Thermal and structural performances of insulated cavity rammed earth wall houses

Xiang DONG

Thesis submitted in fulfilment of the requirements for the degree
of Doctor of Philosophy

The University of Adelaide
Faculty of Engineering, Computer and Mathematical Sciences
School of Civil, Environmental and Mining Engineering

Table of Contents

Abstract

Rammed earth (RE) wall construction is perceived to carry extremely low embodied energy and have desirable thermal performance without much energy input for heating and cooling due to the thermal mass effect. In Australia, however, because of the low thermal resistance (R-value) of RE material, it is very difficult for houses constructed with only solid RE walls to comply with the *Deemed-to-Satisfy Provision* provided in the National Construction Code (NCC) by the Building Code of Australia, which specifies the minimum R-value for external walls. The NCC provides an alternative provision, named the *Energy Efficiency Provision*, which states a maximum allowance of energy use by a residential house. As houses have the potential to consume little energy load particularly when passive design strategies are implemented, houses built with RE walls may still be able to comply with the *Energy Efficiency Provision* of the NCC.

Adding thermal insulation to the wall construction is one way to ensure that RE wall houses comply with NCC. Normally, rigid board foam insulation can be inserted in the middle of RE walls to maintain the aesthetics of the wall surfaces and part of the thermal mass effect. The result of this solution is an insulated cavity rammed earth (ICRE) wall system. This solution, however, generates three questions. On one hand, inserting insulation in between two rammed earth wall “leaves” is likely to have an impact on the structural strength of the building and the integrity of the wall system. Using the ICRE wall system in seismically prone areas in Australia may not be wise since the seismic resistance of the walls is mainly achieved through flexural strength. On the other hand, although this solution can meet the R-value requirement of the NCC, the actual thermal performances (thermal comfort and energy demand for heating and cooling) of houses built with ICRE walls are unknown. In addition, the construction and operation costs during the life cycle of the house may be considerably increased.

In order to address these questions, in the presented research, firstly the energy loads of a hypothetical house constructed by uninsulated RE walls were investigated using thermal simulation, taking into account passive design strategies. The results indicate that uninsulated RE wall houses struggle to meet the *Energy Efficiency Provision*, particularly in cold climates. Secondly, the structural strengths (compressive and flexural) of ICRE walls were investigated by laboratory tests which proved that this wall system can be safely used for single story houses in any seismic zone in Australia, as long as the wall thickness and height are within a specified range. Thirdly, the thermal performances of houses constructed with ICRE walls (both naturally ventilated and air-conditioned) were investigated, from which the effects of key design parameters on the thermal comfort and energy loads were quantified, including the window size in each wall, window shading, window construction type, ventilation rate, the amount of thermal mass and insulation thickness. Also, the life-cycle cost of an ICRE wall house was minimised by optimising these key design parameters.

Statement of Originality

I, Xiang Dong, hereby certify that this work has not been previously accepted for any other degree or diploma at any other University or Institution. To the best of my knowledge and belief, no material in this thesis is from the work of other people, except where due reference are made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

I acknowledge that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I give permission for the digital version of this work being made available on the web, via the University's digital research repository, the Library catalogue, the Australian Digital Thesis Program (ADTP) and also through web search engines, unless permission has been granted by the University to restrict access for a period of time.

Signed……………………Date: …………………………

Acknowledgements

I would like to sincerely acknowledge my principal supervisor Professor Michael Griffith and co-supervisor Associate Professor Veronica Soebarto for their guidance, support and encouragement during all my Ph.D. candidature period. Without their valuable advice and comments, I would not have been able to complete my project, nor would I have produced four journal papers.

I would like to show my appreciation to Dr Craig Willis and Associate Professor Terry Williamson who have provided me great suggestions on my research. Special thanks to the school editor, Ms. Barbara Brougham, who has been of great assistance in bringing to completion both the thesis and the papers associated with it.

I would like to sincerely acknowledge the assistance from David Robert from Stabilized Earth (Adelaide) Pty Ltd. who provided the specimens for material tests and the full-scale RE wall. And the lab staff from the School of Civil, Environmental & Mining Engineering was also of great assistance in the conduct of the experimental program. Many thanks also go to Dr Stephen Carr for the IT service.

Finally, I would like to thank the University of Adelaide and the China Scholarship Council for awarding me the scholarship to support my Ph.D. program.

List of Figures (excluding figures in papers)

List of Tables (excluding tables in papers)

Chapter 1 Introduction

1.1 Research background

Buildings in Australia, including residential premises, are important contributors to greenhouse gas emissions and climate change (Centre for International Economics, 2007; Morrissey and Horne, 2011) where the residential sector consumes 8% of the total energy use (Australian Bureau of Statistics, 2009a) and produces 9% of greenhouse gas emissions (Australian Bureau of Statistics, 2010). More than 40% of this energy consumption is used for space heating and cooling (Australian Bureau of Statistics, 2009b). Therefore, the development of residences containing low embodied energy and which require little energy for space heating and cooling is of prime interest to architects and builders. For buildings, the embodied energy is the sum of energy input for production and transportation of building materials, as well as for assembling materials to form the building (Reddy and Jagadish, 2003).

As an ancient construction technique for building structural walls, rammed earth (RE) has experienced a revival in recent years. It is perceived to be environmentally friendly and sustainable in many respects. First of all, the main material used for RE constructions is raw earth, which contains extremely low embodied energy, in particular when locally available materials are used (Morel, et al., 2001; Reddy, et al., 2014; Reddy and Kumar, 2010b; Treloar, et al., 2001). Moreover, buildings consisting of mass elements, such as RE walls, may benefit from the thermal mass effect from the walls, which help moderate indoor temperatures (Soebarto, 2009; Taylor and Luther, 2004). This effect results in maintaining thermal comfort and reduce energy demand for space heating and cooling, in particular when the mass effect is implemented with the passive design strategies (Baggs and Mortensen, 2006).

Because of the low thermal resistance (R-value) of RE material, it is difficult for house designs using only uninsulated RE external walls to satisfy the *Deemed-to-Satisfy Provision* of the Building Code of Australia (BCA) within the Australian National Construction Code (NCC) (Australian Building Codes Board, 2013). Table 1 summarizes the minimum R-value for external walls for Class 1 buildings (residential), for each climate zone in Australia. According to the BCA, climate zones are “defined for specific locations, having energy efficiency provisions based on a range of similar climatic characteristics” (Australian Building Codes Board, 2013).

Table 1. 1 Minimum R-Value requirements for exterior walls in different climate zones

Climate zone	Example city	Target R-value, m^2k/w
1	Cairns	2.8
2	Brisbane	2.8
3	Longreach	2.8
4	Griffith	2.8
5	Adelaide	2.8
6	Melbourne	2.8
7	Ballart	2.8
8	Perisher Smiggins	3.8

According to previous studies (Hall and Allinson, 2009; Taylor and Luther, 2004; Walker and Standards Australia, 2002; Yan, et al., 2005), a typical 300mm thick RE wall has an R-Value of only 0.27- 0.70m^{2}K/W. The NCC has an alternative requirement for external walls with a surface density greater than 220kg/m^2. It states that equivalent wall insulation with an R-Value of 0.5 to 1.0m^{2}K/W (depending on other design parameters) shall be added. A typical 300mm thick RE wall normally has a surface density between 540 and 660kg/m^2 (Taylor and Luther, 2004). Thus insulation with an R-Value of 0.5 to 1.0m^{2}K/W is required for solid RE walls in all climate zones except for the Alpine zone.

The NCC provides an alternative provision, which is known as the *Energy Efficiency Provision*, or *Star Rating Requirement*. This provision requires the total predicted energy loads for heating and cooling of a house to be equal to, or less than, the maximum allowance. With the benefits of the thermal mass effect, RE wall houses located in climates with moderate weather may be able to meet the *Energy Efficiency Provision*, in particular when passive design strategies are implemented, such as direct gain passive heating and night ventilation passive cooling (Balaras, 1996; Givoni, 1991; Shaviv, et al., 2001).

According to some studies conducted on the actual thermal performance of RE buildings, the buildings cannot necessarily provide the expected thermal comfort with low energy consumption (Soebarto, 2009; Taylor, et al., 2008). Thermal mass only performs well when there is a large variation of daytime and nighttime temperatures. The variation in daily temperature provides the time and circumstances required by the thermal mass to delay the extreme outdoor temperatures reaching the inside of a house until the evening drop in temperature can moderate their effect. In situations with constant low or constant high temperatures, even buildings with considerable amount of mass require large amounts of energy for space heating or cooling since they either get hot and stay hot or remain as cold as the external environment, In this case, the thermal resistance (R-value) of the building envelope is essential to control the indoor thermal environment. In cold or hot climates, or in situations with little temperature variation, such as during winter days and nights, improving the building envelope with high insulation can effectively prevent heat draining from the inside to the outside of the building or cold settling in.

Consequently, adding insulation to solid RE walls seems to be the only practical way to possibly meet either the *Deemed-to-Satisfy Provision* and/or the *Energy*

Efficiency Provision of the NCC. There are however challenges in adding insulation to RE walls. The insulation cannot be installed on the interior surface of the wall without compromising the benefits to be gained from the thermal mass. Install the insulation on the exterior wall, on the other hand, will sacrifice the aesthetic appearance of RE walls. Therefore, installing insulation (normally with rigid board insulation) in the middle of two earthen leaves is the most common way, forming an insulated cavity rammed earth (ICRE) wall system (Hall and Swaney, 2005).

The structural performance of this wall system, however, requires investigation as making a cavity and adding insulation inside RE walls is likely to affect their strength and integrity. It may be risky to use an ICRE wall system in seismically prone zones, for example. Furthermore, although ICRE walls can meet the provisions of NCC as long as sufficient insulation is installed, there is no guarantee of satisfactory thermal comfort and energy reduction. Other building parameters, such as glazing, shading and ventilation, as well as the influences of local climate (Baggs and Mortensen, 2006), are critical. In addition, the potential cost increase caused by adding insulation was unknown. No published study was found to address these issues. Therefore, in order to fill these research gaps, the thermal and structural performances of this wall system, as well as the life-cycle cost of houses constructed with ICRE walls required investigation.

1.2 Research objectives

The major objectives of this research therefore were:

Aim 1: to investigate the structural performance of the ICRE wall system strictly based on experiments.

- *Aim 1.1:* to evaluate the material properties of RE material including compressive strength, flexural strength, Young’s modulus and stress-strain relationship, by testing small scale specimens.

- *Aim 1.2:* to investigate the flexural behaviour of full-scale solid RE walls and ICRE walls under out-of-plane lateral load.
- *Aim 1.3:* to estimate whether ICRE wall system can be safely applied in seismic prone zones in Australia.

Aim 2: to determine whether uninsulated RE wall houses can meet the Energy Efficiency Provision of NCC in three different climates in Australia – hot arid, warm temperate and cool temperate. In order to take full advantage of the thermal mass effect and passive solar strategies, a set of key design parameters related to external RE walls are optimised, including window size in each wall, window shading, window openable rate, the amount of thermal mass and window construction type.

Aim 3: to investigate the thermal performance of naturally ventilated ICRE wall houses in three different climate zones in Australia, taking into account the effects of key design parameters including window size in each wall, window shading, window openable rate, the amount of thermal mass and insulation thickness.

Aim 4: to minimise energy loads and life-cycle cost of air-conditioned houses constructed with ICRE walls by optimizing a number of key design parameters including window size in each wall, window shading, the amount of thermal mass and insulation thickness.

1.3 Organization of the thesis

This is a “thesis by publication”, which means the thesis “comprises a portfolio of publications that have been published and/or submitted for publications” (Adelaide Graduate Centre 2014). In this thesis, the published and accepted manuscripts can be found in Chapters 4 to 7, which contain the results of the research.

This thesis starts with Chapter 1 to provide a brief background of this research, followed by Chapter 2 which presents a detailed literature review on relevant studies and standards. At the end of the literature review, the research gaps are presented. Chapter 3 provides a brief methodology of this study addressing these research gaps, followed by Chapters 4, 5, 6 and 7, which is a collection of published and accepted journal papers, corresponding to research aims 1, 2, 3 and 4, respectively. In Chapter 8, the major outcomes of this research are summarised, and the limitations of this research are listed for future studies.

Chapter 1 presents the research background, objectives and major contributions. The logical sequence of this research starts with a question: whether uninsulated RE wall houses can meet the *Energy Efficiency Provision* of the NCC.

Chapter 2 provides a detailed literature review. First of all, a background knowledge of RE is provided, especially the construction process. Secondly, the principle of thermal mass effect is described, including thermal time lag and decrement factor, followed by a review of thermal resistance and its effects on the thermal performance of a house. Then, the *Deemed-to-Satisfy Provision* and the *Energy Efficiency Provision*/*Star Rating Requirements* of BCA are introduced, followed by a review of passive design strategies (direct gain passive heating and night ventilation passive cooling). Some studies on the thermal performance of real RE wall houses are reviewed. The structural properties of RE material and the structural requirements of RE walls are then discussed, followed by a review of studies focused on the flexural behavior of cavity/veneer walls. Finally, studies related to thermal performance simulations are reviewed including some details on the software *AccuRate* as well as the adaptive comfort standard and life-cycle cost analysis. Research gaps based on the literature review are presented.

Chapter 3 presents a brief methodology of this study. Both experimental investigations (for the structural performance of ICRE walls) and simulations (for the thermal performance of ICRE wall houses) were conducted.

Chapter 4 describes the research completed in relation to the issue of whether ICRE walls have sufficient strength (in particular flexural strength) to be used in Australia. Experimental tests were conducted to determine the flexural strength of a full-scale ICRE wall (consisting of two 175mm thick RE wall leaves with a 50mm thick polystyrene insulation between them). Material tests were also conducted to determine whether the strength of full-scale walls can be reasonably predicted by small scale specimens taken from the full-scale walls. Finally, the feasibility of using ICRE walls in Australia is analyzed.

Chapter 5 reports on the research into the potential reduction of heating and cooling loads in an uninsulated RE wall house by optimizing a number of design parameters, and whether an uninsulated RE wall house can comply with the star rating requirement in Australia. The research was conducted by simulation using *Accurate* software (CSIRO, 2004).The analysis described in this chapter was conducted in three different climate zones in Australia– zones 3, 5 and 7- representing hot arid, warm temperate and cool temperate climate, respectively. The relative design parameters were the window size in each wall, window shading, window openable rate, the amount of thermal mass and the window construction type. The findings presented in Chapter 4 indicate that it is difficult for uninsulated RE wall houses to meet the requirements of NCC, particularly in cold climates. Therefore, insulation should be added to RE walls.

In **Chapter 6,** research involving the indoor operative temperatures of naturally ventilated RE houses is described, including using the software *AccuRate* (CSIRO, 2004) , considering a set of key design parameters such as window size, window shading, window openable rate, the amount of thermal mass and insulation thickness. Then the predicted indoor temperatures are compared to the adaptive comfort standard. Based on the simulation results, the optimum value of each design parameter corresponding to maximum thermal comfort is determined.

Chapter 7 is an expansion of Chapter 6, which describes the investigations into the effects of key design parameters on the thermal performance (energy loads) and life-cycle cost of ICRE wall houses.

In **Chapter 8,** major outcomes of this research are presented and the limitations of this research are also noted, along with indications for future studies.

In **Appendix A,** material test results are provided, including the tests for compressive strength, Young's modulus, stress-strain relationship and flexural tensile strength. Comparisons are made between the strengths derived from testing molded specimens and cut specimens. **Appendix B** provides the *Batch*

Files Code which is used to run the thermal performance simulation. **Appendix C** presents the copy of published journal papers.

1.4 Research contributions

Experimental tests were conducted to investigate the structural performance of ICRE wall systems, in particular the pioneer test of ICRE walls under out-of-plane vertical bending. The feasibility of using this system for wall construction in one-storey residential houses in Australia was proven by the test results, which indicate that typical ICRE walls on the current construction market seem to be conservative and much thinner walls could be used to save construction costs and increase the indoor usable area. Also, some recommendations on predicting the strength capacity of ICRE walls were proposed.

With optimisation conducted by parametric studies, the research identified a set of key design parameters that will maximise thermal comfort and minimise energy loads and life-cycle cost. This parametric study, conducted by thermal simulations, contributes significantly to the development of sustainable residential houses in Australia, providing an opportunity to reduce the energy consumption and CO_2 release in the residential area.

The main contributions delivered by this research can be summarised as:

1. The test on the full scale walls (*Chapter 4*) is the first known work for the flexural behaviour of real size solid RE and ICRE walls under out-of-plane vertical bending. Researchers and engineers will be able to use the results for research and structural design. It was found that Flexural strength capacity of a full-scale ICRE wall can be predicted by the sum of strength capacities of the two RE leaves, and ICRE (with each wall leaf thicker than 125mm) has sufficient flexural strength to be applied in any seismic zone in Australia for single story houses. The material properties of RE including the compressive strength,

Young's modulus, stress-strain relationship and flexural strength were also evaluated by testing both molded and cut/cored specimens from full-scale walls (see *Appendix*). In terms of compressive strength, specimens made in molds and taken from walls gave similar results. The differences between the flexural strengths of these two types of specimens imply that the construction joints between two ramming layers are weak points in terms of tension. Recommendations are proposed for preparing representative test specimens for determining the flexural strength of RE walls. Specimens taken from real size walls give reasonable predictions, while using strengths derived from molded specimens may overestimate the strength of full size walls. In terms of compressive strength, specimens made in molds and taken from walls provided similar results. For structural designs, if testing of flexural strength of RE material is not available, the characteristic flexural strength of RE material can be taken as 10% of the characteristic compressive strength.

2. The research confirmed that adding insulation is the only practical method for RE wall houses to meet the requirements of NCC (*Chapter 5*). Star ratings of houses constructed using uninsulated RE walls were investigated, considering key design parameters including window size, window shading, window openable rate, the amount of thermal mass and window construction type. Results of tests demonstrated that, in hot arid climates, uninsulated RE wall houses can meet the star rating requirement of the NCC only if a number of design parameters are optimised. In warm temperate climates, it is possible, but difficult, to control the energy loads within the maximum allowance in the NCC. In cool temperate climates, however, it is impossible for solid RE wall houses to meet the star rating requirement and space heating is necessary to maintain thermal comfort.

3. It has been proven by the study that houses in hot arid climates and warm temperate climates and constructed using ICRE walls can provide satisfactory thermal comfort without additional heating and cooling, as long as key design parameters are optimized (*Chapter 6*). The effect of each design parameter on the indoor operative temperatures was quantified. Therefore, designers and house

owners are able to make informed design decisions based on the simulation results. For example, in a hot arid climate, small windows are desirable to prevent solar heat from entering the house; however, if large window are preferred for better views by house owners, they can be installed in the south wall (for houses located in the northern hemisphere, this should be read as ‘north wall’), as windows in this wall have only a minor influence on the overall thermal comfort of the house. In cool temperate climates, a heater will be required to achieve thermal comfort.

