose of the software is to predict the energy consumption for air-conditioned buildings and the zone air temperatures for free-floating buildings [8]. It allows for the comparison of the thermal performance of different styles and designs of buildings. It is an indicator of the energy needed to be added or removed to keep the conditioned floor area of the building comfortable. AccuRate assigns a star rating to a residential building based on its calculated annual heating and cooling energy requirements [9].

The software requires detailed information about the building such as orientation, construction type, insulation levels, window size and orientation, shading, overshadowing, ventilation, etc [10]. The mathematical basis of the AccuRate software is the "Frequency Response" method in which the system (i.e. the building) inputs and outputs are viewed as being sinusoidal in time [2]. The building is assumed to consist of a number of zones each comprised of elements, such as the floor, roof, ceiling, walls, windows, etc. Each building element is considered to be composed of a series of homogeneous (uniform in structure) layers, referred to as "slabs" [2]. By combining the response of the individual slabs, the response of the building to a given input file can be determined. The input file is usually in the form of a weather data file, which is generally a year of data representing typical climatic conditions of a given geographical location (outdoor dry bulb air temperature, relative humidity, wind speed, wind direction, global solar radiation on the horizontal plane, diffuse solar radiation on the horizontal plane, cloud index, pressure). In the case of Newcastle, the year 1974 has been selected as a typical weather pattern for the Newcastle area. The input data for AccuRate cannot be changed by the user.

The model calculates heating and cooling energy data on an hourly basis over a period of one year. The output from the model is a simple report detailing the quantity of heating and cooling energy that would be required to maintain conditions within the building to the assigned comfort zone [6]. A one-to-ten star rating is given to the building corresponding to the energy performance with ten stars given to the most efficient building design. Star ratings correspond to different energy consumption rates depending upon the climate zone.

AccuRate is a second generation energy rating tool. The upgrade of the NatHERS software has seen improvements in natural ventilation modelling, user-defined constructions, improved modelling of roof spaces, sub-floor spaces, skylights and horizontal reflective air gaps, and the availability of many more zones [2].

The heating and cooling temperatures are set by AccuRate and cannot be changed by the user. The thermo stat settings can be seen in Table 1 below.

JMP Statistical Software

JMP is a division of SAS Institute Inc. and was developed by John Sall and others to perform simple and complex statistical analyses. It provides a comprehensive set of statistical tools as well as design of experiment and statistical quality control. It dynamically links statistics with graphics to interactively explore, understand, and visualize data [11].

In this application of JMP, multiple linear regressions using the stepwise method for the selection of variables into the model was used. The influence of a variable or interactions of variables, errors and other factors are all calculated and presented within the model. To ensure the model logically represented the data, manual override by the investigator was used so as the main effects were selected first, followed by sensible interactions. This model allows for the effect of each wall on energy consumption to be quantified. The model developed can also be used as an energy consumption predicting tool rather than using a complex thermodynamic model such as AccuRate.

Details of Walling Systems and Building Design

Three different walling systems commonly used in the eastern states of Australia (i.e. CB, BV, and LW construction) together with an unconventional novel design RBV, were considered in this study. All walling systems were examined without and with insulation in the cavity (note that insulated walling systems are referred to as ICB, IBV, LW, and IRBV, respectively). The systems are described in Table 2 detailing the external and internal leaf of the walls and cavity. The systems are also shown schematically in Figure 1.

For this comparative study relatively simple idealised hypothetical building envelopes (referred to as modules hereafter in this paper) were considered rather than a complete house. This allowed the direct comparison of various forms of building envelopes without the complexities which would be

TABLE 1. AccuRate's Thermostat Setting.

Area	Actual Location	BCA Climate Zone	AccuRate Climate Zone	Heating Living, Kitchen, other zones	Heating Bedroom Zones 00:00–07:00	Heating Bedroom Zones 08:00–16:00	Cooling All Zones
Newcastle	Williamtown	5	15	20	15	18	25

TABLE 2. Description of walling systems.

		External Leaf	Cavity	Internal Leaf
Lightweight	LW	Fibre-cement	90 mm timber stud wall	10 mm Plasterboard
Insulated Lightweight	ILW	Fibre-cement	90 mm timber stud wall containing R1.5 m^2K/W	10 mm Plasterboard
Brick Veneer	BV	110 mm medium in colour brickwork	40 mm unventilated air gap, 90 mm timber frame followed by reflective foil	10 mm plasterboard
Insulated Brick Veneer	IBV	110 mm medium in colour brickwork	40 mm unventilated air gap, 90 mm timber frame containing R1.5 m^2K/W insulation batts followed by reflective foil	10 mm plasterboard
Reverse Brick Veneer	RBV	Fibre-cement	90 mm timber stud wall	110 mm medium in colour brickwork
Insulated Reverse Brick Veneer	IRBV	Fibre-cement	90 mm timber stud wall containing R 1.5 m^2K/W batts	110 mm medium in colour brickwork
Cavity Brick	CB	110 mm medium in colour brickwork	40 mm unventilated Air Gap	110 mm medium in colour brickwork
Insulated Cavity Brick	ICB	110 mm medium in colour brickwork	50 mm air-gap, R1 rigid polystyrene insulation attached to the internal wall in the cavity	110 mm medium in colour brickwork

FIGURE 1. Schematic representation of various walling systems.