4. Optimisation of ICRE walls for houses was conducted to minimise the energy loads and life-cycle cost (*Chapter 7*). Both single parameter optimisation and multiple parameter optimisations were performed. Recommendations on design parameters are provided including window size on each wall, window shadings, wall thickness and insulation thickness. The study quantified the effect of each parameter on the energy loads and the life-cycle cost of ICRE wall houses. With the given results, designers and house owners will be able to design cost effective RE wall houses by balancing the choice of design decisions and their cost. In general, the thicker the walls/insulation was applied, the less the energy load, but the higher the life-cycle cost. The effects of other parameters on the energy and life cycle cost, however, varied depending on climates.

Chapter 2 Literature review

2.1 Background knowledge about rammed earth

RE is an ancient construction technique for building structural walls using raw earth, and recently there has been a revival of RE construction because it is perceived to be environmentally friendly and sustainable in many aspects. As a construction material, RE carries extremely low embodied energy, especially when the raw material can be sourced locally (Morel, et al., 2001; Reddy and Kumar, 2010b; Treloar, et al., 2001). Modern RE material is commonly stabilised by cement (in a range of 3-12% by weight) for greater structural strength and duration (Morel, et al., 2007; Ngowi, 1997; Reddy and Gupta, 2005; Walker, 1995). Even when 8% cement (in weight) is used as stabiliser, RE still has a low embodied energy of only 0.5GJ/m3, which is 15-25% of the value for the same volume of burnt clay brickwork walls (Reddy and Kumar, 2010b).

The raw earth material for RE normally consists of clay, silt, sand and gravel in proportion, varied according to different standards (Delgado and Guerrero, 2007). The raw earth materials should be filtered to exclude large particles greater than 20mm (Middleton and Schneider, 1992; Walker and Standards Australia, 2002), Then water of less than 15% in weight (Delgado and Guerrero, 2007) is added for maximum compaction. The right moisture content can be determined by a ‘drop test’ (Easton, 2007): dropping a ball of the material from chest height onto a firm surface to determine from its behaviour whether it is too dry, too wet or ready for use. Once the earth mixture is prepared, it can be poured into a stiff frame work and then compacted into a solid panel at a density of between 1800 to 2200kg/m^3

(Hall and Djerbib, 2004). The construction process is shown in Figure 2.1, where it can be seen that after the wall is completed, there are construction joints between the rammed layers.

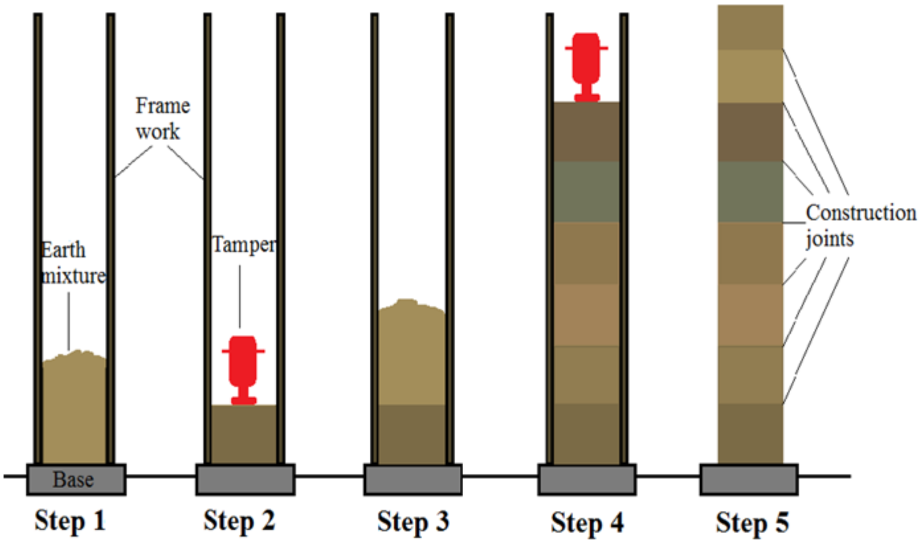


Figure 2.1 Construction process of RE walls

2.2 Thermal mass effect and thermal resistance of rammed earth wall

2.2.1 Thermal mass effect

Building elements with large thermal mass (for example RE walls) are essential for passive heating and cooling strategies (Gregory, et al., 2008). It has been claimed that buildings with large thermal mass will be able to provide thermal comfort and reduce the energy required for heating and cooling (Baggs and Mortensen, 2006). In summers, the thermal mass can be used as a heat sink to reduce the amount of solar heat from entering the house through the wall as well as the speed with which it enters (known as the 'thermal flywheel effect' (Baggs and Mortensen, 2006)). The internal maximum temperature of a RE house is reached hours later than the external maximum temperature (known as the 'time lag', see Figure 2.2. It has, in fact, been reported (Baggs, et al., 1991a) that a 250mm thick RE wall can provide a time lag of 10.3 hours, which means peak indoor temperatures can be delayed by a long thermal time lag until nighttime ventilation is available to cool the house. On the other hand, thermal mass can reduce the size of the energy wave once heat has moved through RE walls (known as the 'decrement factor', see Figure 2.2 (Baggs and Mortensen, 2006).

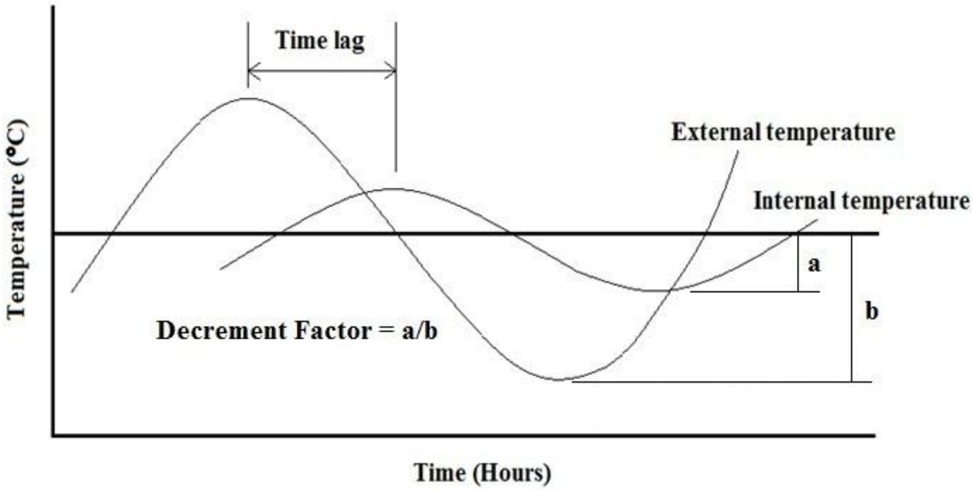


Figure 2.2 Time lag and decrement factor

With the function of storing solar heat and delaying heat transfer, the internal temperature swing of RE wall houses can be smoothed out and energy input for space cooling can be reduced. This has been proved by a study from Taylor and Luther (2004), where the indoor temperatures and heat flux through RE walls was measured. Their measured data indicated that the indoor temperature swing was effectively reduced and heat transfer from the outside of the house to the inside of the house was delayed, and once the heat enters the house, indoor temperatures can be reduced by night cooling.

2.2.2 Thermal resistance (R-value)

It should be noted that the thermal mass effect of external walls can only reduce and delay indoor extreme temperatures, and it works best in climates where there are clear diurnal temperature cycles. In a hot climate with hot temperatures in both daytime and nighttime or where cool nighttime ventilation is not available, houses will experience extreme hot indoor temperatures if external walls (with low R-value) cannot effectively prevent heat entering the house, particularly after several days with extreme outdoor temperatures. Consequently, a large amount of energy may be required for cooling in such climates. Moreover, the required energy may be greater than that for houses constructed with lightweight materials, because some of the cooling effort may be directed toward cooling the thermal mass of external walls.

In winters, the thermal mass can be used for heat storage to absorb and store solar heat during the day which will be released back into the house at night, reducing the heating load (Baggs and Mortensen, 2006; Soebarto, 2009). This will happen only when solar heating is sufficient in daytime; otherwise, thermal mass will not be as effective. Moreover, in spite of the benefit of thermal mass, the thermal performance of buildings in cold climates is mainly determined by thermal resistant capacity (R-value) of the building envelope. For example, in a cold climate, the heat drainage through external walls (with a low R-value) may outweigh the heat gains absorbed and then released by the thermal mass of the external walls. In this situation, a large amount of energy input may be required for space heating of the indoor environment. Furthermore, some of the heating effort may be toward warming the thermal mass. This was proved in a study by Soebarto (2009), where it was argued that the heating load in houses with uninsulated RE walls may be greater than that for insulated masonry houses.

2.3 Compliant with BCA requirements

2.3.1 Deemed-to-Satisfy Provision

According to previous studies (Hall and Allinson, 2009; Taylor and Luther, 2004; Yan, et al., 2005), a typical 300mm thick RE wall has an R-value of only

0.27-0.70m^{2}K/W, which is very low compared to the R-value of insulating materials with the same thickness. For example, 300mm thick extruded polystyrene insulation board has an R-value of 8.6-12.0m^{2}K/W (Papadopoulos, 2005). Because of the low R-value of RE, it is currently difficult for house designs using only RE walls to satisfy the *Deemed-to-Satisfy Provision* of the Building Code of Australia within the Australian National Construction Code (NCC) (Australian Building Codes Board, 2013), where it requires that for Class 1 buildings (detached residential) located in all climatic zones in Australia, except the Alpine zone, the minimum required R-Value for external walls is 2.8m^{2}K/W. (In the Alpine zone the minimum requirement is 3.8m^{2}K/W.)

The NCC has an alternative requirement for external walls with a surface density greater than 220kg/m^2, which states that an equivalent wall insulation with an R-value of 0.5 to 1.0m^{2}K/W (depending on the other design parameters) shall be added. This means that for a typical 300mm thick RE wall (R value of 0.27-0.70m^{2}K/W), with a surface density of between 540 and 660kg/m^2(Taylor and Luther, 2004), a minimum insulation with an R-value of 0.5 to 1.0m^{2}K/W is still required.

2.3.2 Insulated cavity rammed earth walls

For RE walls, insulation cannot be installed on the interior wall without compromising the benefits to be gained from the thermal mass. Nor can insulation be installed on the exterior wall as this will sacrifice the aesthetic appearance of RE walls. Therefore, rigid insulation board (extruded polystyrene or polyisocyanurate) is commonly installed in the middle of two earthen leaves, forming an insulated cavity rammed earth (ICRE) wall system (Hall and Swaney, 2005), as shown in Figure 2.3. This wall system, which can easily meet the R-value requirement of the NCC, is well-accepted and gaining popularity (Hall and Swaney, 2005).

Figure 2.3 Insulated cavity rammed earth wall

The cost and difficulty of making ICRE walls are, however, much greater than that for making solid RE walls. On one hand, the costs of insulating materials and wall ties have to be added and the amount of labour for installing them will increase. In addition, inserting an insulation layer in the middle of two wall leaves makes the ramming work much more difficult and time consuming because the insulating material is brittle; extra attention is required to protect the insulation layer when ramming the earth. Moreover, placing thermal insulation in the middle (of a cross section) of a RE wall is suspected to reduce its structural integrity.

2.3.3 Energy Efficiency Provision (Star Rating Requirement)

If adding insulation is not preferred, there is an alternative option for uninsulated RE walls to potentially meet the requirement of BCA, which is known as the star rating requirement (Australian Building Codes Board, 2013). According to this requirement, there are 10 star ratings (1 to 10) in the

Nationwide House Energy Rating Scheme (NatHERS) (NatHERS National Administrator, 2012), each stating a reference value of the total heating and cooling loads. The more stars achieved, the less energy is required for heating and cooling to maintain comfort. The star rating is based on space heating and cooling only; other energy demands, such as domestic hot water (DHW) and lighting are not included. The star rating bands vary according to "climatic regions". According to NatHERS, the 8 Australian climate zones are then further divided into 69 climate regions (unfortunately NatHERS also uses the term climate zones. For clarification, the term climate region is used in the thesis), and each climate region varies sufficiently from the others and require significant differences in house design (NatHERS National Administrator, 2012). In other words the climate regions, each representing a city with typical local climate conditions, are the further subdivisions of the climate zones. For example, Adelaide and Ceduna are both in BCA Climate Zone 5 (Warm temperate) , but in NatHERS, Adelaide is in climate region 16 while Ceduna is in climate region 53.

The same star rating can correspond to different energy load rates for different cities considering the extremes of the local weather conditions. In Adelaide (climate region 16), the 6-star rating states a maximum energy load of 96MJ/m^2 per annum, while in Ballarat (climate region 66) the 6-star rating states an energy load of 197MJ/m^2 per annum. By comparing the predicted energy loads for heating and cooling in order to maintain indoor thermal comfort to the reference value for each star rating load, a building design can be assigned a star rating. From 2010, Class 1 buildings (residential) have to achieve a 6-star rating as a minimum. In other words, the total predicted energy load for heating and cooling of the building must be equal to or less than the maximum allowed for each climate region for a 6-star rating.

Table 2. 1 Maximum allowance for 6-star ratings in some climate regions

Climate region	Climate type	Typical city	6-star rating (MJ/m^2 p. a)
3	Hot arid	Longreach	141
16	Warm temperate	Adelaide	96
66	Cool temperate	Ballarat	197

2.3.4 Passive design strategies

Passive design strategies (such as direct solar gain for passive heating and natural ventilation for passive cooling) have been reported to be effective in reducing energy input for heating and cooling if properly implemented with thermal mass (Balaras, 1996; Givoni, 1991; Shaviv, et al., 2001). Direct gain uses thermal mass to store solar heat which is collected through window glazing, and to release the heat during the cool night. Direct gain passive solar strategy depends on features such as glazing location, orientation, size and type, as well as the amount and design of thermal mass (Givoni, 1991). The passive cooling strategy (natural nighttime ventilation) depends on cool night winds to lower indoor temperatures. When natural nighttime ventilation is coupled with a suitable amount of thermal mass, it is an effective way of reducing the cooling load since the thermal mass cooled by the night ventilation can be used as a heat sink during the day (Shaviv, et al., 2001).

2.3.5 Thermal performance of occupied rammed earth houses

Although passive design strategies were perceived to be able to reduce the heating and cooling loads of uninsulated RE wall houses theoretically, applying these strategies cannot guarantee that the heating and cooling loads of RE wall houses are being controlled within the maximum allowance for

6-star ratings. Some studies have indicated that the real thermal performance of uninsulated RE wall houses was actually unsatisfactory.

Paul and Taylor (2008), conducted a survey to compare the occupants' satisfactory level of thermal comfort (in terms of indoor temperature) and other comfort aspects (such as humidity, ventilation, aesthetics, serenity, lighting and acoustics) of a RE office building and a nearby conventional office building constructed of insulated brick veneer. These two buildings were located in southeast Australia with a Mediterranean climate (hot dry summer and cool wet winter). The RE building was naturally ventilated, while the insulated brick veneer building was air-conditioned. The survey results indicated that the RE building cannot provide better thermal performance than the conventional buildings, and occupants claimed that the internal environment was warm, leading to an unsatisfactory thermal comfort. In addition, no evidence was observed to prove that R building performed better than the conventional building on the other comfort aspects.

Later, Taylor et al. (2008) investigated the thermal comfort and energy use of the uninsulated RE office building by monitoring the indoor temperature. According to the coincidence of the measured data and the adaptive comfort zone (de Dear and Brager, 1998), during a four week period in summer, the three monitored offices provided comfortable indoor environment for 73-81% of the time. During a 38-day period in winter, however, the three offices only provided comfort indoor environment for 13-70% of the time. Moreover, with this unsatisfactory thermal comfort, this office building consumed 30% more energy than the maximum allowance of NCC (Australian Building Codes Board, 2013). Later, aiming to reduce the energy load, two strategies, namely adding insulation to external walls and a combination of adding insulation, using low-E windows and reducing the infiltration, were investigated by simulation. The results showed that for the stated 38-day winter period the heating load was reduced significantly from 390.5 to 249.0MJ only by insulating the external walls and the value was further reduced to 62.3MJ when the low-E windows and a lower infiltration rate were applied.

Soebarto (2009) investigated the thermal performance of two solid RE wall houses and an insulated RE wall house. The monitored indoor temperatures showed that in summer, these three houses had similar performance, while in winter, the insulated RE house provided indoor temperatures of $5^{o}C$ higher on average than the two uninsulated RE houses. Later, in order to confirm that the differences in thermal performance between insulated and uninsulated RE wall houses was not caused by different house design, size and occupancy, the thermal performance of three hypothetical houses was simulated. Two model houses were developed based on the two monitored uninsulated RE houses except that the external walls were replaced by insulated RE walls. The third model house was developed based on the monitored insulated RE houses except that the external walls were replaced by uninsulated RE walls. The simulation results indicated that the indoor temperatures of two uninsulated RE houses could increase by $4.9^{o}C$ on average in winter (corresponding to a 26-29% decrease in discomfort degree hours) if the external walls were insulated in winter. On the contrary, if the external walls of the insulated RE houses were replaced by uninsulated RE walls, the indoor temperatures would be reduced by $4.7^{o}C$ on average (corresponding to a 19% increase in discomfort degree hours).

In summary, adding thermal insulation to solid RE walls will improve the thermal performance of RE houses and meet the requirements of NCC simultaneously.

2.4 Structural properties of unreinforced rammed earth walls

2.4.1 Vertical resistance of unreinforced rammed earth walls and design requirements

The compressive strength of cement stabilised RE material has been widely tested and reported in a large number of published studies (Ciancio and Gibbings, 2012; Morel, et al., 2007; Reddy, et al., 2007a; Reddy and Kumar, 2011a; Reddy and Kumar, 2011b; Reddy and Kumar, 2010c). The compressive strength of cement stabilised RE material reported in these studies varied significantly from 0.5MPa to 25.0MPa, depending on many factors, including how the material specimen was obtained (manufactured in a mold or taken from walls), as well as the material's dry density, clay content, soil grading, specimen size, specimen shape, curing time, moisture content, and stabiliser (cement) content. For compressive strength of full-scale RE walls, however, the investigation was limited. A study reported by Reddy and Kummar (2010a) observed a stress reduction factor of 0.72 for a RE wall with a slenderness ratio of 16.8 and subjected to compressive stress with no eccentricity.

As load bearing structural elements, RE walls must have sufficient compressive strength to resist the compressive stress created by elements above the walls. RE is commonly used for one or two storey houses, and the compressive stress above the wall is mainly contributed by the wall weight and the weight of ceiling and roof. This stress is approximately 0.1MPa for single storey houses (Jayasinghe and Kamaladasa, 2007) and between 0.8 to 1.0MPa for two storey houses (Jayasinghe, 1999).

The *Australian Earth Building Handbook* (Walker and Standards Australia, 2002) and *Australian Standard AS3700* (Standards Australia, 2001) state that for compressive strength design, a capacity reduction factor not greater than 0.45 should be applied (handbook: page 98; standard: page 34). This factor is used because the material strength in real structural members may differ from the strength derived from material tests. For structural design of members in compression, another reduction factor should be applied regarding the effect of slenderness ratio (wall height / wall thickness) and eccentricity. According to the *Australian earth building handbook*, the maximum slenderness ratio is 18 (Handbook: page 100) for a wall simply supported at top and bottom but rotationally free, which corresponds to a reduction factor of 0.48 for walls with floor or roof type other than concrete slab

(Standards: page 61). Hence, for single storey houses, the characteristic compressive strength of RE material should be at least 0.5MPa. This value agrees well with the suggested design compressive strength (0.4-0.6MPa) by the handbook for the situation when compressive strength experimental testing is not available. For two storey houses, the characteristic compressive strength of RE material should be at least 3.7MPa. Based on the results of experimental studies reviewed above, although the compressive strengths presented in these studies were mean values, it is not difficult to comply with the requirements of *Australian Standard AS3700* and *The Australian Earth Building Handbook* using RE for construction of single storey houses; and it is also possible to build two story houses using RE walls as the vertical load bearing elements.

2.4.2 Vertical resistance of unreinforced insulated cavity rammed earth walls and requirements

Limited studies have been conducted on the vertical resistance of insulated cavity masonry walls subjected to compressive loading. Wang et al. (1997a) and Wang et al. (1997b) performed numerical and experimental studies on the behaviour of cavity walls under eccentric loading. In their studies, the vertical load was subjected to the concrete block backup wall leaf (with a slenderness ratio of 28), only with different eccentricities. A hinge was applied along the top and bottom of the backup wall, and lateral movement was restricted at the top. The brick veneer was placed on a shelf angle and connected to the backup wall with shear wall ties. The results of these studies indicated that the vertical load capacity and ductility of cavity walls were much greater than that of single leaf block walls subjected to the same load.

The main failure pattern for walls with high slenderness ratios and subjected to vertical loads, with or without eccentricity, was buckling rather than material compression failure. Thus the researchers' results implied that the unloaded leaf connected to the loaded leaf with shear wall ties can help to improve the wall resistance under a high level of deflections. For cavity walls with two leaves connected with traditional flexible ties, composite actions between two wall leaves may not be achieved. Also, the cavity width had no considerable effect on the ultimate load resistance of cavity walls.

For structural designs of cavity walls, the *Australian standard AS3700* (Standards Australia, 2001) provides a method which requires that each wall leaf should be assessed separately. If both leaves are supported at top and bottom and the compressive stress is shared by them, the method for predicting the design compressive strength for each wall leaf is the same as that for single leaf walls. It is a conservative method which ignores any interaction between the two leaves, because only the minimum compressive and tensile strengths are required in the standard hence interaction between two leaves cannot be guaranteed due to the unknown shear stiffness of wall ties.

2.4.3 Lateral resistance of unreinforced rammed earth walls and requirements

Under out-of-plane lateral loads, such as wind loads and seismic load, the behaviour of RE walls mainly depends on their flexural strength and boundary conditions. Traditional RE constructions usually perform unacceptably during seismic events mainly because of the large weight and low flexural strength of RE walls (Yamin, et al., 2004; Zhou, et al., 2010). According to the study by Yamin et al. (2004), the flexural strength of the full scale RE wall tested was only 0.013MPa, which is much smaller than that of unreinforced brick masonry walls (0.49MPa) (Griffith, et al., 2004). Modern RE materials are usually stabilised with cement for greater strengths.

Jayasinghe and Mallawaarachchi (2009) tested the flexural strength of compressed stabilised earth walls with 10% cement. It was found that the flexural strength of stabilised RE wall was 0.46MPa, parallel to bed joints, and 0.92MPa, perpendicular to bed joints. Bahar et al. (2004) tested the tensile strength of cement-stabilised soil with different cement content of between

0-22% by weight. The test results showed that the tensile strength of cement-stabilised soil increases as the cement content increases and the tensile strength was approximately 0.8MPa.

Reddy et al. (2007b) conducted experimental studies on the flexural tensile strength of soil-cement blocks considering different cement content (4% and 8% by weight) and clay content (5-22% by weight). Note that in their study, the term ‘soil-cement blocks’ was used instead of stabilised RE. The results indicated that specimens with 8% cement had significantly greater flexural tensile strength than specimens with 4% cement, and clay content had an impact on the flexural tensile strength of soil-cement blocks. The optimum clay content was observed to be between 14-16%, and further increase the clay content over 16% would significantly decrease the strength. With 8% cement and clay content of between 5-16%, the average flexural tensile strength of tested specimens was 0.84MPa. Reddy and Gupta (2005) conducted an experimental program to investigate the material properties of soil-cement blocks considering three different cement contents namely 6%, 8% and 12%. According to their results, the tensile strength was much smaller than the flexural strength (0.29MPa versus 1.05MPa for specimens with 8% cement). As the cement content increased from 6% to 8%, the flexural strength increased from 0.48 to 1.05MPa, while a further increase in the cement content to 12% resulted in a moderate increase in flexural strength by 0.17Mpa.

According to the experimental studies reviewed above, ignoring different soil types, the flexural strength of cement stabilised RE material with cement content of 8-10% was between 0.46MPa and 1.05MPa.

With such an improved flexural strength, RE wall houses can have better seismic performance. In September 2010 and February 2011, two earthquakes occurred in New Zealand. The performance of earth buildings during these two earthquakes was inspected immediately after these earthquakes (Morris, et al., 2011; Morris, et al., 2010). During the first earthquake (with a magnitude of 7.1), stabilised RE wall houses with concrete/reinforced concrete floors and reinforced bond beams had relatively good performance, with only slight or moderate damages (minor damage occurred to non-structural elements or non-threatening damage to structural elements). These RE houses surveyed had a wall thickness of between 200mm and 500mm (with a wall slenderness ratio of 4.7-12.0) and experienced earthquake shaking with peak ground acceleration (PGA) of 0.15-0.80g. Another RE wall house built with 500mm thick RE walls was severely damaged with complete wall collapse, probably because the RE walls were subjected to strong shocking (with a PGA of 0.80g). The most common damage types of RE walls were classified, including out-of-plane damage, mid-height flexure damage, as well as diagonal and vertical crack damage (in particular adjacent to openings). After the later earthquake (with a magnitude of 6.3), another survey was conducted in nine cement-stabilised RE wall houses (with a wall thickness of between 150mm and 250mm). All of the RE walls were unreinforced but bonded with reinforced concrete bond beams. The inspection indicated that most of the RE houses only suffered minor damage with minor cracking that occurred after the earthquake.

Although during the survey, the cement content and the flexural strength of the RE materials were not available, the seismic performance of these houses during the two earthquakes implied that unreinforced cement stabilised RE walls have adequate flexural strength to resist moderate seismic loads, as long as they are constructed following instructions given in three New Zealand standards relating to earth buildings (Standards New Zealand, 1998a; Standards New Zealand, 1998b; Standards New Zealand, 1998c).

These three New Zealand standards are performance-based standards with specific requirements for safety design and construction of earth buildings to resist earthquake loading. *NZS 4297* presents the limit state design principles for engineers to follow (Standards New Zealand, 1998a). For unreinforced earth walls, an energy method is used to assess the ultimate seismic resistance of the walls based on the collapse mechanism, which defines the out-of-plane resistance by ultimate displacement capacity after cracking rather than the elastic flexural strength capacity before cracking. *NZS 4298* specifies the requirements for producing earth walls, including test methods of determining characteristic strengths and the minimum required strengths. *NZS 4299* provides details for design and construction of earth wall houses, covering key building elements such as footings, floor slabs, earth walls, bond beams and structural diaphragms.

The design method provided by *NZS 4297* is actually the displacement based design (Doherty, et al., 2002; Griffith, et al., 2003), which takes into account the reverse capacity of cracked walls under dynamic seismic loading. Compared to the force based method, this method is perceived to give better predictions of seismic resistance for unreinforced masonry walls, in particular for walls with large thicknesses. In Australia, however, the conservative force based method is applied in the only guidance for design of earth buildings- the *Australian Earth Building Handbook* (Walker and Standards Australia, 2002), to assess seismic resistance of earth walls. According to this guideline, the resistance capacity of an earth wall under out-of-plane seismic loading is determined by the flexural strength of the wall material and the compressive stress subjected at the top of the wall.

If experimental tests of flexural strength are not available, it is assumed that the flexural strength of RE material can be ignored (Walker and Standards Australia, 2002). In the New Zealand Standards (Standards New Zealand, 1998a), the flexural strength of RE material can be taken to be a value of 0.1MPa, or 10% of the characteristic compressive strength, in case the compressive strength tests are available. If experimental tests are available, the characteristic flexural strength of RE material derived from experiments should be modified by a reduction factor between 0.6 and 0.8 (Standards New Zealand, 1998a; Walker and Standards Australia, 2002) for structural capacity designs. The moment capacity of RE walls under out-of plane vertical bending can be calculated as (Walker and Standards Australia, 2002):

$$M_{cv} = (\emptyset\, f_t + f_d) \times Z \qquad \text{Eq. (1)}$$

where f_t is the characteristic design flexural strength of RE material; $\emptyset$ is the capacity reduction factor; f_d is the design compressive stress applied to the cross-section; Z is the section modulus of the considered cross-section, $Z = Lt^2/6$, L and t are the wall length and thickness, respectively.

Under seismic acceleration, the lateral load subjected to structural walls is mainly caused by their self weight. The demand moment of a RE wall under vertical bending can be calculated as:

$$M_{dv} = \omega H^2/8 \qquad \text{Eq. (2)}$$

where ω is the load caused by wall self weight; $\omega = ma$, m and a are wall weight and seismic acceleration, respectively; H is the wall height.

Based on Equations 2.1 and 2.2, it is clear that the required flexural strength of a RE wall under seismic loading depends on its dry density, geometry and seismic acceleration factor.

2.4.4 Lateral resistance of unreinforced insulated cavity rammed earth walls and requirements

No analytical study has been conducted to investigate the flexural behaviour of ICRE walls under out-of-plane lateral load, while some studies investigated the flexural behaviour of cavity and veneer walls with or without insulation. RE is commonly considered as a masonry material as its structural properties are similar to those of brick or block masonry (Jaquin, et al., 2009; Jayasinghe and Mallawaarachchi, 2009). Therefore, it is assumed that the behaviour of cavity brick walls is similar to that of cavity RE walls.

An extensive experimental study has been conducted by the British Ceramic Research Association in order to investigate the lateral resistance capacity of cavity walls subjected to lateral loads (West, et al., 1979; West, et al., 1977). There were in total 53 full-scale cavity walls with dissimilar or similar wall leaves and different types of wall ties. The wall leaf type included aerated concrete, heavy aggregate, lightweight aggregate and two different brick walls. The wall ties used in these cavity walls included vertical twist wall ties, butterfly wall ties, polypropylene wall ties and truss type reinforcement. Based on the test results, conclusions can be made as: (1) the flexural strength of cavity masonry walls under lateral loads can be safely predicted by adding the flexural strength of each wall leaf, the average ratio of the tested lateral strength of cavity walls to the sum of strengths of two wall leaves for 24 of the tested walls was 1.08; (2) some composite actions between two wall leaves may be obtained with narrow cavities and stiff vertical twisted ties; (3) there was no considerable effect of cavity width on the flexural strength of cavity walls; and (4) if two wall leaves had significant different stiffness, stiff ties were required for safe designs.

Memari et al. (2002) developed a 2-dimension finite element analytical model to investigate the flexural behaviour of brick veneer-concrete masonry backup wall system under seismic loading. The model was developed as a five-story structure, while only the wall system at the fifth floor was analysed. In the fifth floor, the lateral movement of the backup wall at top and bottom was restricted. Vertical movement and rotation at the top of the backup wall was allowed. The bottom of the backup wall was assumed to be attached to the floor at the beginning, but after cracking of the bottom interface, the bottom of the backup wall was assumed as a rotational spring. For the veneer wall, the top was not restricted for lateral movement or rotation, while the bottom was assumed as a rotational spring. The ties (HRT60 stainless steel with a cross section of 8mm) were modelled as pin-ended tension-compression elements connecting the veneer and backup wall. Accelerations were input at the bottom of the structure to evaluate the forces in wall ties. It was found that forces in wall ties were not equally distributed and the ties at top and bottom of the wall system experienced the largest force. They also pointed out that if other types of wall ties were used, different behaviour might be observed.

Brown and Elling (1979) investigated the load distribution in cavity walls under lateral loading by an analytical model. The results indicated that: (1) the force in the ties at floor level was much larger than that in other ties; and (2) it is unacceptable to predict the load distribution is cavity walls only based on the flexural rigidity of each wall leaf suggested by most design standards. The effects of wall ties (tie spacing, size, stiffness and strength) and boundary conditions of each wall leaf should be considered.

Page et al. (2007) conducted research on the force in wall ties of cavity or veneer walls subjected to lateral load. A cavity wall was built and tested under lateral loading through an air bag. Both leaves of the cavity wall were constructed by brickwork and two leaves were connected with medium duty stainless steel wires. The loaded leaf was free at bottom, while the unloaded leaf was supported at top and bottom. The main test result provided by the study was the force distribution in the wall ties, which indicated that the force in the ties increased as the height of ties embedded in the wall increased, suggesting that the connection at the top of two wall leaves should be enhanced. Unfortunately, the load distribution of each wall leaf was not given.

Page et al. (1996) analysed the flexural behaviour of cavity and veneer walls under lateral loading considering a set of key factors that would govern the behaviour of the wall system, aiming to provide a design procedure of wall ties. According to their analysis, the flexural behaviour of cavity walls with comparable wall leaves depended on the stiffness and boundary conditions of each wall leaf, the wall tie stiffness and the wall tie layout. The characteristics and layouts of the wall ties were inessential factors that govern the load distribution in wall leaves. If both leaves were supported and connected with rigid ties, the leaves would share the lateral load in proportion to their flexural stiffness. The stiffer the ties, the better the load sharing between leaves. The stiffness of so called rigid ties, however, was not defined in the study.

According to the analysis, the wall would have adequate performance even if flexible ties were used as long as the ties would not fail by bulking or pull-out. Thus it was believed that the 'heavy duty ties' defined in *Australian Wall Ties Standard AS2699* (Standards New Zealand, 2000) had adequate stiffness to transfer the load between leaves.

Zmavc (1991) developed a simple method to predict the flexural capacity of cavity walls with two leaves connected by shear wall ties. The study indicated that the shear wall ties allowed any applied load to be effectively shared by two leaves hence composite action was achieved. The moment capacity of the wall system was increased and deflection of the wall system was reduced. Also, the moment capacity increased with increasing cavity width.

In all of these studies, the effect of insulation on the flexural behaviour of cavity walls was not considered because in cavity and veneer masonry walls the insulations were not necessarily rigid panels and there was usually an air gap between the insulation and wall leaves. Therefore, the insulation used in these wall systems cannot transfer any horizontal force or sheer force between wall leaves. Although the effect of inserting insulation layers in the middle of RE walls on their flexural behaviour has not been evaluated, it is assumed that the insulation layer will have a positive effect on delivering the loads between the two wall leaves. Firstly, the rigid insulation board can help the wall ties to transfer the compression load between wall leaves. Secondly, since the insulation layer is tightly bonded with RE wall leaves, some composite action between wall leaves can be obtained due to the fact that some sheer stress can be transferred between RE wall leaves with the assistance of friction between two leaves and the insulation layer. Hence, the lateral resistance of ICRE walls can be improved, or at least can be conservatively assumed to be the sum of the lateral resistance capacity of the two leaves.

Because of the complexity of the behaviour of cavity walls under lateral load, in Australia, only general design procedures for cavity walls are provided by *Australian Standard AS3700* (Standards Australia, 2001), where it is assumed that under lateral loads, two leaves of a cavity wall share the load in proportion to their flexural stiffness, as long as the wall ties are designed according to the provision given in *Australian Standard AS3700* and *Australian Standard AS2699*, or it is assumed that the stronger leaf will withstand all the lateral load.

2.5 Thermal performance simulation

Once the structural requirements can be achieved, designers and house owners may then turn their attention to the economical consequence of using ICRE walls, because the running cost for heating and cooling may be reduced by adding insulation, while doing so will increase the initial cost of construction. Also, they may be curious about how much insulation is adequate, and how to properly implement ICRE walls, considering their interactions with other parameters, such as glazing, shading and ventilation, as well as the influences of building usage and local climate, in order to achieve satisfactory thermal comfort and energy saving.

In order to make informed decisions for each key design parameter, their effects on the thermal performance and total cost of an ICRE wall houses should be quantified. Also, the interactions between these parameters should be investigated. This is essential because appropriate combinations of these parameters may result in higher thermal performance or lower life-cycle cost.

2.5.1 Thermal simulation software

To quantify the effects of design parameters on the thermal performance (thermal comfort and energy loads) of a RE houses, computer simulation would be the most effective and practical method. Currently, there are three software tools that can be used for rating the thermal performance of house designs in Australia: *AccuRate*, BERS Professional and *FirstRate*. All three software tools use the same calculation engine developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and they are accredited in Nationwide House Energy Rating Scheme (NatHERS) (NatHERS National Administrator, 2012). In this study, the simulations were conducted using the thermal analysis software *AccuRate* (CSIRO, 2004). This is because *Accurate* is able to predict the indoor temperature of model houses (under a non-rating model). This thermal assessment tool can also predict the energy loads of model houses for heating and cooling (under a rating model), and a star-rating can be assigned based on an area-adjusted energy load, which is modified from the calculated energy load considering floor area (NatHERS National Administrator, 2012).

AccuRate predicts the thermal behaviour of a building using a frequency response method, the key technique of which is to obtain the frequency response functions and transient response factors from the relationship between a set of inputs (climatic information and thermal properties of building elements) and outputs (the software can output the energy loads for heating and cooling that are required to produce thermal comfort, or export the indoor temperatures for houses without air conditioning) (Walsh and Delsante, 1983).