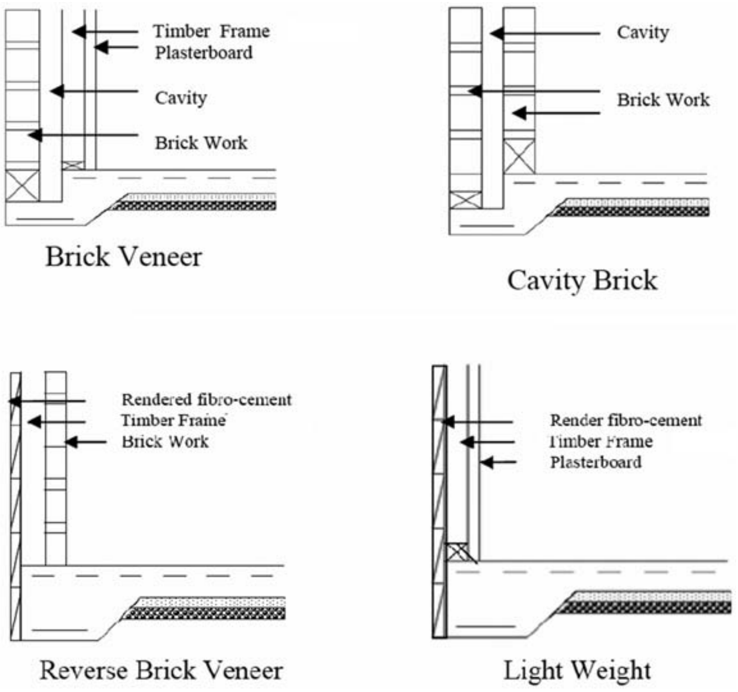
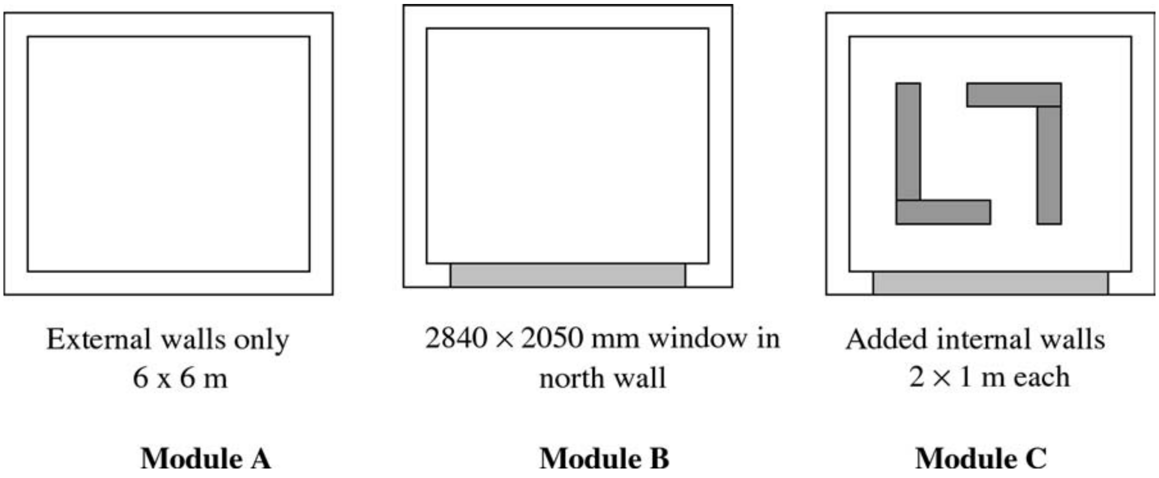


FIGURE 2. Top views of building modules considered in this study.



present if a complete house design was considered. Three envelope types were considered (Figure 2):

- Module A: Module A is a 6 m square module, consisting of only the exterior walling systems under investigation and with no doors, internal walls or windows.
- Module B: The physical configuration of this module is based on Module A with an additional 2.05 m × 2.84 m single glazed 6.38 mm thick window on the north wall to examine the effects solar radiation entering the modules.
- Module C: Module C is a modified version of Module B in which internal walls of bare brickwork panels 2 m by 1 m (see Figure 2 for configurations) have been added to examine the effect of additional thermal mass. In previous studies, it was found that Module C with a north facing window and internal bare brick wall was the most energy efficient module [6].

Each module was assumed to be constructed on a 100 mm reinforced concrete slab-on-ground. No floor coverings were present to ensure the thermal mass of the slab was exposed. The roof construction was assumed to be from light coloured tiles with reflective foil underlay, at a pitch of 22 degrees with a plasterboard ceiling and R 3.5 m^2K/W glass insulation batts.

EXPERIMENTAL STUDIES

Bench-Scale Setup

The bench-scale setup (Figure 3) was designed and constructed to study the behaviour of different walling systems in a rapid, reproducible manner under controlled laboratory settings.

The physical dimensions and configuration of the bench-scale setup were carefully selected to ensure that the setup represented an exact 1/8 replica of the University of Newcastle full-scale thermal test house modules constructed in 2002 [3, 4, 12].

The bench-scale setup consisted of a 25 mm thick reinforced square shape concrete slab (750 mm × 750 mm) on which four side wall panels were mounted (Figure 4a, 4b). The roof was constructed from several layers of blue board insulation. The wall panels were independently mounted so that identical (i.e. conventional approach) or dissimilar constructions (i.e. hybrid wall concept) could be employed. Special attention was given to the construction of wall panels to ensure that the thermal characteristics of their full-scale counterparts were accurately represented. This was achieved by maintaining the thermal conductivity (k) and thermal mass (ρC_p) of the bench-scale setup at levels similar to those used in full-scale modules. The wall panels were fitted with electrical elements to mimic the external heat flux received by the external walls of the full-scale test

FIGURE 3. Bench-Scale Setup.

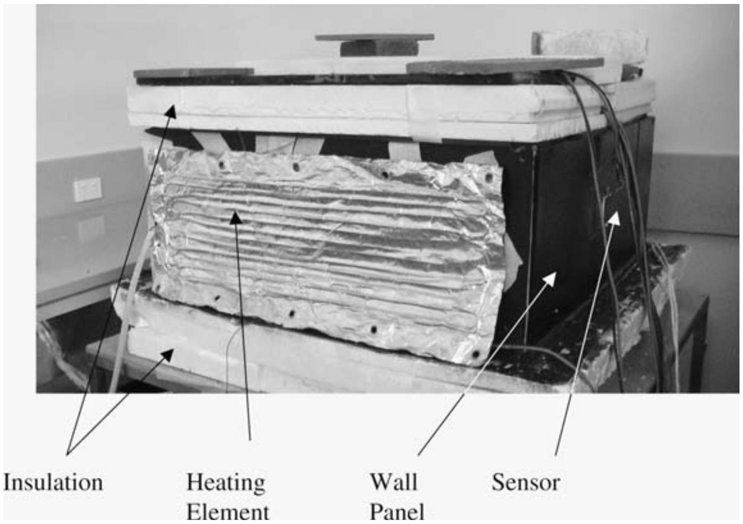


FIGURE 4A. Schematic representation of the Bench-Scale setup.