The software has been validated both empirically and through intermodal comparisons. Daniel, et al. (2012b) evaluated the *AccuRate* Engine by comparing the simulation results of a hypothetical mass building derived from AccuRate and another two simulation engines named *EnergyPlus* (Crawley, et al., 2008) and *Ener-Win* (Degelman and Soebarto, 1995). Also, the simulation results of *AccuRate* were compared with real measured data. Both comparisons showed that results from *AccuRate* agreed reasonably with those from the other two simulation engines and the measured data. Earlier, Delsante (2004) validated the Accurate engine using the BESTEST method (Neymark and Judkoff, 1995) in order to determine whether *AccuRate* could give favourable predictions on annual energy loads and peak demand for heating and cooling, as well as indoor temperatures for un-conditioned models.

The results gave good agreements. Later, Delsante (2006) compared the prediction of *AccuRate* and the measured date of a house constructed by mud brick. Again, the results indicated that *AccuRate* was suitable for thermal performance simulations.

2.5.2 Adaptive comfort standard

In general, a desirable thermal performance means that a building can provide occupants with desirable thermal comfort. Thermal comfort is “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE, 2013), which is affected by two types of parameters: environmental and personal (ASHRAE, 2004). The environmental factors include temperature, thermal radiation, humidity and air speed, and personal factors involve occupants’ activities and clothing.

To judge the thermal performance of non-conditioned buildings, *ASHRAE Standard 55* (ASHRAE, 2013) recommends the use of the adaptive model of thermal comfort (ASHRAE, 2013; de Dear and Brager, 1998). This model was developed from field studies of 160 buildings around the world, which can be applied in buildings where there are opportunities for the occupants to adjust their thermal environment by, for example, opening the windows or turning on fans, and where the occupants are free to adapt their clothing to the indoor and outdoor thermal conditions.

Basically, the model specifies the boundary conditions (upper and lower limits) of a space that provides an acceptable thermal environment (indoor operative temperature) for 80% or more of the occupants; and the thermal performance of a building can be judged by comparing the indoor operative temperatures and the boundary conditions. To determine the boundary conditions, firstly the prevailing mean outdoor temperature (T_o) needs to be determined based on a simple arithmetic mean of the mean daily outdoor air temperatures of no fewer than seven and no more than 30 sequential days prior to the day in question, using the exponentially weighted running means (de Dear, 2006; de Dear, 2011):

$$T_o = 0.34T_1 + 0.23T_2 + 0.16T_3 + 0.11T_4 + 0.08T_5 + 0.05T_6 + 0.03T_7$$

Eq. (3)

Then, the acceptable indoor operative temperature can be calculated with the following equation (de Dear and Brager, 2002):

$$T_i = 0.31 * T_o + 17.8$$ Eq. (4)

The upper and lower limits of the operative temperature corresponding with 80% (90%) acceptability are defined by extending the acceptable indoor operative temperature by ±2.5°C (±3.5°C) (de Dear and Brager, 2002).

Figure 2.4 shows an example of the 'adaptive comfort zone' for Adelaide, Australia based on the outdoor long term average database over a 12-month period.

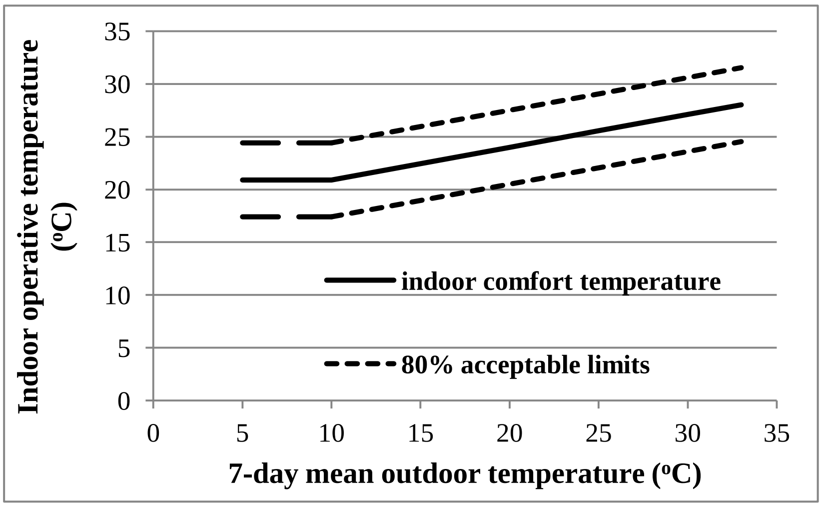


Figure 2.4 Acceptable indoor temperatures for naturally ventilated buildings (Adelaide)

It should be noted that in *AccuRate* the predicted indoor temperatures are a mixture of both indoor air temperature and radiant temperature, which is very similar to operative temperature (CSIRO, 2004). While the comfort limits in *AccuRate* are not the same as the limits suggested by the adaptive model, it is reasonable to compare the indoor temperatures derived from *AccuRate* to the adaptive comfort zone model, as shown later in Chapter 6.

2.5.3 Thermal performance in air-conditioned rammed earth buildings

For an air-conditioned building, thermal performance mainly refers to the amount of energy load required for heating and cooling to maintain internal thermal comfort. Taylor et al. (2008) investigated the thermal comfort and energy use in an office building constructed by RE walls. Although air conditioner was not installed, the building was heated and cooled by a hydronic heating and cooling system. They found that the building was warm in summers and cold in winters. Compared with another air-conditioned building built with concrete blocks, the RE building consumed more energy for heating. Also, a simulation indicated that adding insulation to RE walls can significantly improve the thermal comfort and reduce the energy use of the RE building. Later, Paul and Taylor (2008) compared the thermal comfort and energy use (during a summer period from December 2000 to February 2001) of this RE office building with two fully air-conditioned buildings constructed by insulated brick veneer walls. They found that the RE building consumed much less energy as no cooling was operated, however, occupants in the RE building claimed that the building was warm, which indicated low level of thermal comfort.

In summary, using RE only cannot guarantee a desirable thermal comfort and energy conservation. Other design parameters, such as insulation, should be implemented with thermal mass for higher thermal satisfaction.

2.5.4 Life-cycle cost

Life-cycle cost assessment is commonly conduced to investigate the financial impact of a certain building design for a life time (Çomaklı and Yüksel, 2003; Hasan, 1999; Kaynakli, 2008; Kneifel, 2010). By comparing the cost of a certain design to the cost of its alternatives, the most cost-effective design decisions can be made, for example, the optimum insulation thickness and optimum window size. In addition to the initial construction cost (C_i), the Life-cycle cost assessment for a building design also takes into account all the other related costs, for example, the corresponding running cost over an assumed life time, considering the interest rate and inflation rate. Assuming that the interest rate is greater than the inflation rate, the running cost $C_n$over a life time (n years) can be evaluated to the present value C_p (Hasan, 1999):

$$C_p = C_n \times (1+g) \times \{1 - [1 + (I-g)/(1+g)]^{-n}\}/(I-g) \qquad \text{Eq. (5)}$$

where I and g are interest rate and inflation rate, respectively.

The total LCC is then the sum of all initial or investment costs and the present value of the running cost over a life time of the building.

$$LCC = C_i + C_p \qquad \text{Eq. (6)}$$

2.6 Research gaps

Based on the literature review, research gaps can be summarized as follows:

1. Flexural strength of full-scale RE walls has been insufficiently studied. In particular, no study has been found to address the flexural strength of ICRE walls. Although solid RE wall houses have been built for decades, and even though the ICRE wall system has been applied in Australia for years, there is no specific standard for this unique construction method. Local builders tend

to construct RE wall houses following the only guidance presented in The *Australian Earth Building Handbook*, which was written based on the experiences of engineers, designers and architects. Hence, it is essential to conduct academic research to evaluate the strengths of this ICRE wall system, in particular the flexural strength under out-of-plane seismic loading.

2. Buildings built with RE walls are perceived to be sustainable due to the thermal mass effect which enables the building to provide occupants desirable thermal comfort with low levels of energy required for heating and cooling. A building design with only uninsulated RE walls cannot comply with the Deemed-to-Satisfy provision in BCA. The Energy Efficient Provision (Star Rating Requirement) provides an alternative way to meet the requirements of BCA, while it is not guaranteed that the energy loads of uninsulated RE houses can be controlled less than the maximum allowance in the Star Rating Requirement. Hence the minimum energy loads required by uninsulated RE houses should be quantified.

3. Adding insulation enables RE walls to meet the Deemed-to-Satisfy provision and improve thermal comfort of RE houses (in particular in winters), however, doing this cannot necessarily provide satisfactory thermal performance if the houses is totally naturally ventilated. This is due to the fact that the thermal performance can be influenced by many factors related to passive solar strategies, such as window size, window shading, ventilation, the amount of thermal mass and insulation. The effect of these factors on the thermal performance of RE wall houses, however, has not been investigated comprehensively.

4. Energy loads for air-conditioned RE houses can be effectively reduced by adding insulation to external RE walls, while adding insulation may considerably increase the initial construction cost. The more insulation is added, the more initial cost is increased. Thus the optimum insulation thickness should be quantified considering the total life-cycle cost. Also, the other design parameters such as window size, shading, ventilation and the

amount of RE should be optimised for minimum life-cycle cost. The effect of these key design parameters on the life cycle cost of RE wall houses has not been evaluated.

Chapter 3 Research Methodology

To fill the research gaps, both experimental tests (addressing research gap 1) and computer simulation (addressing research gaps 2-4) were conducted during the present study. The details of the relevant methods will be explained in each of the following chapters.

3.1 Experimental investigation on structural properties of rammed earth walls

The experimental program was conducted in three phases. The detailed arrangements are summarized as follows:

Phase 1 (Appendix A)

- Six cubic specimens made in molds (side length: 100mm) were tested under uniaxial compression for ultimate compressive strength of RE material.
- Three cylindrical specimens made in molds (100mm diameter by 200mm tall) were tested for the ultimate compressive strength, Young's modulus and stress-strain relationship of RE material.
- Six small beams made in molds (100mm*100mm*500mm) were tested under four point bending to evaluate the flexural tensile strength of RE material.

Phase 2 (Chapter 4)

- A solid RE wall (300mm thick by 1200 long by 2400mm tall) and an ICRE wall (400mm thick by 1200mm long by 2400mm tall, consisting of two 175mm thick RE wall leaves with an 50mm thick insulation) were tested under out-of-plane vertical bending to evaluate their flexural behavior.

- Four beams (nominally 100mm by 100mm by 500mm) cut from the failed solid wall were tested under four-point bending to determine the flexural tensile strength of the solid wall material.

Phase 3

- Four cubic specimens cut from both of the failed walls were tested under uniaxial compression to determine the compressive strength of the full-scale wall material **(Appendix A)**.
- Three cylindrical specimens cored from both of the failed walls were tested under uniaxial compression to determine the compressive strength, Young's modulus and stress-stain relationship of the full-scale wall material **(Appendix A)**.
- Four beams cut from both of the failed walls were tested under four-point bending to determine the flexural tensile strength of the full-scale wall material **(Chapter 4)**.

3.2 Investigation on thermal performance of rammed earth wall houses with simulation

The investigation of thermal performances of houses built with solid RE walls and ICRE walls were conducted by simulation using the software *AccuRate*. The simulation started with a basic model as a reference, and then parametric studies were performed considering a range of options for a set of key design parameters including window size in each wall, window shading, window openable rate, window construction type (for research aim 1 only), the amount of thermal mass and insulation thickness.

The basic model was developed as a simple single-zone model facing true north (as shown in Figure 2.5), given a zone type of kitchen/living zone. No partition walls (commonly constructed by lightweight materials) were applied in the base case house as their impact on the optimization analysis of external walls is minimal as they only affect the heat transfer between two adjacent zones and not the heat exchange between the inside and outside of a house. Moreover, in practice, internal or partition walls may be placed anywhere depending on different designs while the zone types (e.g. living room and bedroom) vary according to the designer and house owners (e.g. the living room may not necessarily be planned on the north side).

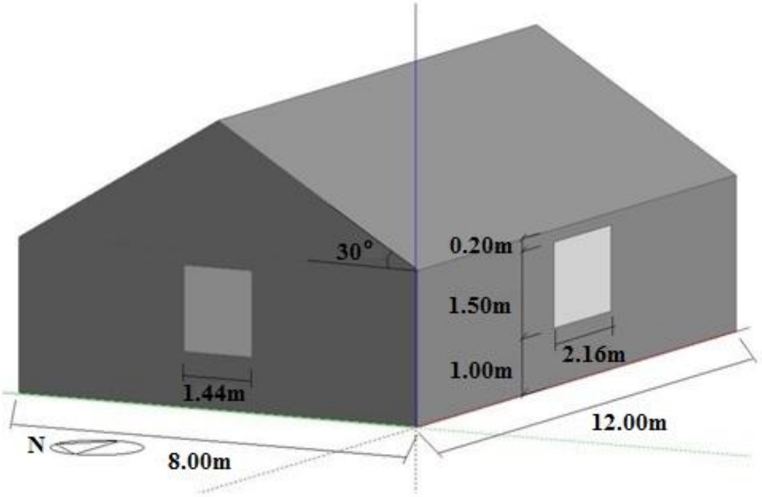


Figure 2.5 Basic model house

The simulation program was conducted in three phases, each corresponding to a research aim. In Phase 1, energy loads of uninsulated RE wall houses was investigated in order to determine whether houses built with only RE walls can meet the Energy Efficient Provision (research aim 2). Then in Phase 2, indoor temperatures of the model house were simulated in a non-rating mode, meaning that neither heating nor cooling was applied to investigate the thermal comfort of naturally ventilated ICRE wall houses (research aim 3). Phase 3 involved simulations of energy loads in an ICRE wall houses under a rating mode, and life-cycle costs of the model house with different design parameters were evaluated (research aim 4). In each phase, the simulation program was conducted in three different Australian climate zones, namely climate 3, 5 and 7, representing a semi-arid climate (Bsh), hot Mediterranean climate (Csb) and moderate oceanic climate (Cfb) in the Koppen climate classification system, respectively (Kottek, et al., 2006; McBoyle, 1971).

It should be noted that in *AccuRate*, the outcome of each case simulation is generated in a unique file, while the data of this file is covered by the outcome of the subsequent case simulation. Therefore users have to save each outcome file elsewhere before running the subsequent simulation. Considering that thousands of cases with different combinations of design parameters were involved in this study, a batch file code was developed to automatically record the data in each file after it has been generated and combine them into one file. This led to a significant time saving and made it convenient to analyse the simulation results. The detailed code is given in the Appendix B.

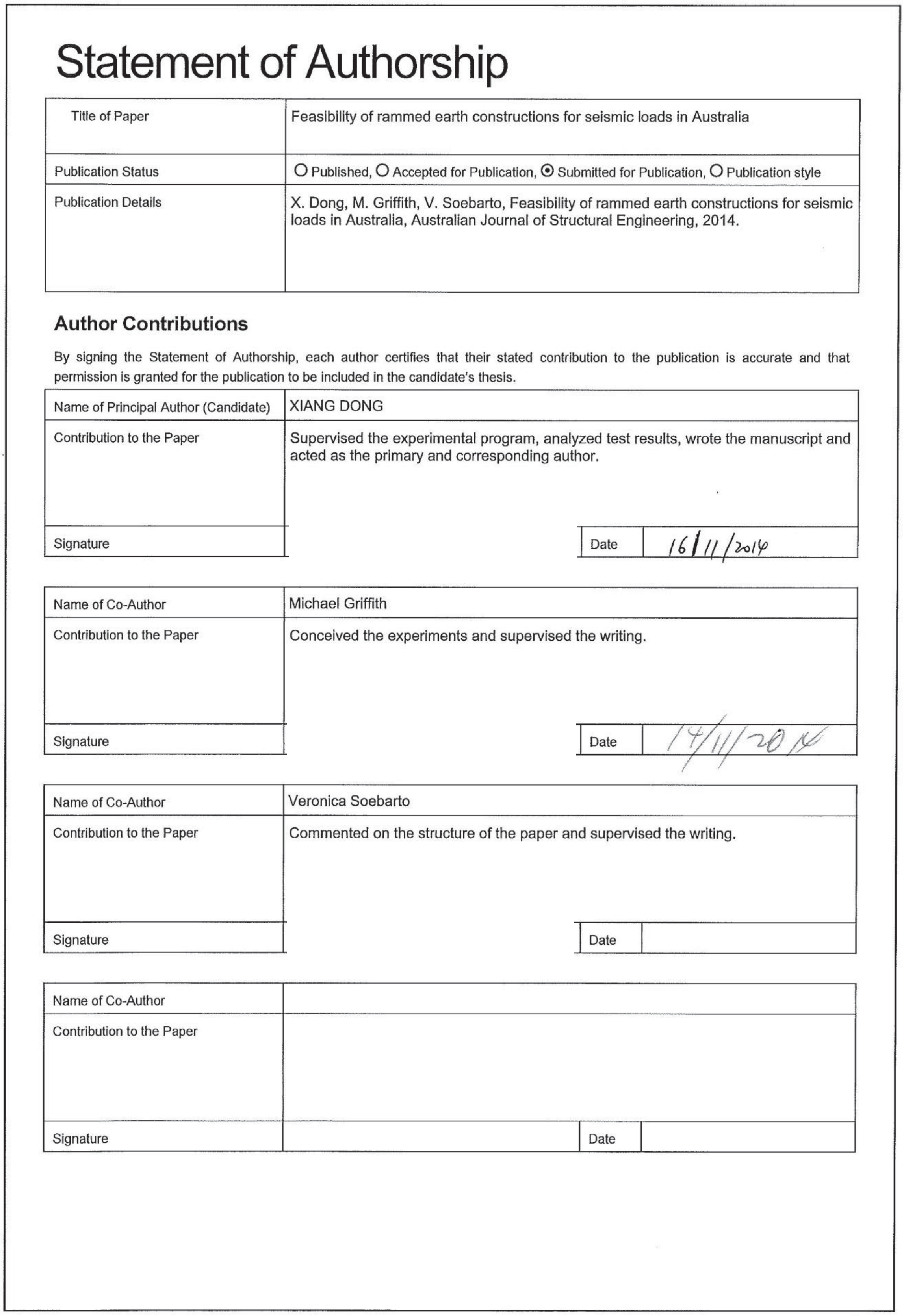
Chapter 4 Experimental Investigation on Flexural Performance of Insulated Cavity Rammed Earth Walls

Introduction

Since adding insulation is the only practical way to meet the requirements of BCA, and for RE walls the insulation is normally inserted in the middle of the wall for aesthetic reasons, the influence of the insulation layer on the structural performance of RE walls should be investigated. This chapter introduces the experimental program of investigating the flexural behavior of ICRE walls under out-of-plane lateral load (for example, seismic load). Also, a solid RE wall was also tested under flexure for comparison. Feasibility analysis of using this ICRE wall system in seismic zones in Australia was conducted. The compressive strength of RE material, as well as the Young's modulus and stress-strain relationship were also evaluated by testing material property test specimens, the results of which were presented in Appendix A.

List of Manuscript

X. Dong, M. Griffith, V. Soebarto, Feasibility of rammed earth constructions for seismic loads in Australia, Australian Journal of Structural Engineering. (Accepted by Australian Journal of Structural Engineering on 16th February, 2015)



Statement of Authorship

Title of Paper	Feasibility of rammed earth constructions for seismic loads in Australia
Publication Status	○ Published, ○ Accepted for Publication, ● Submitted for Publication, ○ Publication style
Publication Details	X. Dong, M. Griffith, V. Soebarto, Feasibility of rammed earth constructions for seismic loads in Australia, Australian Journal of Structural Engineering, 2014.

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author (Candidate)	XIANG DONG		
Contribution to the Paper	Supervised the experimental program, analyzed test results, wrote the manuscript and acted as the primary and corresponding author.		
Signature		Date	16/11/2014

Name of Co-Author	Michael Griffith		
Contribution to the Paper	Conceived the experiments and supervised the writing.		
Signature		Date	14/11/2014

Name of Co-Author	Veronica Soebarto		
Contribution to the Paper	Commented on the structure of the paper and supervised the writing.		
Signature		Date	

Name of Co-Author			
Contribution to the Paper			
Signature		Date	

Dong, X., Griffith, M. & Soebarto, V. (2015) Feasibility of rammed earth constructions for seismic loads in Australia.
Australian Journal of Structural Engineering, (Submitted manuscript)

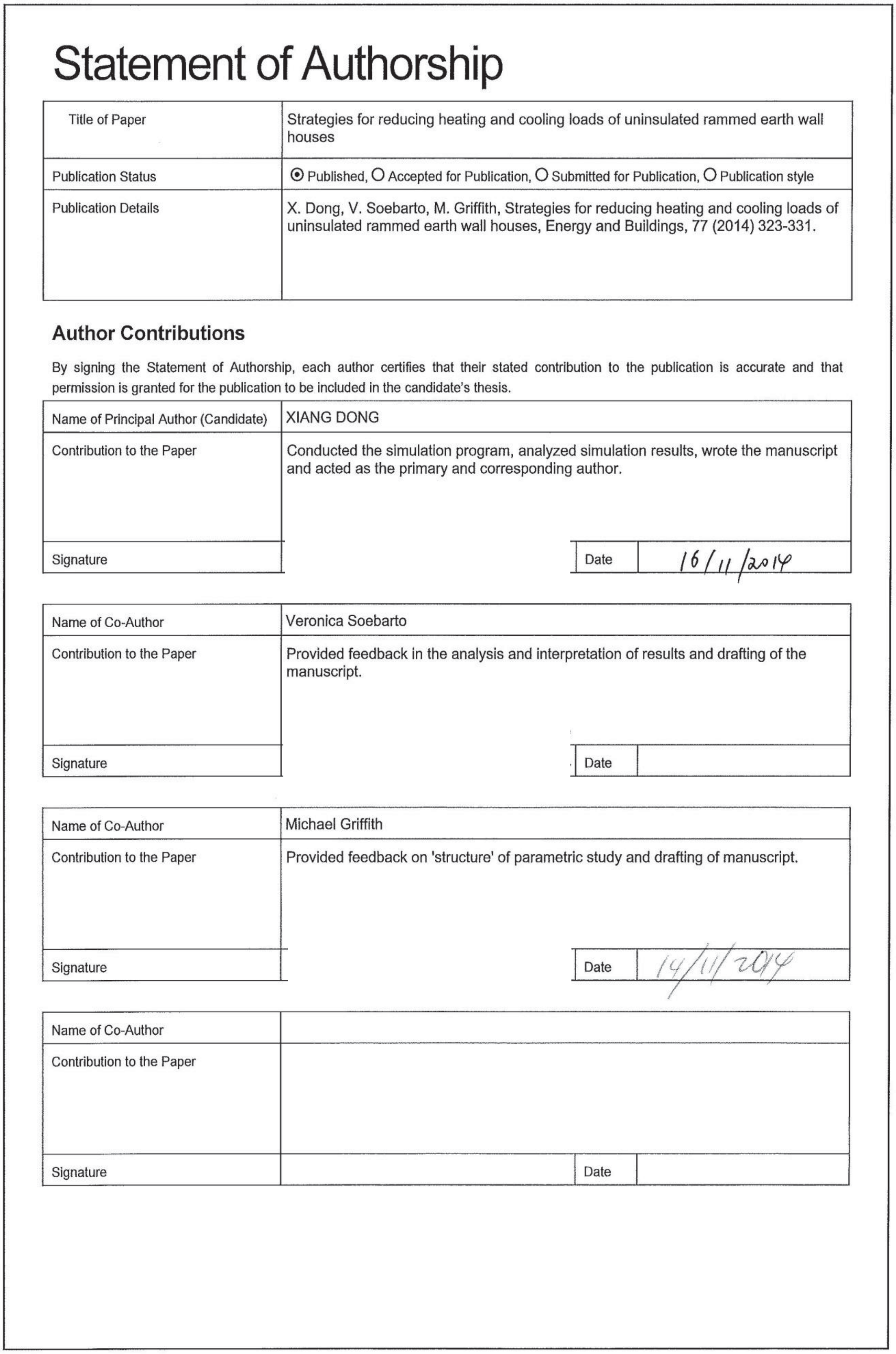
Chapter 5 Prediction of Energy Loads of Uninsulated Rammed Earth Wall Houses

Introduction

RE wall houses are perceived to be able to provide thermal comfort with low level of energy required for heating and cooling. It is not guaranteed that the heating and cooling energy loads of houses built with only RE walls (without insulation) can be controlled within the maximum allowance in the Star-Rating Requirements. This chapter conducted simulations to determine whether uninsulated RE wall houses can comply with the Star-Rating Requirements, by optimizing a set of key design parameters (related to passive solar strategies) including window size, window openable rate, window shading, window construction type and the amount of thermal mass. In order to take into consideration the effects of climates, the simulation program was performed in three different Australian climate zones namely climate zone 3, 5 and 7.

List of Manuscript

X. Dong, V. Soebarto, M. Griffith, Strategies for reducing heating and cooling loads of uninsulated rammed earth wall houses, Energy and Buildings, 77 (2014) 323-331.



Statement of Authorship

Title of Paper	Strategies for reducing heating and cooling loads of uninsulated rammed earth wall houses
Publication Status	● Published, ○ Accepted for Publication, ○ Submitted for Publication, ○ Publication style
Publication Details	X. Dong, V. Soebarto, M. Griffith, Strategies for reducing heating and cooling loads of uninsulated rammed earth wall houses, Energy and Buildings, 77 (2014) 323-331.

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author (Candidate)	XIANG DONG		
Contribution to the Paper	Conducted the simulation program, analyzed simulation results, wrote the manuscript and acted as the primary and corresponding author.		
Signature		Date	16/11/2014

Name of Co-Author	Veronica Soebarto		
Contribution to the Paper	Provided feedback in the analysis and interpretation of results and drafting of the manuscript.		
Signature		Date	

Name of Co-Author	Michael Griffith		
Contribution to the Paper	Provided feedback on 'structure' of parametric study and drafting of manuscript.		
Signature		Date	14/11/2014

Name of Co-Author			
Contribution to the Paper			
Signature		Date	

Strategies for reducing heating and cooling loads of uninsulated rammed earth wall houses

Xiang Dong , Veronica Soebarto , Michael Griffith

ABSTRACT The research reported in this paper investigated the potential reduction of heating and cooling loads in a hypothetical uninsulated rammed earth wall house. The analysis was performed in three different climate zones in Australia, namely: climate zone 3, 5 and 7, representing hot arid, warm temperate and cool temperate climate, respectively. The investigation involved simulating the energy load for a rammed earth house with different building parameters using the home energy rating software *AccuRate* developed by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO). In Australia, new building designs must comply with the energy efficient provision of the Building Code of Australia in the National Construction Code (NCC), and one method of compliance is through an assessment of the predicted energy loads. The simulation results show that it is possible for an uninsulated rammed earth wall house in Australian climate zones 3 and 5, to fulfil the minimum requirement of the NCC as long as the building is designed carefully by optimising a number of passive solar strategies. In climate zone 7, however, uninsulated rammed earth houses cannot meet the NCC requirement even after applying passive solar design strategies.

Keywords: rammed earth; thermal performance; simulation; passive solar strategy; energy load; star rating.

1. Introduction

Energy used for space heating and cooling accounts for over 40% of the average total household energy consumption in Australia (Wilkenfeld and Associates, 1998). Buildings constructed with large thermal mass (such as rammed earth) can provide desirable thermal performance in summer and significantly reduce the cooling load because the large thermal mass slows heat transmission through external walls by providing a long thermal time lag (Soebarto, 2009). In summer this means the indoor temperature will be lower than the outdoor temperature, and the peak indoor temperature will occur several hours after the peak outdoor temperature. Further, with high thermal capacitance and density, the rammed earth walls will absorb and retain build-up internal heat, reducing the indoor temperature during the day, while during cool nights this heat will be released back to the internal space (Givoni, 1991). In addition, rammed earth construction is perceived to be sustainable due to its very low embodied energy. According to Reddy and Kummar (Venkatarama Reddy and Prasanna Kumar, 2010), cement stabilised rammed earth walls (with 8% cement) have an embodied energy of 0.5 GJ/m^3, which is 15-25% of the value for the same volume of burnt clay brickwork walls.

Although there are many benefits to be gained by using rammed earth construction, it also has its shortcomings. In winter, the long time lag of rammed earth will delay the desired warming (by solar energy) of the building during daytime. Moreover, the low thermal resistance (R-value) of rammed earth will allow considerable heat to drain from the building over time. Therefore, some researchers argue that rammed earth buildings may have undesirable thermal performance in winter (Soebarto, 2009; Taylor, et al., 2008). Soebarto (Soebarto, 2009), for example, monitored the indoor temperature of two uninsulated rammed earth wall houses in a warm temperate climate in winter, and found that the minimum and average indoor temperatures without the use of any space heater were 8^{o}C and 12.5^{o}C, respectively. Furthermore, Taylor, Fuller and Luther (Taylor, et al., 2008) measured the indoor temperatures of three offices in a rammed earth wall building located in a hot and dry climate (or categorised as climate zone 4). Space heating and cooling of the building was provided by a hydronic heating and cooling system and pipes embedded in ground floor and ceiling slabs. Their results indicated that in winter, two out of the three offices were perceived to be comfortable only 70% of the time, while the third office was perceived comfortable for only 13% of the time.

To comply with the Building Code of Australia, the Australian Building Code Board has established in the National Construction Code (NCC) the Deemed-to-Satisfy (DTS) Provision (Australian Building Codes Board, 2013). This provision requires that for Class 1 buildings (detached residential) located in all climatic zones in Australia except the Alpine zone, the minimum required R-value for the external walls is 2.8 m^2K/W. In the Alpine zone the minimum requirement is 3.8 m^2K/W. The descriptions of each climate zone are shown in Table 1.

Table 1 Detail of each Australian climate zone and its minimum R-value requirement for external walls

Climate zone	Description	Typical city (latitude, Longitude)
1	High humid summer, warm winter	Cairns (16° 55’ S, 145° 46’ E)
2	Warm humid summer, mild winter	Brisbane (27° 29’ S, 153° 8’ E)
3	Hot dry summer, warm winter	Longreach (23° 27’ S, 144° 15’ E)
4	Hot dry summer, cool winter	Griffith (34° 16’ S, 146° 1’ E)
5	Warm temperate	Adelaide (34°55’ S, 138°36’ E)
6	Mild temperate	Melbourne (37° 47’ S, 144° 58’ E)
7	Cool temperate	Ballarat (37° 34’ S, 143° 51’ E)
8	Alpine	Perisher Smiggins (36° 24’ S, 148° 24’ E)

The above requirement means that, with a thermal resistance of 0.24 to 0.70 m^{2}K/W for typical 300mm thick rammed earth walls (Hall and Allinson, 2009; Taylor and Luther, 2004; Walker and Standards Australia, 2002; Yan, et al., 2005), a fully rammed earth house without thermal insulation will not meet the NCC requirement if it is assessed with the deemed-to-satisfy provision. The NCC has an alternative requirement which requires that for external walls with a surface density greater than 220 kg/m^2, wall insulation with an R-value of 0.5 to 1.0 m^{2}K/W shall be added (Australian Building Codes Board, 2013). This means that for a typical 300mm thick rammed earth wall (with a surface density of between 540 and 660 kg/m^2 (Hall and Djerbib, 2004)), a minimum insulation with an R-value of 0.5 to 1.0 m^{2}K/W is required.

Insulation for rammed earth walls

Adding insulation to rammed earth walls is an effective way of increasing their thermal resistance. Insulated rammed earth wall houses exhibit much better thermal performance. Soebarto (Soebarto, 2009) and Taylor, Fuller and Luther (Taylor, et al., 2008) investigated the effect of insulation on the thermal performance of rammed earth wall houses by monitoring and simulation, and the results confirmed that adding insulation to external walls can significantly reduce the energy load of rammed earth houses. There are, however, disadvantages associated with adding insulation on either the inner or the outer side of rammed earth walls. Adding insulation detracts from the aesthetic appeal of natural earth walls in both appearance and concept; and if the insulation is placed on the inner side of the walls, it will weaken the benefits of the thermal mass. Adding insulation in the middle of rammed earth walls is a possibility; however, it considerably complicates the construction process and construction cost.

Moreover, placing thermal insulation in the middle (of a cross section) of a rammed earth wall reduces its structural integrity. According to Walker and Standards Australia (Walker and Standards Australia, 2002), the vertical bending moment capacity of a rammed earth wall is proportional to the square of the wall thickness, which means that if the wall thickness is reduced to half its original thickness, its moment capacity will be reduced to only 25% of the original value. For cavity walls, a design method provided by AS 3700 (Standards Australian, 2001) states that under a lateral bending load, the lateral load can be designed to be carried by only one wall leaf (the thicker one) or by two wall leaves, taking into consideration the flexural rigidities of each wall leaf. Therefore, if an uninsulated rammed earth wall is separated by insulation into two leaves with the same thickness, the moment capacity of the cavity wall will be half the capacity of the uninsulated wall.

Star rating requirements

The NCC (Australian Building Codes Board, 2013) provides another option for complying with the energy efficiency provision for Class 1 buildings (residential), known as the *star rating requirement*. According to this requirement, every capital city is assigned 10 star ratings, each corresponding to a level of thermal performance. For example, in Adelaide, South Australia, which is in the climate zone 5 or warm temperate, a 1 star rating means an energy load of 480 MJ/m^2 per annum, while a 10 star rating means an energy load of 3 MJ/m^2 per annum. The star rating is based on space heating and cooling loads only, other energy demands such as domestic hot water (DHW) are not included. The same star rating can correspond to different energy load rates for different cities considering the extremes of the local weather conditions.

Starting from 2010, new residential buildings have been required to meet a 6-star rating as a minimum. In other words, the total energy load for heating and cooling of the building must be equal to or less than the maximum allowed for each climate zone. This star rating system provides an alternative way for houses with uninsulated rammed earth walls to meet energy efficiency requirements; that is, the predicted energy loads for heating and cooling must be less than or equal to the reference values.

Meeting building requirements

Implementing passive solar design strategies is a way to reduce a building's energy consumption. For passive heating, "direct gain", one of the most effective passive solar heating strategies, is of most interest because it is a technique that can be used readily by many conventional structures (Wray and Balcomb, 1979). Direct gain uses thermal mass to store solar heat which is collected through window glazing, and to release the heat during cool nights (Givoni, 1991). Rammed earth construction, carrying a large amount of thermal mass, is ideal for the implementation of direct gain strategies. According to Givoni (Givoni, 1991), the main parameters that affect the effectiveness of direct gain buildings are glazing (location, orientation, size and type), and the amount and design of thermal mass.

On the cooling side, natural night-time ventilation is an effective strategy, which mainly refers to using cool night winds to lower indoor temperatures, thus reducing the energy required for cooling. Moreover, when natural night-time ventilation is coupled with a suitable amount of thermal mass, it is an effective way of reducing the cooling load since the thermal mass cooled by the night ventilation can be used as a heat sink during the day (Givoni, 1984). It should be noted that the NCC allows for the overall openable area of the windows to be at least 5% of floor area. The benefits of this passive cooling strategy are confirmed by Shaviv, Yezioro and Capeluto (Shaviv, et al., 2001). The main factors that affect this strategy are the ventilation rate and the amount of thermal mass.

In summary, the effectiveness of the direct gain (passive heating) and the natural night-time ventilation (passive cooling) are mainly controlled by several factors namely, window size in each wall, window type, ventilation rate, shading and the amount of thermal mass. Careful implementation of these features can reduce the need for heating and cooling. In other words, although uninsulated rammed earth walls do not meet the minimum R-value requirement, when the overall building design is taken into consideration, it may still be possible for a fully rammed earth building to meet the NCC requirements.

The research project

The current study investigated the effects of these five factors – glazed area, window type, shading, ventilation and wall thickness – on the heating and cooling loads of a hypothetical uninsulated rammed earth house located in three different climate zones in Australia. The aim of this study is to provide recommendations for home owners when designing their house rather than providing an optimal solution. In reality, there is no optimal design as the building parameters may change depending on homeowners' preference and changing one parameter may cause different optimal values of the other parameters. In this study, influences of each parameter on energy loads of the case models which can meet the minimum star rating requirements are investigated.

The model houses used for this study were located in three cities – Longreach (Queensland), Adelaide (South Australia) and Ballarat (Victoria) – covering climate zones 3, 5 and 7, representing semi-arid climate (Bsh), hot Mediterranean climate (Csb) and moderate oceanic climate (Cfb) in the Koppen climate classification system (Kottek, et al., 2006; McBoyle, 1971), respectively. The simulations of cases in other climates were also conducted; however, since the simulation results for adjacent climates were similar; this paper only presents the typical results for climate zones 3, 5 and 7. The detailed information about these climate zones was obtained from NCC documents (Australian Building Codes Board, 2013) and is summarised in Table 2. The central objective was to determine whether uninsulated rammed earth wall houses are able to meet the NCC requirement through optimised passive solar strategies.