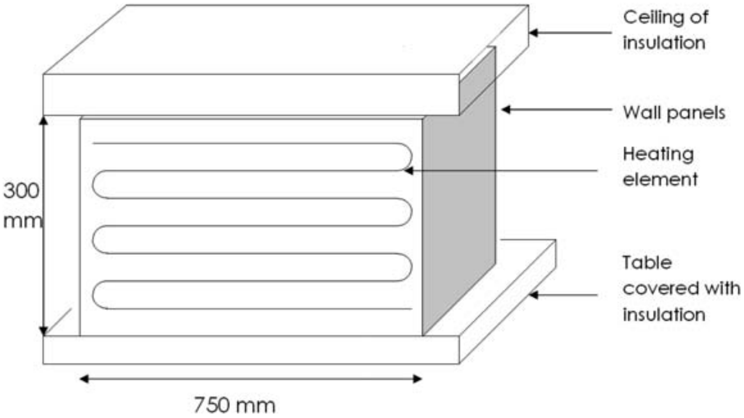
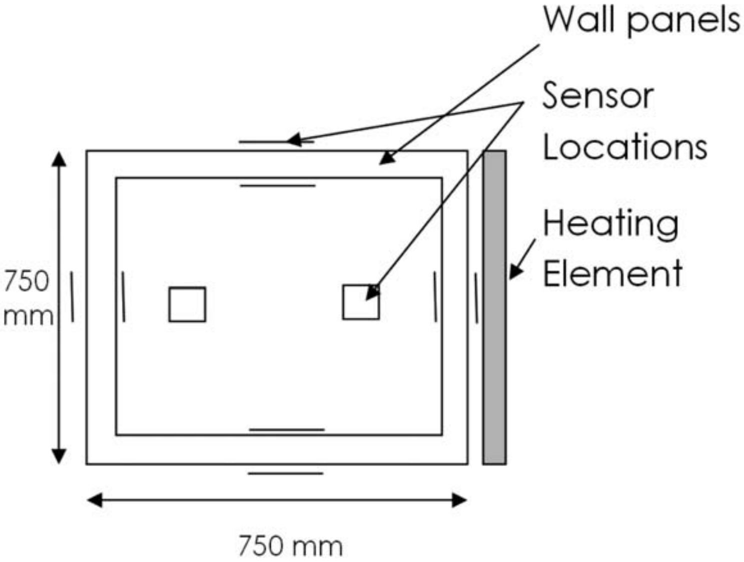


FIGURE 4B. Schematic representation of the Bench-Scale setup, bird's eye view.



house modules described in our earlier publication [9-11]. The setup (wall panels, slab, roof, inside cavity, etc) was fully instrumented with thermocouples and heat flux gauges and experimental data were collected every minute over weekly cycles. The ambient temperature in the laboratory was maintained at 25°C throughout the experiments.

RESULTS AND DISCUSSION

Each module was initially modelled with a uniform walling system in which the North (N), South (S), East (E), and West (W) walls have identical construction (see Table 3).

In the case of Module A the use of a uniform IBV walling system results in the lowest energy consumption of 65.5 MJ/m^2 per annum. This is expected as Module A does not contain a window and hence the internal layer of thermal mass of the external wall cannot be engaged. For Modules B and C, however, the ICB walling system has the lowest energy consumption of 45.5 MJ/m^2 per annum and 42.4 MJ/m^2 per annum, respectively.

It would be ideally desirable to model the interaction of each of the different walling systems, (LW, BV, RBV, CB, ILW, IBV, IRBV, and ICB) on each different orientation (N, S, E and W). This, however, leads to a total of 4096 combinations for case studies. As it is not practical to model this many permutations, the case studies needed to be reduced. Hence, each walling system has been studied in combination with the ICB construction which according to studies carried out on uniform walling systems (see Table 2) is the best performing construction. The possible combinations using BV as an example for Module A have been shown in Table 4.

As can be seen in Table 3 there are 16 different combinations and this is repeated for each walling system making it 112 combinations per module or 336 combinations in total. All combinations were modelled in rating mode, where the amount of energy needed to be added or removed to the module to keep the module within a specific temperature range (18–25°C) was calculated.

In Module A (Figure 5) the energy consumption of a uniform module can be decreased by installing ICB walls. In the case of LW construction the energy consumption is largely decreased by installing an ICB walls, and the most efficient position is on the south or west wall. This modification on the west wall offers an energy saving of 43.3 MJ/m^2 per annum. Furthermore combining ICB walls on the south and west or east and west, or south and east, energy consumption will further decrease by 36.3 MJ/m^2 per annum. This trend is also evident in RBV and CB. Installing ICB walls in BV, IBV, ILW and IRBV constructions does not offer a significant improvement in energy efficiency.

TABLE 3. Energy consumption (MJ/m^2 per annum) for uniform walling systems for each building module.

	Module A	Module B	Module C
ICB	72.4	45.5	42.4
IRBV	68	46.3	42.5
IBV	65.5	72.5	50.7
ILW	75.6	75.8	60.1
BV	82	62.9	60.7
CB	131.8	83.9	82.5
RBV	170.9	121.1	120.5
LW	202.9	206.3	184.2

TABLE 4. Combinations for hybrid walling studies.

	N	E	S	W	Star	Energy
1	BV	BV	ICB	BV	5.4	78.8
2	BV	ICB	ICB	ICB	5.6	73.9
3	ICB	BV	BV	BV	5.3	79.1
4	BV	BV	BV	ICB	5.4	78.2
5	ICB	BV	ICB	ICB	5.6	74.3
6	ICB	ICB	BV	ICB	5.6	74.4
7	ICB	ICB	ICB	BV	5.6	74.3
8	BV	ICB	BV	BV	5.5	78.8
9	BV	ICB	BV	ICB	5.5	75.7
10	BV	BV	ICB	ICB	5.5	75.4
11	ICB	ICB	BV	BV	5.5	77
12	BV	ICB	ICB	BV	5.5	76.3
13	ICB	BV	BV	ICB	5.5	75.9
14	ICB	BV	ICB	BV	5.5	75.4
15	ICB	ICB	ICB	ICB	5.7	72.4
16	BV	BV	BV	BV	5.2	82

FIGURE 5. Energy consumption for Module A predicted by AccuRate energy rating software.