Table 2 Detailed information of climate zones

Climate zone	Climate type	Typical city	Temperature range (^oC) Mean minimum-mean maximum		6-star rating (MJ/m^2 p.a)
			Summer	Winter	
3	Hot arid	Longreach	22.5—36.7	9.3—26.6	141
5	Warm	Adelaide	16.6—28.6	8.5—17.0	96
7	Cool	Ballarat	10.6—24.2	3.9—11.8	197

Currently, there are three software tools that can be used for rating the thermal performance of house designs in Australia: *AccuRate*, BERS Professional and *FirstRate*. All three software tools use the same calculation engine developed by the *Commonwealth Scientific and Industrial Research Organisation* (CSIRO) and they are accredited in *Nationwide House Energy Rating Scheme (*NatHERS*)*. In this study, the investigation was conducted by using the energy rating software *AccuRate*. *AccuRate* calculates the annual heating and cooling load required to maintain thermal comfort in a model building based on the response factor method (CSIRO, 2004). The software has been validated both empirically and through intermodal comparisons (Daniel, et al., 2012a; Delsante, 2006; Delsante, 1995; Delsante, 2004). The inputs to this program include the characteristics of the building envelope (external walls, ceiling, roof and floor), window size, window type, shading and ventilation rate, etc. The output is a certificate reporting the annual heating and cooling loads and a star rate based on the energy loads. The detailed mathematical basis of this energy rating tool has been reported elsewhere (Walsh and Delsante, 1983).

The assumptions of modelling using *AccuRate* are as follows and these assumptions are also applied in the models of this study:

- Weather: For each climate zone, the long term average hourly weather data is provided by *AccuRate* climate database derived from Bureau of Meteorology weather data[1].

- Internal gains: For modelling of single zone houses, the zone type should be selected as Living/Kitchen as required by *AccuRate*. For this zone type, it is assumed that there is daytime occupancy and cooking heat gains is included.

- Use of heating and cooling: Heating is applied when the zone temperature at the end of the hour without heating is below the heating thermostat setting. Cooling is applied when the zone temperature is outside the comfort region even if nature ventilation/ceiling fans are applied. (Heating thermostat setting: 20^{o}C for each of the three cities; cooling thermostat setting: 27^{o}C, 25^{o}C and 23.5^{o}C for Longreach, Adelaide and Ballarat respectively)

- Infiltration: the infiltration is determined by the number of unsealed items such as chimney, wall/ceiling vents, and exhaust fans. In the basic model of this study, none of these items is applied. For windows, the infiltration is determined by its gap size (small/medium/large) and in this study the gap size for all windows is set to be ‘medium’.

- Window opening schedule: in *AccuRate*, the window opening schedule is automatically controlled by the program. Windows are opened for natural ventilation when the zone temperature is greater than a trigger temperature and 4 degrees higher than the outdoor air temperature. The trigger temperature is generally 0.5 degrees below the cooling thermostat temperature, but with an upper limit of 26 ℃. If the zone temperature is still higher than the comfort temperature, windows will be closed and space cooling will be applied.

---

[1] The hourly weather data in AccuRate are based on “weighted multivariate mean of weather elements (maximum, minimum and mean dry-bulb temperature; maximum, minimum and mean wet-bulb temperature; maximum and mean wind speed; total global irradiance; and total diffuse irradiance).

2. The basic model and options of parameters

Basic model

A basic model house was developed as a control. The other model houses considered in this parametric study were designed with the control house as a base, each being modified according to the design factor being varied. Once the optimum value of a parameter was determined, this optimum value was applied in the subsequent investigation of the other parameters in order to explore the potential of energy saving with all the parameters being optimized. The basic model house was a single zone house facing true north. No window shading was designed for the basic model house. The ceiling was highly insulated in order to minimize the effect of the roof on the energy load of the model house. Similarly, no internal walls were applied in the basic model as this study aimed at investigating the effect of the main design parameters that relate to the external envelope (which play an important role on the heat exchanges between the inside and outside of a house) on the energy loads. The pitched roof had an angle of 30^{o}. The diagram of the basic model house is shown in Figure 1 and the characteristics of the basic model are summarized in Table 3.

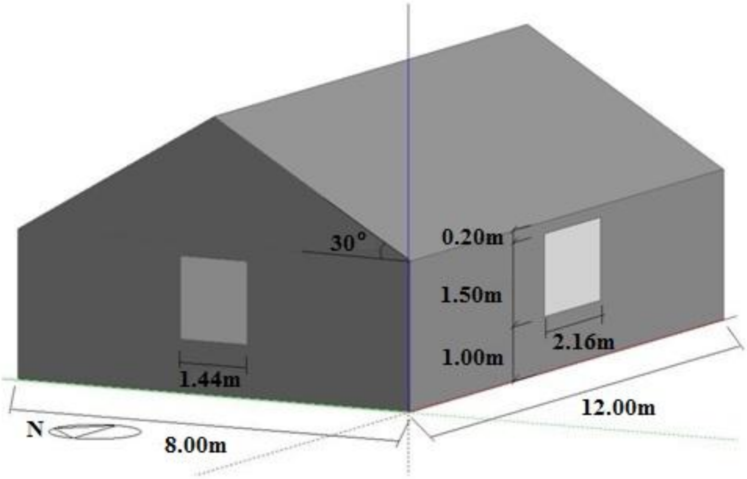


Fig. 1. Basic model house

Table 3 Characteristics of the basic model

Parameters	Descriptions
Floor area	96 m^2 $(12m \times 8m)$
External wall height	2700mm
External wall thickness	200mm cement stabilised rammed earth
Concrete floor	100mm thick
ceiling	R 3.0 glass fibre batt + 10mm thick plasterboard
Pitched roof	R 1.0 glass fibre batt insulation + 1mm steel sheet
Window to wall ratio	10% of all direction
Window type	Single-glazed clear glass window with timber frame (25% openable, overall heat transfer coefficient=5.75, Solar heat gain coefficient =0.69)
Window location	Windows are installed 1.0m above floor, and window height is fixed at 1.5m

The simulation of heating and cooling load was conducted for the basic model houses located at a typical city in Australian climate zones 3, 5 and 7, and the simulation results are presented in Table 4. It is clear from the results that the basic model house consumes much more energy than the 6-star rating requirements reported in Table 2 for the three climate zones considered.

Table 4 Simulation results of basic models

City	Energy load (MJ/m^2 p.a)				Star rating
	Heating	Cooling	Total	Area-adjusted[a]	
Longreach	13.0	242.1	255.1	218.3	4.1
Adelaide	211.2	63.8	275.0	224.2	3.0
Ballarat	624.3	6.4	630.7	519.9	2.5

[a] the Area-adjusted load shown in Table 4 was calculated by adjusting the total load in proportion to the total building surface area to floor area ratios of a range of dwellings in a particular Climate Zone. The star rating was assigned based on the area-adjusted load [24].

Options of parameters

Five factors which are known to affect the effectiveness of passive solar heating and cooling strategies were evaluated, including window size (window to wall ratio, WWR), window shading (determined by projection factor: the ratio of the depth of the eave to the height of the window (from the window sill to the bottom of window eave), see Figure 2), ventilation rate (controlled by window openable area), the amount of thermal mass (determined by wall thickness) and window construction type. The options for each parameter are as follows:

- *Window size of each wall*: Window size was determined as the window to wall ratio (WWR). Five options of WWR were evaluated, namely: 10%, 20%, 30%, 40% and 50%. It should be noted that according to NCC, the minimum required glazed area for habitable rooms is 10% of the floor area. For the basic model in this study, the overall glazed/window area was 10.8 m^2 which is more than 10% of the floor area (9.6 m^2).

- *Shading*: In the model house, window shading was provided by eaves installed 0.2m above the window. Five options of projection factor were considered, namely: 0.00, 0.15, 0.30, 0.45 and 0.60 (corresponding to an eave width of 0.00m, 0.25m, 0.50m, 0.75m and 1.00m, respectively).

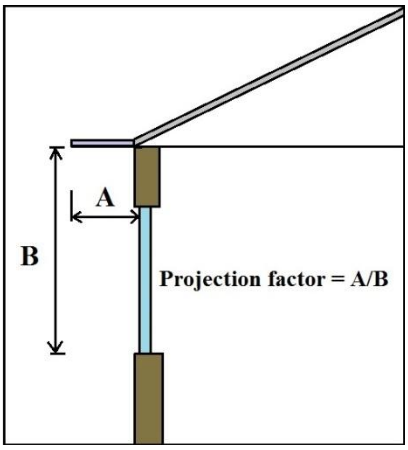


Figure 2 Projection factor

- *Ventilation rate*: In this analysis, ventilation rate was controlled by the window openable rate. Four options were considered, namely: 25%, 50%, 75% and 100%. *Rammed earth wall thickness*: Uninsulated rammed earth walls commonly have a thickness of 200-400mm. In this study, five options were evaluated ranging from 200mm to 400mm with 50mm increments.

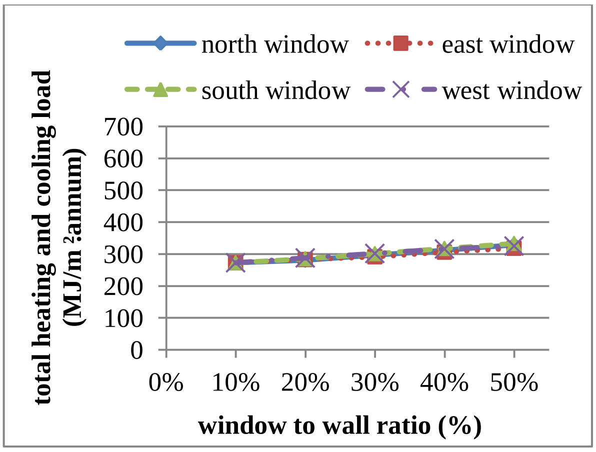
- *Window construction type*: Besides the window type applied in the basic model house (single-glazed clear glass window with timber frame), the impact of using a double-glazed clear glass (12mm air gap) window with timber frame (Overall Heat Transfer Coefficient =3.25 W/m ^{2}K, Solar Heat Gain Coefficient =0.62) was also evaluated.

3. Simulation results and discussions

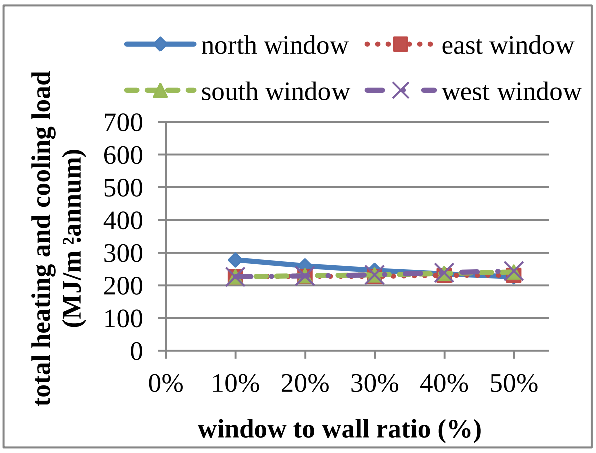
This section presents the simulation results of the effect of each parameter on the energy load of the model house in three different climate zones, as shown in Figure 3 to Figure 7. The energy loads presented in these figures are the calculated load. When investigating the cases that can meet the 6-star rating requirement in each climate zone (as shown in Figure 8 and Figure 9) the corresponding area-adjusted load was applied.

3.1 Effect of window size

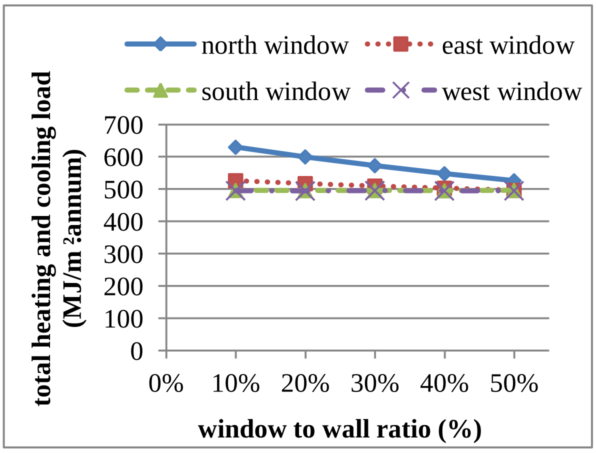
The effect of north, east, south and west window size on the energy load were investigated successively as shown in Figure 3. It is worth noting that when the order of the investigation of these window sizes is changed, the optimum size of some windows may change; however, the energy load of the model house with different optimum window sizes is very similar to each other. Hence the results of cases with other investigating orders are not presented.



(a) Longreach



(b) Adelaide



(c) Ballarat

Figure 3 Effect of each window size on the total energy load

Figure 3 (a) shows that in Longreach (climate zone 3, hot arid) the effects of each window size on each wall orientation on the total energy load were similar to one another. Increasing the size of each window led to a considerable rise in energy load (by 21%, 17%, 22%, and 19% for the north, east, south and west window, respectively). Therefore, the optimum WWR for each window was 10%, corresponding to the minimum total energy load of 272.8 MJ/m^2 per annum. It is clear from Figure 3 (a) that the worst WWR for each window was 50%. The total energy load of the model house with a WWR of 50% in each wall was also simulated, which was 542.7 MJ/m^2 per annum. This dramatic increase in energy load (approximately 100% increase) reveals that window size can significantly affect the energy load of rammed earth houses. Normally large windows are favoured by occupants in order to capture more natural light and external views, thus an optimum window size of 10% on each wall area may be perceived as being unacceptably small. This study aims to provide information to occupants about how window size can affect the energy load, thus based on the findings above, the occupants can make an informed judgment on whether or not large windows should be applied.

The simulation results indicate that in climate zone 3, which has hot dry summers and warm winters, small windows are also desirable. This is due to the fact that in this climate zone, most of the energy consumption of a residential house is used for space cooling, and larger windows allow more solar energy to get inside the house. As a result, the indoor temperature will rise and more energy will be required for cooling.

In Adelaide (climate zone 5), the size of a window in different orientations had different effects on the total energy load as shown in Figure 3 (b). As the WWR of the north window increased from 10% to 50%, the total energy load of the model house dropped by 19% from 277.7 to 226.1 MJ/m^2 per annum. Increasing the other three window sizes, however, led to negative results. As the WWRs of the east, south and west window increased from 10% to 50%, the total energy load of the model house increased slightly from 226.1 to

230.7, 240.9 and 243.9 MJ/m^2 per annum, respectively. Therefore, the optimum WWRs were 50%, 10%, 10% and 10% for the north, east, south and west window, respectively.

The above arrangement works because in climate zone 5, a large proportion of the energy consumption is used for heating, and if the north-facing window is able to accept a large amount of solar energy, the heat gains from this virtual heat sink can offset the heat loss. The other windows, however, are not effective solar energy traps because of their orientation, so that more heat will be lost than can be gained from these windows particularly during winter.

In Ballarat (climate zone 7, cool temperate), it is demonstrated from Figure 3 (c) that the total energy load of the model house was effectively reduced by increasing the size of the north facing window. As the WWR of the north facing window increased from 10% to 50%, the total energy load dropped by 16% from 629.8 to 526.0 MJ/m^2 per annum. The size of the other three windows had only a weak influence on the total energy load. According to the simulation results, the optimum WWR for north, east, south and west window was 50%, 50%, 40% and 20%, respectively. The results reveal that comparing to climate zone 3 and 5, larger windows are ideal in climate zone 7. This is due to the fact that almost all the energy load required in this climate zone is used for heating, while large windows are able to accept much solar heat thus reducing the heating load. The north-facing window, however, is the most effective to gain solar heat than the other windows.

Shading has not yet been considered when analysing the effect of window sizes above; the effect of shading was investigated once the optimum window size of each wall was determined. The case in which the effects of window size and shading were considered simultaneously has also been conducted for comparison and the simulation results indicated that the optimum window sizes and shading were the same with the case in which these two parameters were considered separately.

3.2 Effect of window shading

It can be seen from Figure 4 that in Longreach (climate zone 3, hot arid) increasing the projection factor of window shadings led to a slightly better performance. According to the simulation results, the total heating and cooling load reduced by 5.9% from 272.8 to 256.7 MJ/m^2 per annum as the projection factor increased from 0 to 0.60. This is a logical outcome of the fact that wider eaves reduce the amount of solar heat entering the house through the windows, thus reducing the amount of energy required for cooling. Although wider eaves will cause a slight increase in the amount of energy required for heating in the winter, it will not significantly affect the total load since heating only accounts for a small proportion of the total demand in this climate zone.

In Adelaide (climate zone 5, warm temperate), however, increasing the projection factor from 0 to 0.60 increased the total energy load from 226.1 to 256.4 MJ/m^2 per annum. Since in climate zone 5, a larger proportion of energy is required for heating than cooling, the negative impacts of shading in the winter may outweigh the benefits of shading in summer.

In Ballarat (climate zone 7, cool temperate) increasing the factor of window shadings led to a considerable increase in the total energy load. As the projection factor increased from 0 to 0.60, the total heating and cooling energy demand of the model house increased by 17% from 494.5 to 580.3 MJ/m^2 per annum. This is because in climate zone 7, little energy is required for cooling while a large amount of energy is required for heating. Deeper eaves reduce the amount of solar energy entering the house through windows, increasing the need for energy consumption for heating. Although deeper eaves have a positive effect on reducing the cooling load, the negative effect of deep eaves on the heating load outweighs its passive effect on the cooling load.

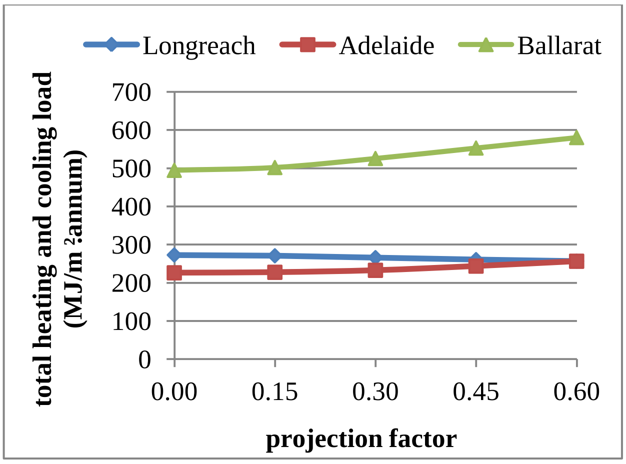


Figure 4 Effect of shading on the total energy load

3.3 Effect of ventilation rate

Figure 5 reveals that in Longreach (climate zone 3) increasing the window openable rate reduced the total energy load of the model house. As the window openable rate increases from 25% to 100%, the total heating and cooling load dropped by 14.3% from 256.7 to 220.1 MJ/m^2 per annum. This is due to the fact that a larger window openable rate allows more natural night ventilation, which can be used to reduce the indoor temperature at night, thus reducing the cooling load.

In Adelaide (climate zone 5), as the window openable rate increased from 25% to 100%, the total energy demand reduced slightly from 226.1 to 218.8 MJ/m^2 per annum. This may reflect the fact that a greater window openable rate allows more natural ventilation to enter the house at night through open windows, which may effectively reduce the cooling load but barely change the heating load. Nevertheless the total load is hardly affected as the cooling load only accounts for a small part of the total energy load.

In Ballarat (climate zone 7), the window openable rate had no significant effect on the total energy load, while less ventilation offered a slightly better performance. This is because night ventilation can only reduce the cooling load; however, space cooling is barely required in Ballarat, hence window openable rate does not have much impact on the total energy load.

The simulation results demonstrated that window openable rate has no significant influence on the total energy load in all three climate regions. This means the occupants can control the window opening according to their preference, especially when considering noise and security condition.

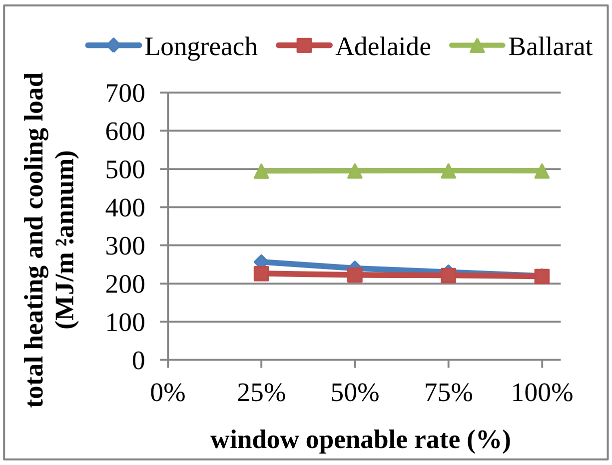


Figure 5 Effect of window openable rate on the total energy load

3.4 Effect of wall thickness

Figure 6 indicates that in Longreach (climate zone 3, hot arid) increasing the wall thickness was a very effective way of improving the energy efficiency of the model house. According to the simulation results, the total energy load dropped by nearly 50% from 220.1 to 112.4 MJ/m^2 per annum as the wall thickness increased from 200mm to 400mm. Similar results were observed in Adelaide (climate zone 5, warm temperate), as the wall thickness increased from 200mm to 400mm, the total energy demand reduced by 43.2% from 218.8 to 124.2 MJ/m^2 per annum. This remarkable reduction in energy load is due to the amount of thermal mass that can significantly affect the effectiveness of both the passive solar heating and cooling strategies. Therefore, better thermal performance can be achieved in the winter if the external walls are thick because they can assist the thermal resistance, blocking more heat from moving outwards. In summer, the greater thermal mass means that more heat can be absorbed during the daytime without seeping into the home. Thus, the cooling load can be reduced.

In Ballarat (climate zone 7, cool temperate), however, the effect of wall thickness on the total energy load was relatively smaller compared to the effect in climate zones 3 and 5. As the wall thickness increased from 200mm to 400mm, the total heating and cooling energy demand reduced by 20.3% from 494.5 to 393.9 MJ/m^2 per annum but only due to reduced cooling load, while the heating load could not be significantly reduced. Since in this climate zone, heating load accounts most of the total energy load of a house, increasing thermal mass will not reduce the total energy as much as it does in other climates where much space cooling is demanded.

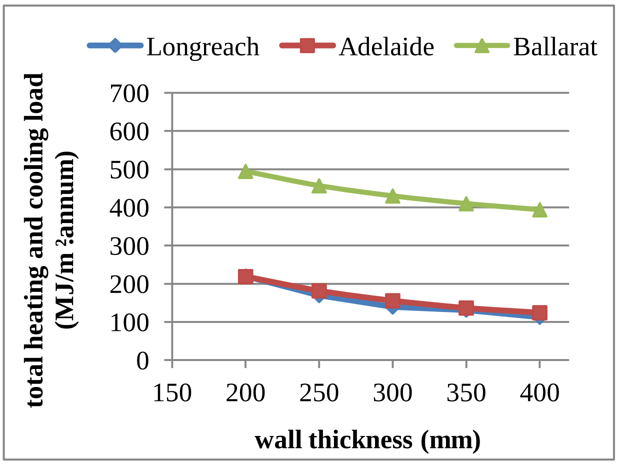


Fig. 6. Effect of wall thickness on the total energy load

3.5 Effect of window construction type

To further reduce the energy load, the effect of using double glazed window was evaluated. Figure 7 shows that using double glazed windows reduced the total energy load while the amount of reduction in energy load depended on climates. Once the other parameters were optimized, the total energy load of the house with double glazed windows was reduced slightly from 112.4 to 105.3 MJ/m^2 per annum in Longreach (climate zone 3). Since the energy load of model houses with single glazed windows was already much less than the 6-star rating requirement, it is not necessary to use double glazed window in this climate region.

In Adelaide (climate zone 5), the total energy load was reduced by 14% from 124.3 to 106.6 MJ/m^2 per annum by applying double glazed window, and the area-adjusted value for this energy load was 86.8 MJ/m^2 per annum, which was less than the 6-star rating requirement for this climate region (96 MJ/m^2 per annum).

In Ballarat (climate zone 7), the total energy load for model house with other parameters being optimised was reduced from 393.9 to 304.4 MJ/m^2 per annum when double glazed windows were applied. The area-adjusted value of this load was 250.9 MJ/m^2 per annum, however, it was still larger than the 6-star rating requirement which specifies an energy load of 197 MJ/m^2 per annum, meaning that in climate zone 7, although all the design parameters were optimized and double-glazed windows were applied, uninsulated rammed earth wall houses would still require more total heating and cooling load than the maximum allowed for a 6-Star rating design in the NCC.

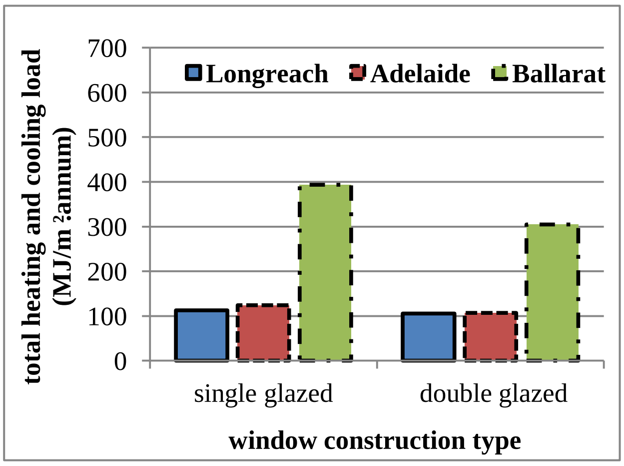


Figure 7 Effect of window construction type on the energy loads

3.6 Cases that can meet the energy rating requirements

As the parameters being optimised, many model houses consumed less energy than the 6-star requirements specified for Longreach and Adelaide. In Ballarat, however, using passive strategies could not potentially reduce the energy load of uninsulated rammed earth houses below the 6-star rating requirement.

Figure 8 presents all the cases in Longreach (those located at the right side of each line) that can meet the energy rating requirement as long as windows of the optimum size were installed (single glazed windows were applied in these cases). It can be seen from Figure 6 that if the window openable rate was less than 25%, the required wall thickness became very large to meet the energy rating requirement. In reality, it is impractical and uneconomic to build walls more than 400mm thick. Hence it is recommended that in this climate zone, the window openbale rate should be at least 25% and the larger the better. The projection factor should be as large as possible as increasing the projection factor helped reduce the required wall thickness to meet the energy rating requirement. Since the cost of an eave can be much less the cost of rammed earth walling, the cost of construction could be reduced by doing this.

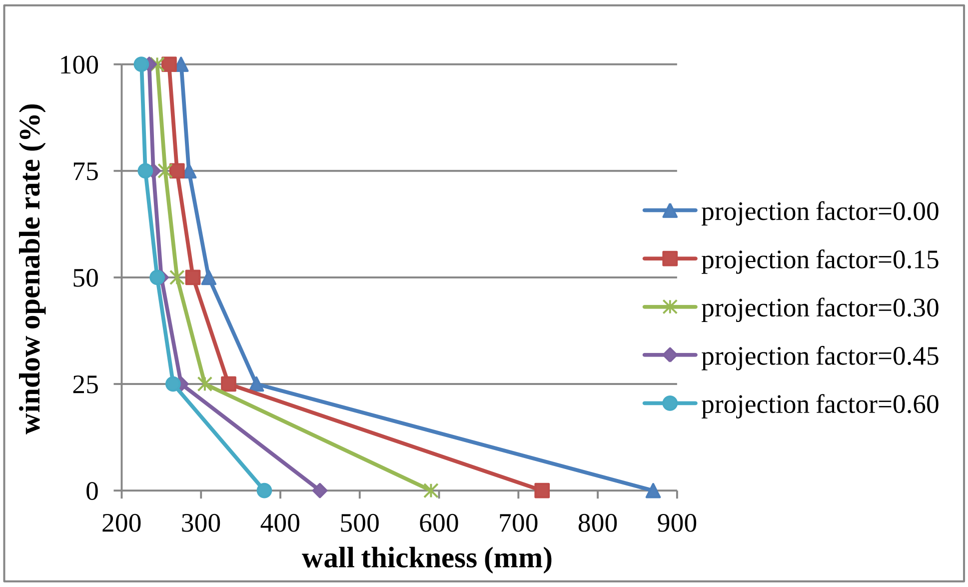


Figure 8 Cases that can meet the 6-star rating requirements (Longreach)

Figure 9 presents all the cases in Adelaide (those located at the right side of each line) that could meet the energy rating requirements, as long as the optimum window size and double glazed window were used. It is clear that small or no eaves were ideal, and the window openable rate should be at least 25% to ensure that the required wall thickness was kept at a reasonable value (less than 400mm).

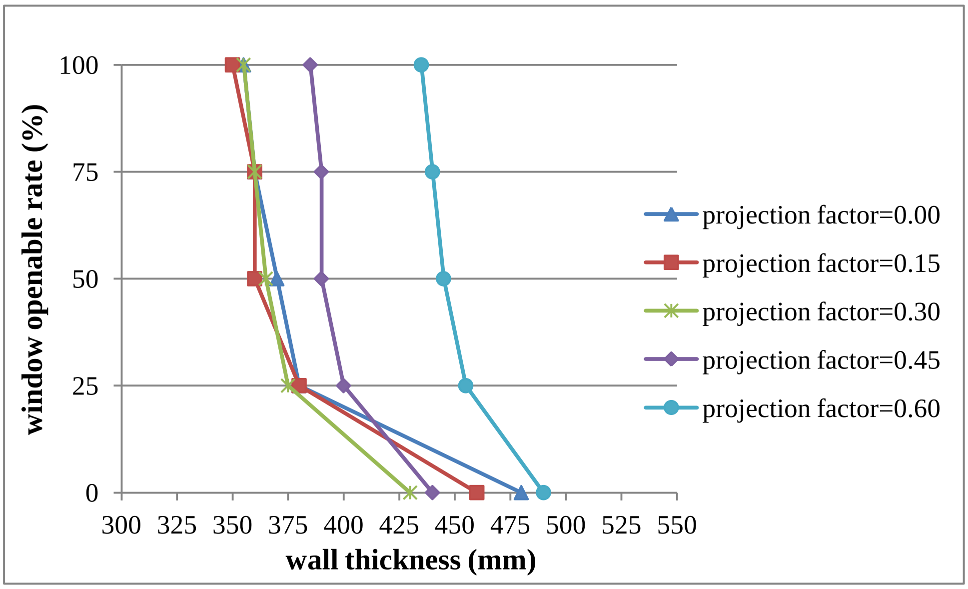


Figure 9 Cases that can meet the 6-star rating requirements (Adelaide)

4. Conclusions

In order to explore the possibility that uninsulated rammed earth wall houses can meet the requirements of the NCC without adding insulation, the current study investigated the influence of several factors on the total heating and cooling load of uninsulated rammed earth wall houses located in three different climate zones in Australia. Recommendations of design strategies for uninsulated rammed earth houses in each climate are summarised according to the simulation results.

In climate zone 3, with hot dry summers and warm winters, uninsulated rammed earth wall houses can meet the 6-star rating requirements as long as they are designed carefully. The window size on each wall should be as small as possible to limit the heat passing through, and the eave width should be deep enough to provide the necessary shade. Using natural night breezes to ventilate the rooms can lower the indoor temperature and cooling load, thus the openable window area should be as large as possible. Further increasing the wall thickness can also significantly reduce the total energy load. The minimum wall thickness that enables the house to meet the requirements is 225mm, as long as the other design parameters are optimized.

In climate zone 5, which is a climate with warm summers and cool winters, uninsulated rammed earth wall houses can also exhibit acceptable thermal performance. To meet the 6-star rating requirements, several conditions must be fulfilled. The WWR of north window should not be less than 50%, while the WWR of other windows should not be larger than 10%. Wide eaves are not desirable because with wider eaves, more solar energy is lost, (i.e., not captured by the windows). The window openable area has a slight effect on the total energy load; however, houses with more ventilation tend to perform better. Walls should be thick enough and the usage of double glazed window is necessary to minimize the heat loss in winters. In general, it is hard, but not impossible to meet the requirements of the BCA for rammed earth wall houses without insulation.

In climate zone 7, which is a climate with mild to warm summers and cold winters, uninsulated rammed earth wall houses will fail to fulfil the 6-star requirements. This means that uninsulated rammed earth wall houses cannot perform acceptably in cold climates unless it is insulated. The benefits of their large thermal mass cannot counterweigh the negative impacts caused by their low thermal resistance.

In summary, in Australian climate zones 3 and 5, it is possible for an uninsulated rammed earth wall house to fulfil the minimum requirement of the NCC as long as the house is designed carefully by optimising a number of passive solar design strategies. In climate zone 7, however, uninsulated rammed earth wall houses cannot meet the NCC requirement even after optimising passive solar design strategies.

References

[1] G. Wilkenfeld, Associates, Household energy use in Australia: end uses, greenhouse gas emissions and energy efficiency program coverage, 1998.

[2] V. Soebarto, Analysis of indoor performance of houses using rammed earth walls, The Eleventh International IBPSA Conference, Glasgow, Scotland, 2009, pp. 1530-1537.

[3] B. Givoni, Characteristics, design implications, and applicability of passive solar heating systems for buildings, Solar Energy, 47 (6) (1991) 425-435.

[4] B. Venkatarama Reddy, P. Prasanna Kumar, Embodied energy in cement stabilised rammed earth walls, Energy and Buildings, 42 (3) (2010) 380-385.

[5] P. Taylor, R. Fuller, M. Luther, Energy use and thermal comfort in a rammed earth office building, Energy and Buildings, 40 (5) (2008) 793-800.

[6] Australian Building Codes Board, National Construction Code Standards Australia, Canberra, 2013.

[7] M. Hall, D. Allinson, Assessing the effects of soil grading on the moisture content-dependent thermal conductivity of stabilised rammed earth materials, Applied Thermal Engineering, 29 (4) (2009) 740-747.

[8] Z. Yan, J.C. Lam, J. Liu, Experimental studies on the thermal and moisture properties of rammed earth used in adobe buildings in China, Architectural Science Review, 48 (1) (2005) 55-60.

[9] P. Taylor, M. Luther, Evaluating rammed earth walls: a case study, Solar Energy, 76 (1) (2004) 79-84.

[10] P. Walker, Standards Australia, The Australian Earth Building Handbook, Standards Australia, Sydney, Australia, 2002.

[11] M. Hall, Y. Djerbib, Rammed earth sample production: context, recommendations and consistency, Construction and Building Materials, 18 (4) (2004) 281-286.

[12] Standards Australian, AS 3700-2001: Masonry Structures, Standards Australia, Sydney, Australia, 2001.

[13] W.O. Wray, J.D. Balcomb, Sensitivity of direct gain space heating performance to fundamental parameter variations, Solar Energy, 23 (5) (1979) 421-425.

[14] B. Givoni, Options and applications of passive cooling, Energy and Buildings, 7 (4) (1984) 297-300.

[15] E. Shaviv, A. Yezioro, I.G. Capeluto, Thermal mass and night ventilation as passive cooling design strategy, Renewable Energy, 24 (3) (2001) 445-452.

[16] G. McBoyle, Climatic classification of Australia by computer, Australian Geographical Studies, 9 (1) (1971) 1-14.

[17] M. Kottek, J. Grieser, C. Beck, B. Rudolf, F. Rubel, World map of the Koppen-Geiger climate classification updated, Meteorologische Zeitschrift, 15 (3) (2006) 259-264.

[18] CSIRO, AccuRate Manual, Australian Commonwealth Scientific and Industrial Research Organisation, 2004.

[19] A. Delsante, An Empirical Validation of CHENATH, The National Home Energy Rating Scheme Simulation Engine (DBCE Doc. 95/78 (M)), Melbourne: CSIRO, Division of Building Construction and Engineering, 1995.

[20] A. Delsante, A Validation of the AccuRate Simulation Engine Using BESTEST, Report to the Australian Greenhouse Office. CSIRO Manufacturing & Infrastructure Technology report, CMIT (C)-2004-152, (2004).

[21] L. Daniel, V. Soebarto, T. Williamson, Evaluating the suitability of the AccuRate engine for simulation of massive construction elements, Annual Conference, 2012.

[22] A. Delsante, A comparison of 'accurate' predictions with measured data from a mud brick house, Proceedings of IBPSA Australasia Conference 2006, Adelaide, 2006, pp. 96-103.

[23] P. Walsh, A. Delsante, Calculation of the thermal behaviour of multi-zone buildings, Energy and Buildings, 5 (4) (1983) 231-242.