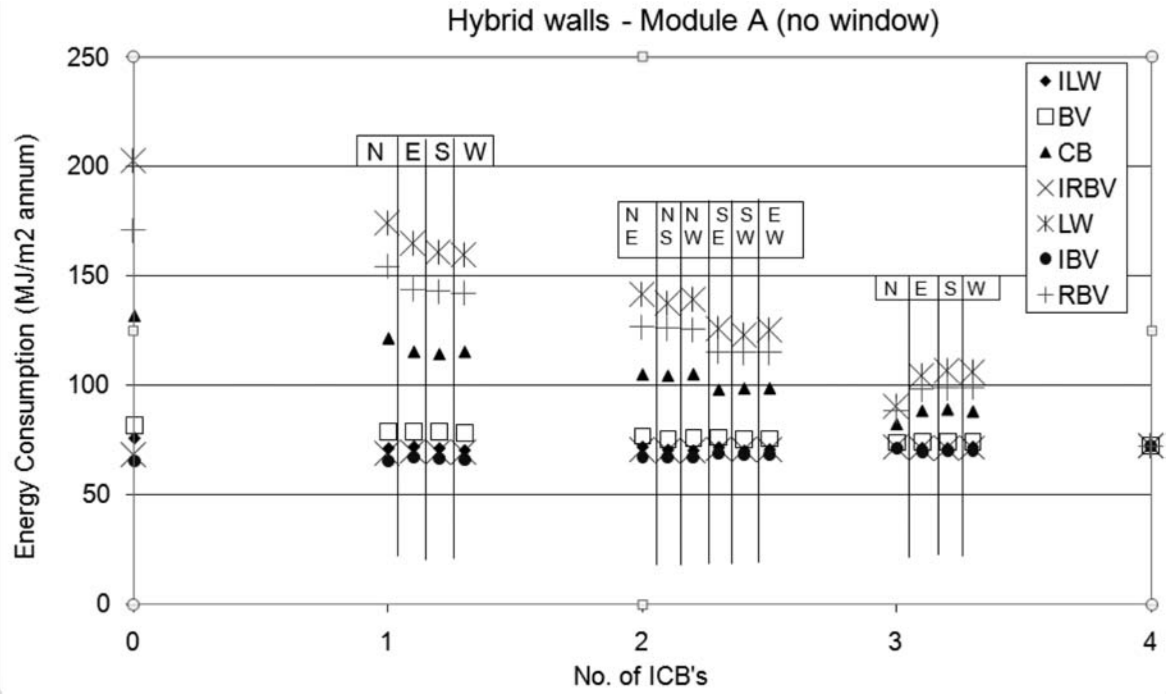
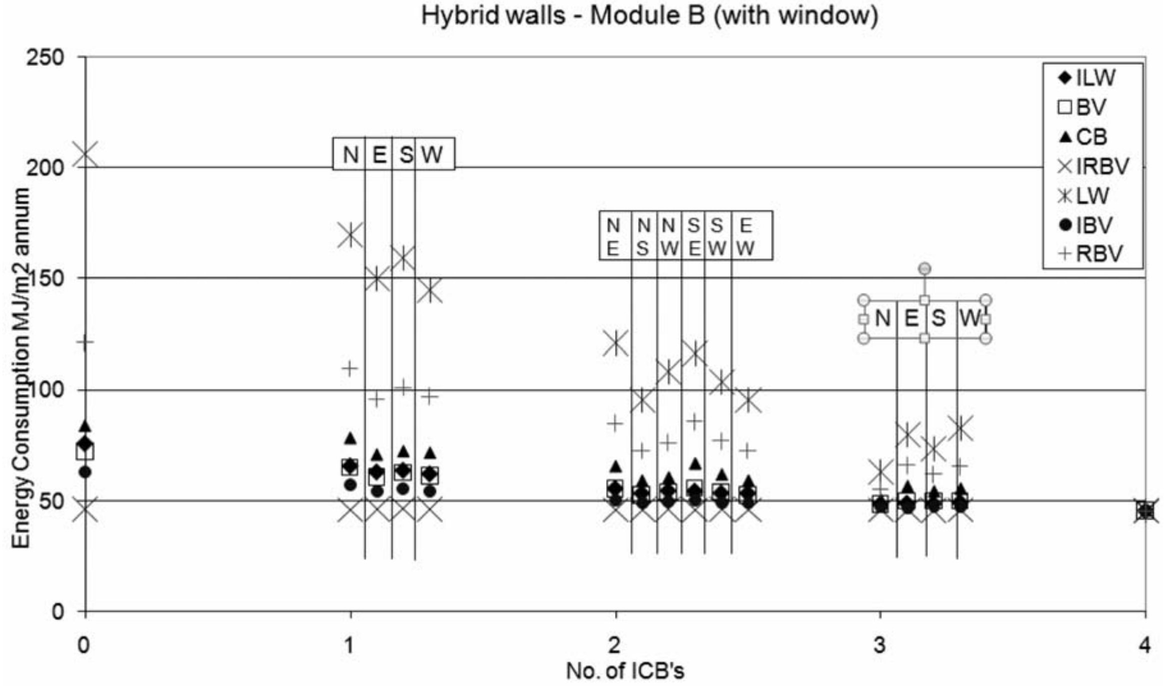


FIGURE 6. Energy consumption for Module B predicted by AccuRate energy rating software.



In Module A, CB performs similarly to LW and RBV rather than heavier materials such as BV. This result was not expected as CB has greater thermal mass as compared with BV construction. This performance may be due to the module not interacting with the internal environment as Module A consists of only external walls.

For Module B it is evident from Figure 6 that LW and RBV walling systems once again have a similar profile to LW system in Module A. Although now, installing one ICB wall on the west or east side of the envelope will have the most influence on reducing energy consumption by 61.7 MJ/m^2 per annum on the west wall. In combination ICB the east and west walls and the north and south offer the lowest energy consumption.

Once again, installing ICB walls in CB, BV, IBV, ILW and IRBV constructions does not offer a significant improvement in energy efficiency.

In Module C, Figure 7, it is evident again that the east and west walls have the most influence in reducing energy efficiency with an ICB wall on the west wall saving 51.6 MJ/m^2 per annum. Although, in combination the north and east wall can decrease energy consumption by 94.9 MJ/m^2 per annum from a uniform LW module.

In Module B and C, CB performance is closer to BV although it is intuitively expected that CB would have a better performance than BV.

The AccuRate predictions for each module were also analysed with JMP statistical software and a multiple linear model was developed. It was based on the structure of each walling systems: External Thermal Mass (O_TM), Internal layer of Thermal Mass of the external wall (I_TM) and if Insulation (I) was present (1 = yes, 0 = no), see Table 5.

There are several aspects of the analysis that may affect the results obtained from JMP. The factor space was analysed using a 3D scatter plot (Figure 8) and it was found that all extremes of the ranges of each variable were used leading to a good fit for the model.

Relevant JMP models were developed for each building module and from this the influence of the

FIGURE 7. Energy consumption for Module C predicted by AccuRate energy rating software.

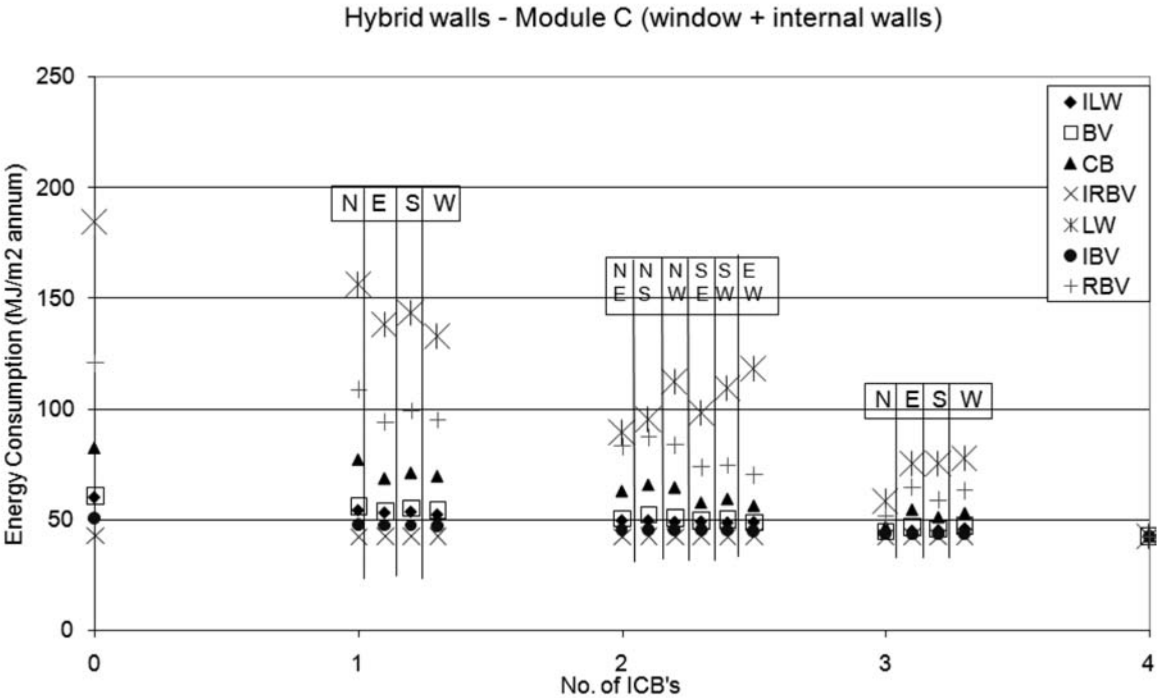


TABLE 5. Properties for each walling system O_TM, I_TM (kJ/K) and I.

Material	O_TM	I	I_TM
BV	2352.082	0	133.056
CB	2352.082	0	2352.082
RBV	145.152	0	2352.082
LW	145.152	0	133.056
IBV	2352.082	1	133.056
ICB	2352.082	1	2352.082
IRBV	145.152	1	2352.082
ILW	145.152	1	133.056

properties of each walling system was quantified by comparing their engineering significance (see Figure 9).

Engineering significance is a statistical term used to describe the influence the change of a variable has on another variable. The JMP model will calculate an estimate for the influence of the variable within the model. In this case to determine the engineering significance the whole range of a variable, for example, O_TM, from the lowest value (145.152 kJ/K) to the highest value (2352.082 kJ/K) is the estimate (-0.0007993) multiplied by the range (2206.9296 MJ/m^2 per annum). This is when O_TM changes from the lowest to the highest value on the north wall of module A, will have an effect of reducing energy consumption by 2 MJ/m^2 per annum.

As Figure 9 indicates for Module A the most influential walls are the west then south followed by the east wall. Insulation on all walls decreases energy consumption dramatically, and has a higher impact on energy consumption than thermal mass. The I_TM on all orientations will increase energy consumption. This is due to the module not having a window and the thermal mass not being able to interact with the internal environment.

The effects of installing a window in Module B can be seen with the reduction of the influence of insulation, with the west wall clearly having the most influence here. Also with a window present I_TM is able to be utilised decreasing energy consumption.

Module C performs similar to Module A, although the effects of insulation are decreased. The addition of internal thermal mass walls requires energy to be added to the module. As there is already a large amount of thermal mass within the module from the I_TM, the addition of thermal mass from the internal walls of bare brick stores more heat from

FIGURE 8. 3D scatter plot from JMP for uniform modules (the data points are predictions by AccuRate energy rating software).

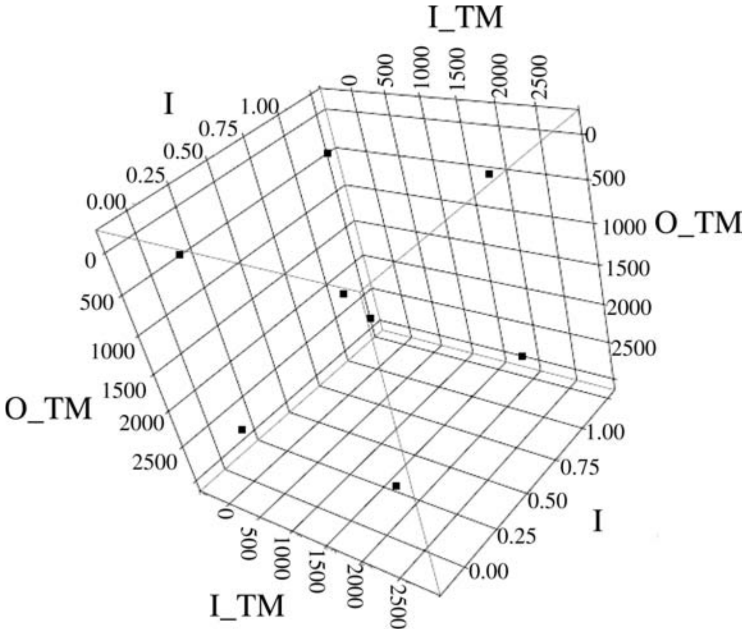
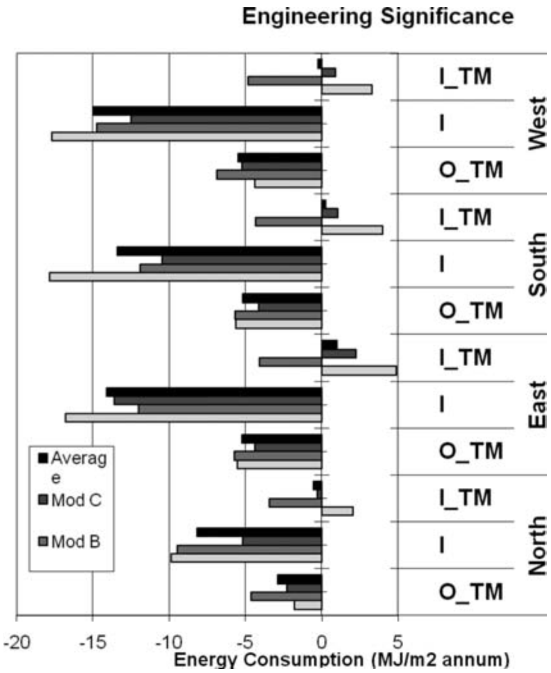


FIGURE 9. Engineering significance of O_TM, I_TM (kJ/K) and I on each wall orientation for each module on energy consumption (MJ/m^2 per annum).



the internal environment which requires more energy to be added to the system. Hence, it is possible to have too much thermal mass within a building. Thermal mass is able to store a substantial amount of heat, but it will also take a significant amount of heat to warm once it has cooled, hence causing a buildings thermostat to respond very slowly [13].

Overall the north and west walls perform similarly requiring high insulation, O_TM and I_TM, whereas, the South and East walls perform similarly requiring high insulation and O_TM, but low I_TM. From this the most efficient module would consist of ICB on the north and west walls and IBV on the east and south. This energy consumption for this design can be seen below in Table 6.

JMP can also identify interactions between different aspects of the wall. Relevant plots have been generated (see Figures 10-12) and the interactions between O_TM and insulation, and O_TM and I_TM have been determined (solid lines). The interaction between I_TM and insulation was also predicted (dotted line).

TABLE 6. Energy Consumption (MJ/m^2 per annum) for ICB on the north and west walls and IBV on the east and south for all building modules.

Module A	Module B	Module C
67	49.8	45.6

If a wall is insulated, and O_TM is increased, energy consumption is also increased, as shown in Figure 10, for Module A. This is due to the module consisting of only external walls, and radiation from the sun cannot enter the module easily. On the other hand, if a wall is insulated and the I_TM is increased, energy consumption is slightly decreased. This demonstrated the interaction of the thermal mass with the internal environment.

When a wall is not insulated, increasing the O_TM dramatically reduces the energy consumption, while increasing the I_TM will slightly increases energy consumption.

When looking at the interaction between O_TM and I_TM, it is best to only have one layer with a large amount of thermal mass. Having large thermal mass on both the external and internal layer of the wall will slightly increase the energy consumption.

The interactions for Module B shown in Figure 11 are slightly different to those of Module A. In Module B, a wall that is not insulated and has high I_TM energy consumption will be reduced at the same rate as if insulation was present. This shows that by installing a window radiation is able to enter the module and the I_TM can interact with the internal environment and better store heat. Without insulation, increasing O_TM will dramatically reduce energy consumption, whereas with insulation energy consumption will increase with increasing O_TM.

In the case of Module C (see Figure 12) interactions are different once again. The increase of O_TM with I_TM does not have a large effect on energy consumption. But once again, the effect of thermal mass with insulation is the same for Modules A and B.

From analysis of interaction plots for modules A, B and C it is clear that the best performing wall has low O_TM, high I_TM and is insulated, such as the IRBV walling system. These results are as expected, as it is known that thermal mass performs

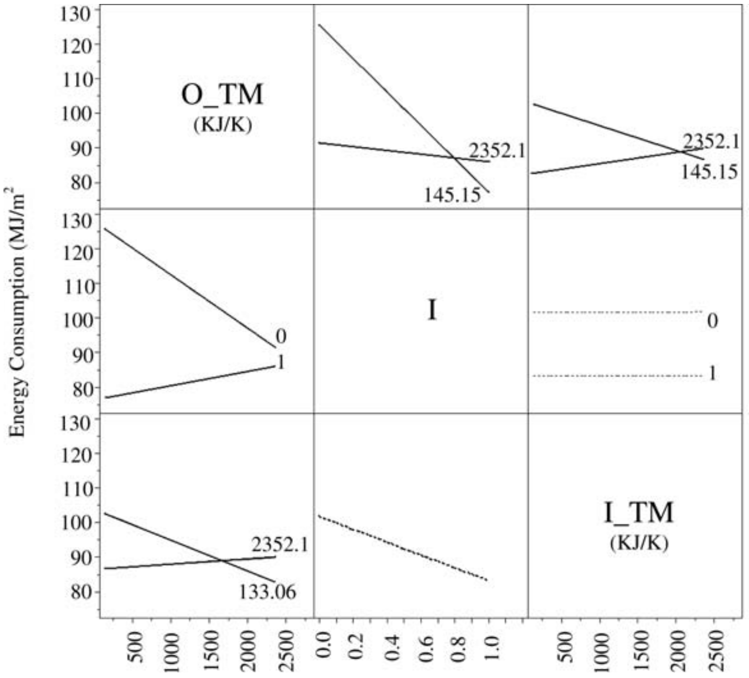


FIGURE 10. Walling structure interactions for Module A.

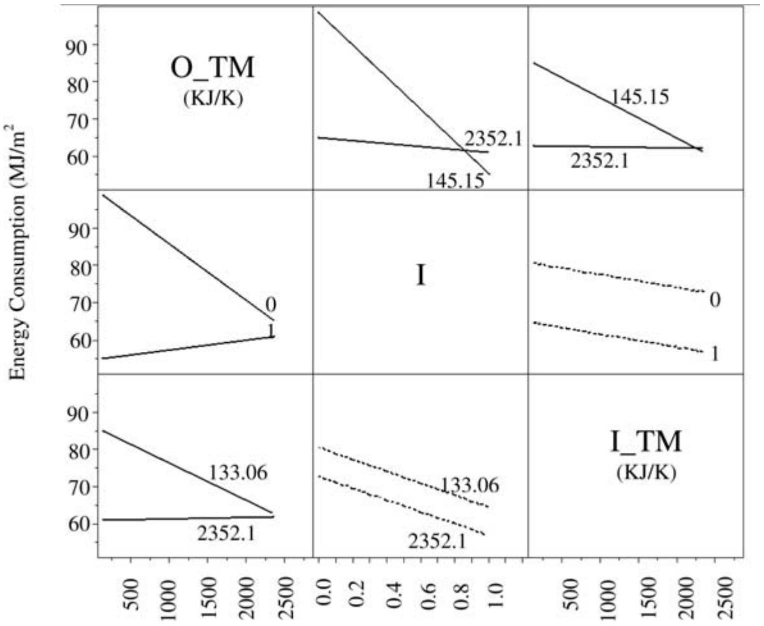


FIGURE 11. Walling structure interactions for Module B.

well within a protective insulating envelope. However, it must be highlighted that for practical reasons (e.g. durability, surface finish, etc) a walling system such as IRVB may not be preferred over more durable constructions like ICB.

To allow the findings to be used in a practical sense, a selection of six different hybrid designs were used for further analysis, see Figure 13. They were based on each individual study being the analysis with AccuRate, Engineering significance, and the

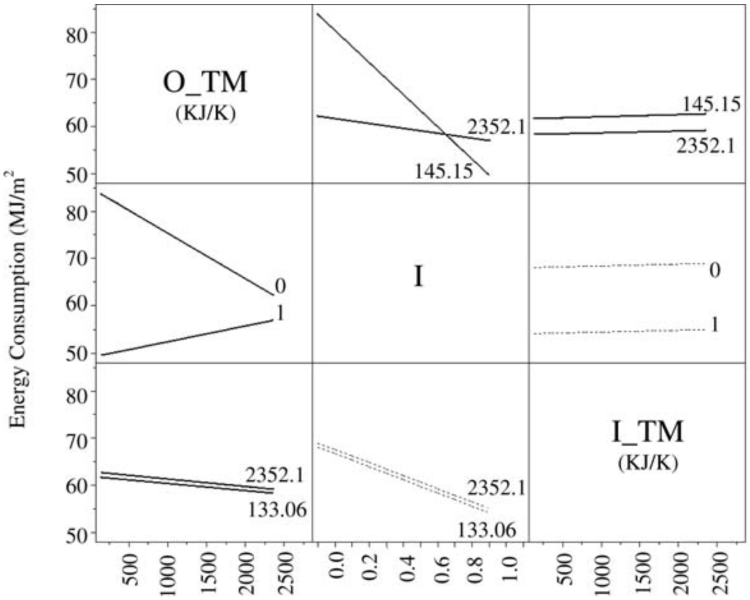


FIGURE 12. Walling structure interactions for Module C.

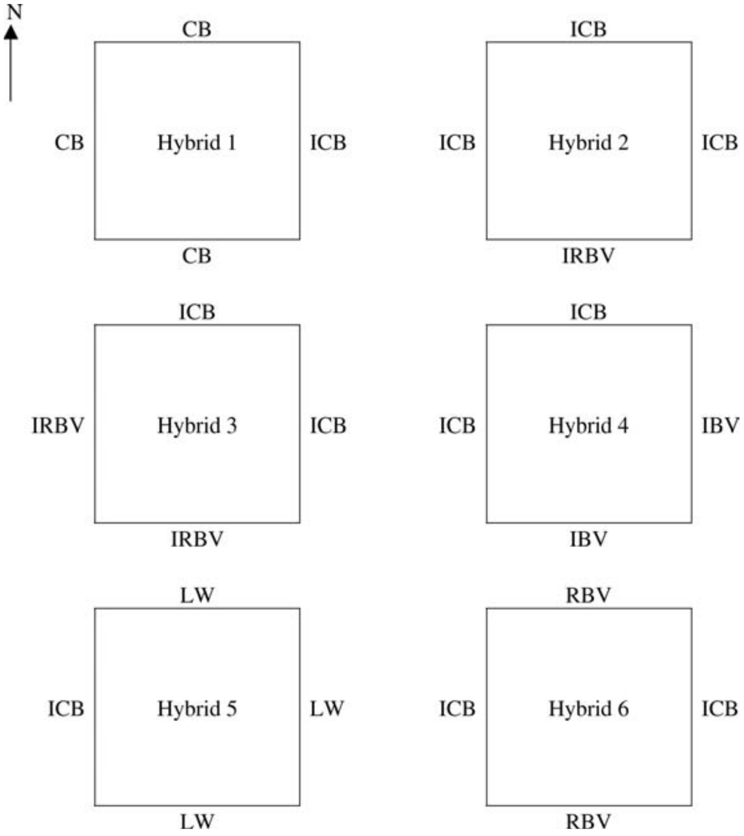
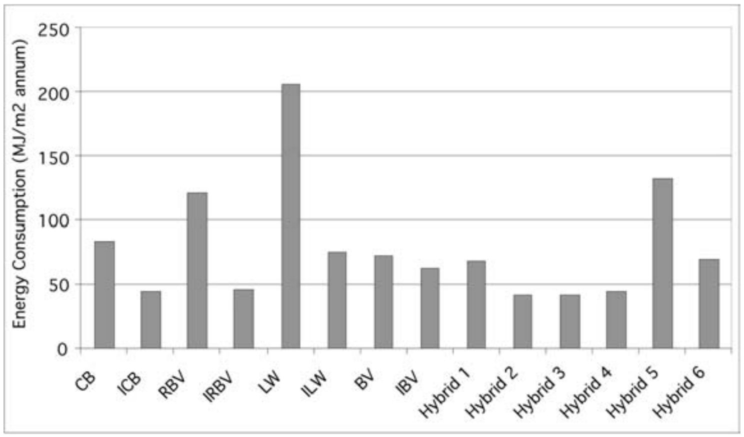


FIGURE 13. Six selected Hybrid Module for further analysis.

FIGURE 14. Energy consumption of uniform and hybrid modules in Module B.



interaction plots from JMP. The modules were selected on their performance in Module B as Module B is thought to perform similarly to a real house, allowing solar radiation to enter the module. To obtain a good comparison of hybrid walling systems a very good, good, and poor performing modules were used in the study.

For comparison of the energy efficiency of each of the designs, Figure 14 shows the energy consumption of uniform modules with hybrid modules, as calculated by AccuRate in Module B.

Hybrid 5 is clearly the worst performer of the hybrid designs, as it consists of mainly LW walls and only one ICB. Although the addition of the ICB wall on the west wall offers a dramatic decrease in energy consumption of 73.7 MJ/m^2 annum. As mentioned earlier, the east and west walls are major players in the transfer of heat, and this is again demonstrated by the reduction in energy consumption in hybrid 6 with the decrease of 50.9 MJ/m^2 annum from a uniform system of RBV.

Hybrid 2 and hybrid 3 perform very similar to the uniform systems of ICB and IRBV, and hence it is evident that the change between these walling systems is not significant.

For further analysis of the hybrid modules the decrement factor as seen in Equation 1, has been employed. The decrement factor is the temperature difference of the inside temperature with the desired room temperature over the temperature difference of the outside temperature with the same desired temperature [6].

$$\text{Decrement Factor} = \frac{T_i - T_D}{T_o - T_D} \tag{1}$$

Where T_D is the desired room temperature
T_i is the inside average daily temperature
T_o is the outside average daily temperature

The decrement factor can only be applied to a single wall and requires the surface temperature of the outside and inside of the wall. AccuRate does not supply this information in the output, hence a Temperature Difference Ratio (TDR) is used here (equation 2), derived from the decrement factor to compare AccuRate and the bench scale results.

$$TDR = \frac{T_{inside}^{\max} - T_{inside}^{\min}}{T_{outside}^{\max} - T_{outside}^{\min}} \tag{2}$$

Where T is the air temperature

The desired result is a low decrement as a low decrement factor as this will offer the least amount of temperature fluctuations [14]. Hence, in the derived TDR, a lower value is also desired.

The TDR results from AccuRate and the bench-scale setup for Module A, presented in Figure 15, display an average TDR difference of 0.132, although the trend is the same in both methods. The difference in results may be due to the TDR for AccuRate being calculated over one year, whereas the TDR for the bench-scale setup was calculated over three days, of experimental runs. To verify this several days were selected from the AccuRate cycle for

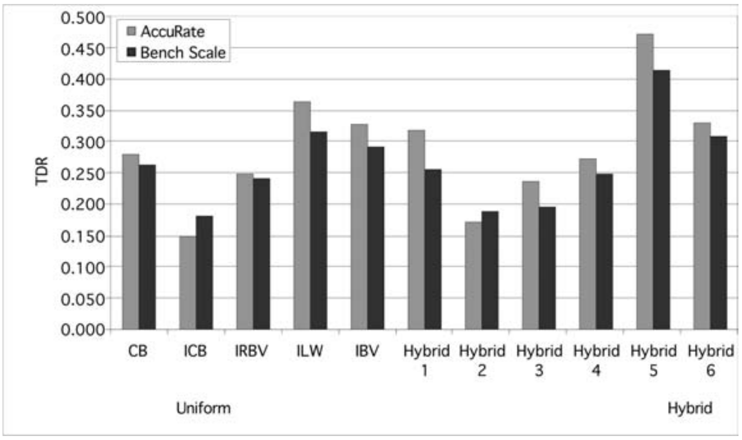


FIGURE 15. TDR results for AccuRate and the Bench Scale Model for uniform and hybrid modules in Module A.

FIGURE 16. Best to worst performing designs.

ICB	Hybrid 2	Hybrid 3	IRBV	Hybrid 4	Hybrid 1	CB	IBV	Hybrid 6	ILW	Hybrid 5

BEST ◄——————————► WORST

hybrid design 6, and the TDR was calculated. It was found that the TDR values ranged from 0.295 to 0.604, depending on the particular days weather, and time of year. An average of these were taken and found to be 0.438, which is relatively close to the yearly value of 0.403.

AccuRate TDR results are very similar for hybrid 2 and hybrid 3, and uniform modules of ICB and IRBV, although results from the bench-scale setup show IRBV to be slightly higher that the other designs and more comparable to hybrid 4.

The uniform and hybrid systems can be ranked from best performing to worst performing based on their energy consumption and TDR (see Figure 16).

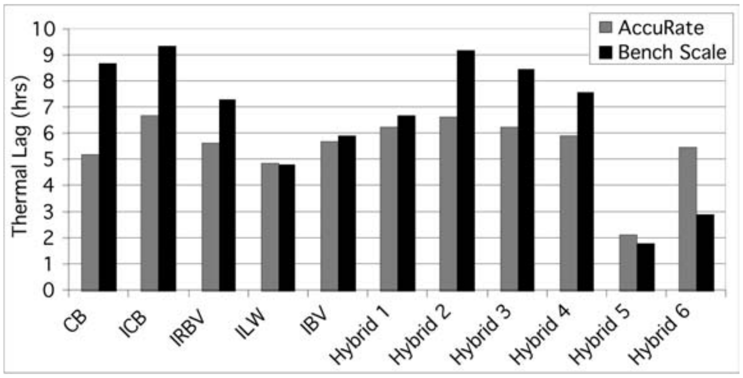
The best performing designs consists of ICB and IRBV which is expected as these walling systems are also the best two performing uniform designs. Better applications of the hybrid walling idea can be seen in hybrid 5 and hybrid 6 (see Figure 14) when the energy consumption of these designs is reduced by the addition of ICB walls.

Another method used for assessing the thermal efficiency of a building material is thermal lag. Thermal lag is a term describing the amount of time taken for a material to absorb and then re-release heat, or for heat to be conducted through the material [15]. A small thermal lag causes a quick change in internal temperature causing thermal comfort within the module to diminish. The desired temperature profile is a slow decrease, hence a large thermal lag. This allows the thermal energy to be slowly released into the module maintaining thermal comfort.

Figure 17 compares the thermal lag for the bench-scale setup and AccuRate predictions. For constructions with a large amount of thermal mass, CB and ICB, the bench-scale setup tends to over predict the thermal lag by approximately 2 hours. In the hybrid systems, hybrid 2, 3 and 4 all have over predictions. These hybrid designs all contain insulation, and hence, the insulation may be performing better than expected within the bench-scale setup. Lighter mass constructions such as ILW, IBV and hybrid 5 compare very close to the AccuRate predictions.

Heat is only able to enter the bench-scale setup through the north wall, where the heating element attached. AccuRate models real world situations

FIGURE 17. Comparison of Thermal Lag for AccuRate Predictions and Bench-Scale Setup.



where heat is transferred through several walls. This explains why the designs in the bench-scale setup have such a longer lag, as there is only one wall for heat gain. Even though this affects the thermal lag value, the bench-scale results have a similar trend to AccuRate predictions, which allows for a thermal performance comparison between designs.

As analysis was performed on a hypothetical module it is not known how well these trends transpose to a real house. The hypothetical modules can be applied to obtain an estimate of the thermal performance of different construction types, but not necessarily to base qualitative analysis on.

As these are only modules a quick examination of the performance of the hybrid wall concept in a completed house, (i.e. Bedrooms, kitchen, bathrooms, etc,) in Newcastle was performed to find the possible energy savings. By applying Hybrid 5, to a LW design, energy consumption can be reduced by up to 15%, while Hybrid 6 offers an energy reduction of 19% from RBV. This reduction from the hybrid wall concept along with other green design aspects has the ability to greatly reduce energy consumption in a residential housing application.

Further, more in-depth analysis of these studies will be implemented into a real house design, to validate AccuRate predictions and the bench-scale setup.

CONCLUSIONS

Analysis with AccuRate and the bench-scale setup shows that the energy consumption of a uniform module can be decreased by installing ICB walls in the case of LW, RBV and CB. Although, installing ICB walls in CB, BV, IBV, ILW and IRBV constructions does not offer a significant improvement in energy efficiency.

Analysis of uniform walling systems in hypothetical modules reveals that increasing window area requires thermal mass to be increased proportionally; hence the most efficient module was Module C. Although, when analysing using engineering significance from the JMP model, all aspects of each walling system studied in Module B decrease energy consumption.

It was also established through AccuRate that ICB construction in these hypothetical modules offer the least energy consumption. From the interaction plots developed using JMP, the best performing walling systems has low O_TM, high I_TM and is insulated, and such construction is IRBV

The engineering significance plots created with JMP, determine that the north and west walls behave similarly requiring high insulation, O_TM and I_TM, while the east and south walls are similar, requiring high insulation and O_TM, but low I_TM. This implies that the best design is ICB on the north and west walls and IBV on the east and south.

The bench scale model was compared to AccuRate results through the TDR and thermal lag, and displayed a similar trend although there is a difference in TDR results of approximately 0.132 in all cases.

As presented in this paper hybrid walling systems have ability to significantly reduce the energy usage in residential buildings. To minimise energy consumption and create a sustainable future smarter use of walling systems needs to be harnessed and thermal mass in buildings need to be utilised.

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