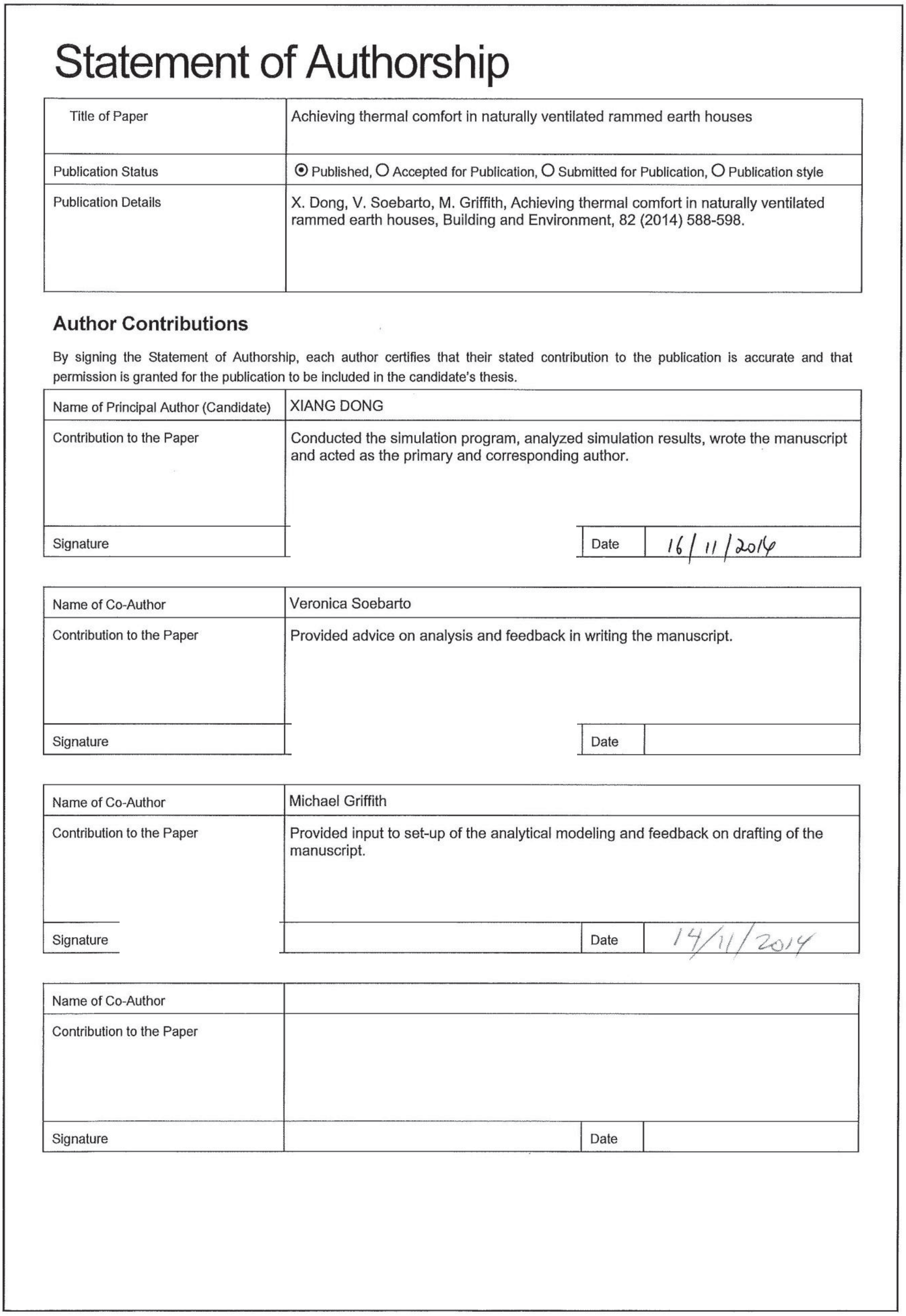
Chapter 6 Prediction of Thermal Performance of Naturally Ventilated Rammed Earth Wall Houses

Introduction

According to Chapter 5, houses built with uninsulated RE walls struggle to meet the Star Rating Requirements, in particular in cold climates. Hence insulation must be added to RE walls to meet the requirements of BCA. Adding insulation only, however, cannot guarantee a satisfactory indoor thermal comfort as the thermal performance of a house is determined by the interaction between a set of key design parameters. This chapter describes the optimization study on the thermal comfort of naturally ventilated ICRE wall houses by optimizing key design parameters including window size, window shading, window openable rate, the amount of thermal mass and insulation thickness. The thermal performance of air-conditioned ICRE wall houses was investigated as well and the results were reported in Chapter 7.

List of Manuscript

X. Dong, V. Soebarto, M. Griffith, Achieving thermal comfort in naturally ventilated rammed earth houses, Building and Environment, 82 (2014) 588-598.



Statement of Authorship

Title of Paper	Achieving thermal comfort in naturally ventilated rammed earth houses
Publication Status	● Published, ○ Accepted for Publication, ○ Submitted for Publication, ○ Publication style
Publication Details	X. Dong, V. Soebarto, M. Griffith, Achieving thermal comfort in naturally ventilated rammed earth houses, Building and Environment, 82 (2014) 588-598.

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author (Candidate)	XIANG DONG		
Contribution to the Paper	Conducted the simulation program, analyzed simulation results, wrote the manuscript and acted as the primary and corresponding author.		
Signature		Date	16/11/2014

Name of Co-Author	Veronica Soebarto		
Contribution to the Paper	Provided advice on analysis and feedback in writing the manuscript.		
Signature		Date	

Name of Co-Author	Michael Griffith		
Contribution to the Paper	Provided input to set-up of the analytical modeling and feedback on drafting of the manuscript.		
Signature		Date	14/11/2014

Name of Co-Author			
Contribution to the Paper			
Signature		Date	

Achieving thermal comfort in naturally ventilated rammed earth houses

Xiang Dong , Veronica Soebarto , Michael Griffith

ABSTRACT Rammed earth buildings are normally perceived to have desirable thermal performance due to the thermal mass effect of the walls; however, this can only be achieved when other design strategies are taken into account such as insulation, double glazing, shading and ventilation. This paper reports on a study of the impact of using rammed earth walls on the indoor temperatures in a non-heated or cooled hypothetical house by using a thermal simulation program. The predicted indoor operative temperatures are compared to the acceptable operative indoor temperatures based on the Adaptive Comfort Standard in ASHRAE 55-20113. The building was considered in three Australian climate zones (zones 3, 5 and 7) representing hot arid, warm temperate and cool temperate climates, respectively.

The effect of four design parameters on the indoor temperatures of this hypothetical uninsulated rammed earth wall house was evaluated, including the influence of window size, shading, ventilation rate and wall thickness. It was found that a house constructed of uninsulated rammed earth with a typical wall thickness of 300mm in climate zones 3, 5 and 7 can only achieve indoor operative temperatures that are within the 80% acceptability limits based on the adaptive model for 77%, 68% and 45% of the time, respectively, if the window size, shading and ventilation rate are optimised. With a 30mm thick layer of polystyrene insulation inserted into the middle of the rammed earth walls, these performance values can be further increased to 89%, 90% and 58% respectively.

Keywords: rammed earth; thermal comfort; naturally ventilated; design parameter; Australian climates

1. Introduction

In recent years there has been a revival of interest in rammed earth (RE) construction. RE is perceived to be environmental friendly and sustainable as it is a construction material with extremely low embodied energy, in particular when locally available material is used (Morel, et al., 2001; Reddy, et al., 2014; Reddy and Kumar, 2010b; Treloar, et al., 2001). Using material that is available locally means considerably reducing the energy consumed for manufacturing and transporting, which accounts for 29%-40% of the total embodied energy of that material (Blengini, 2009; Zabalza Bribián, et al., 2011). In addition, rammed earth houses are claimed to be thermally efficient because they are able to maintain a reasonably comfortable indoor temperatures year around without much input of external energy for heating and cooling (Soebarto, 2009). This is because rammed earth constructions are characteristically built with thick earthen walls for stability (typically 300mm to 600mm thick (Hall and Djerbib, 2004)), and the thermal mass of these thick walls can delay the transmission of heat from the outside to the inside due to the wall's long time lag in hot summer days (typical 300mm thick rammed earth walls can provide a thermal time lag of about 10 hours (Baggs, et al., 1991b; Taylor and Luther, 2004)), meaning that the maximum indoor temperature will occur much later after the outdoor temperature peaks during the day and thus cool night-time ventilation can be used to reduce the indoor temperature (Jaber and Ajib, 2011). In cold winter days, the thermal mass stores much of the heat it absorbs during daytime and the stored heat will be released to the inside of the house at night and help to warm the spaces (Givoni, 1991; Jaber and Ajib, 2011).

According to a survey conducted by Paul and Taylor (Paul and Taylor, 2008), rammed earth buildings do not necessarily provide better thermal performance than conventional buildings. The occupants claimed that the internal environment of the rammed earth buildings was warm in summer, leading to a low level of satisfaction. Another study by Taylor et al. (Taylor, et al., 2008) reported that a naturally ventilated rammed earth office building (with hydronic heating and cooling) could not provide adequate thermal comfort in both winter and summer or expected energy saving, unless the external walls were insulated. Rammed earth walls alone cannot guarantee thermal comfort or energy conservation and the building performance generally improves when other design strategies, such as insulation (Taylor, et al., 2008), glazing, shading and ventilation (Liu, et al., 2010), are implemented. Inappropriate use of thermal mass may in fact cause negative impacts on thermal comfort, hence it is recommended that the integration of thermal mass and other design parameters be optimised and this optimisation be conducted using thermal performance software tools (Baggs and Mortensen, 2006). The study presented in this paper investigated the effects of key design parameters on the thermal comfort of naturally ventilated rammed earth houses (i.e., no heating or cooling), in order to identify the optimum value of each design parameter corresponding to the maximum thermal performance and provide recommendations for more informed designs of rammed earth houses.

2. Thermal performance measure for naturally ventilated buildings

The main focus of the present study is the effect of key design parameters on the thermal performance of a hypothetical rammed earth house without heating and cooling. In naturally ventilated houses, thermal performance mainly refers to the internal thermal comfort as opposed to energy efficiency because heating and cooling systems are not employed thus theoretically there is no weather-dependent energy use to be measured. Thermal comfort is “that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE, 2013).

A large number of studies have been conducted to investigate the key factors that can influence thermal comfort. Fanger (Fanger, 1994) proposed a ‘static’ model based on data obtained in climatic chambers under steady-state conditions, which indicated that thermal preference between people would not be affected by physiological factors or regions. Later, an ‘adaptive’ model developed by de Dear (de Dear and Brager, 1998; de Dear and Brager, 2002) based on data collected from field studies in real buildings, which take into account the responses of occupants to achieve thermal comfort, such as opening windows for ventilation or changing their clothing, has led to a wider range of comfort zone than that for the 'static' model. The adaptive model was then adopted by American Society of Heating, Refrigerating and Air Conditioning Engineers' (ASHRAE) Standard 55 (ASHRAE, 2004), in particular for investigating the thermal comfort of a naturally-ventilated building, where there are opportunities for the occupants to adjust their thermal environment by, for example, opening the windows or turning on fans, and where the occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions. During the last decade, numerous studies have been conducted on the thermal comfort of naturally ventilated buildings around the world, such as studies from McCartney and Nicol (McCartney and Nicol, 2002) (in Europe), Indraganti (Indraganti, 2010), Indraganti et al. (Indraganti, et al., 2014), Indraganti and Rao (Indraganti and Rao, 2010) (in India), Candido et al. (Cândido, et al., 2010) (in Brazil), Goto et al. (Goto, et al., 2007) (in Japan), Zhong et al. (Zhong, et al., 2012) (in China), and Saman et al. (Saman, et al., 2013), as well as Soebarto and Bennetts (Soebarto and Bennetts, 2014) (in Australia).

According to the adaptive model, the acceptable indoor operative temperature T_i have a linear relationship with the prevailing mean outdoor temperature (ASHRAE, 2013; de Dear and Brager, 1998), which can be calculated by: $T_i = 0.31 * T_o + 17.8$, where T_o = Prevailing mean outdoor temperature.

This standard specifies the boundary conditions of a space that provides acceptable thermal environment for 80% or more of the occupants. The upper and lower limits of the indoor operative temperature corresponding with 80% (90%) acceptability are defined by extending the indoor comfort temperature by ±2.5^{o}C (±3.5^{o}C) (de Dear and Brager, 2002). The prevailing mean outdoor temperature (T_o) is determined based on a simple arithmetic mean of the mean daily outdoor air temperatures of seven days prior to the day in question (T_n), using the exponentially weighted running means as explained in (de Dear, 2006; de Dear, 2011) as shown in the following equation: $T_o = 0.34T_1 + 0.23T_2 + 0.16T_3 + 0.11T_4 + 0.08T_5 + 0.05T_6 + 0.03T_7$.

3. Methodology for parametric study

The investigation was based on thermal simulation of a hypothetical base building which is naturally-ventilated and has uninsulated rammed earth external walls. Individual as well as combined design parameters are then implemented methodically to find out their impact on the building's indoor thermal comfort.

The simulation program used was *AccuRate* (CSIRO, 2004), developed by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO). *AccuRate* predicts the thermal behaviour of a building using a frequency response method, the key technique of which is to obtain the frequency response functions and transient response factors from the relationship between a set of inputs (climatic information and thermal properties of building elements) and outputs (the software can output the energy loads for heating and cooling that required to produce thermal comfort, or export the indoor temperatures for houses without air conditioning) (Walsh and Delsante, 1983). The software has been validated both empirically and through intermodal comparisons (Daniel, et al., 2012b; Delsante, 2006; Delsante, 1995; Delsante, 2004).

3.1 The "basic model house"

A basic model house was developed as the reference case, which was a single zone house ($12m \times 8m$) facing true north as shown in Figure 1. A simplified single zone house is commonly used for such investigation, such as in studies conducted by Delsante (Delsante, 2004), Daniel et al. (Daniel, et al., 2012b) and Wang et al. (Wang and Wong, 2009). The ceiling of the basic model house consisted of R 3.0 glass fibre batt and 10mm thick plasterboard, above which there was a pitched roof (with an angle of 30^o) consisted of R 1.0 glass fibre batt insulation and 1mm steel sheet. Ceiling was highly insulated in order to minimize the effect of other parameters (except for the external walls) on the thermal comfort of the model house. Similarly, no internal walls were applied in the basic model as this study aimed at investigating the effect of the main design parameters that relate to the external envelope (which play an important role on the heat exchanges between the inside and outside of a house) on the thermal comfort. Internal walls which are normally constructed with light-weight materials has no significant influence on the overall thermal comfort of the entire house as they mainly affect the heat exchanges between two adjacent zones inside the house rather than heat exchanges between the inside and outside of the house.

A test simulation has been performed to evaluate the effect of internal walls (built by light-weight materials) on the overall thermal comfort (i.e. indoor temperature). A three zone model was developed with the same external envelope of the basic model used in this study, while internal walls (constructed of 110mm thick brickwork) were applied. Openings (10% of the internal wall area) were available for ventilation. The results showed a very small difference with the results for the single zone basic model. For example, in Adelaide, the indoor temperatures that fall inside the comfort zone accounts for 50.7% of the time, while with internal walls, the amount of comfort indoor temperatures in three zones were between 46.7% and 54.5%, with an average value of 50.6%, which agreed closely to the value for the single-zone house.

The model was given external walls of 200mm thick rammed earth (according to the default thermal properties of materials in *AccuRate*, the thermal conductivity and heat capacity of rammed earth are 1.25W/m K and 1940kJ/m^3 K respectively). They were 2.7m high, sitting on 100mm thick concrete floor (R-value = 0.07m^{2}K/W). Window/wall area ratio (WWR) of 10% was applied in each of the four walls and no window shading was installed in the basic model. Windows were selected as single-glazed and timber framed (Overall Heat Transfer Coefficient=5.75W/m^2 K; Solar Heat Gain Coefficient =0.69), and could open to 25% of their area for the basic model house. The height of windows was set at 1.5m and they were installed 1.0m above the floor.

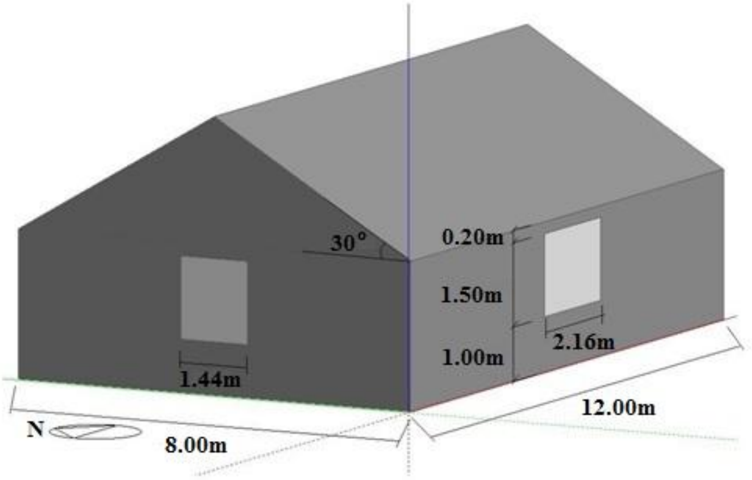


Figure 1 Basic model house

3.2 Design parameters

Four parameters which are known to affect the control of heat exchange in a house were considered in the parametric study, namely window size, window shading, ventilation rate and the amount of thermal mass. Window size was determined by the window/wall area ratio (WWR). Window shading (consisted of simple timber frames and 1mm thick steel sheets were installed 0.2m above the top of windows, representing a common overhang design constructed of corrugated steel sheets on timber supports) was controlled by the projection factor which was calculated by the width of the window shading divided by the distance between the bottom of the window shading and the bottom of the window as shown in Figure 2. The ventilation rate which controls the effectiveness of night ventilation passive cooling was determined by the window area that would open (i.e. window operable rate). The window opening schedule was controlled by the *AccuRate* program itself. In general, if the indoor temperature is higher than the comfort level, the window is assumed to be opened for natural ventilation. The amount of thermal mass was controlled by the rammed earth wall thickness.

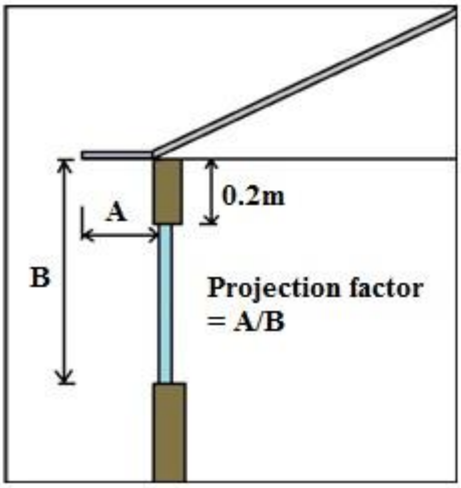


Figure 2 Projection factor

The values considered for each of these parameters is given in Table 1. Realistic values were selected in response to recommendations from local builders based on their experiences of constructing rammed earth houses for decades. The rammed earth wall thickness to be analysed were selected to be between 200mm and 400mm. The minimum thickness is determined by the Australian Earth Building Handbook that requires external rammed earth walls to have a minimum thickness of 200mm (Walker and Standards Australia, 2002), while the maximum thickness of 400 mm was based on recommendations by local rammed earth builders who suggested that it is not practical to construct rammed earth walls more than 400mm thick (Stabilised Earth, 2008). WWR of each wall varied from 10% to 50%. There is no limitation for maximum window area or window operable rate; however, it should be noted that according to the Australian Building Code (BCA) (Australian Building Codes Board, 2013), the minimum required glazed area for habitable rooms is 10% of the floor area. For the basic model in this study, the overall glazed/window area was 10.8m^2, which was more than 10% of the floor area (9.6m^2). Also, the BCA requires the overall operable area of the windows to be at least 5% of floor area, which corresponds to 4.8m^2. If the WWR of 10% for each wall and window operable rate of 25% is applied; the overall operable area of the windows is 2.7m^2, which is less than the minimum requirement, thus will not be implemented (see detailed investigations below). The minimum projection factor of window shading was set at 0.00 as there is no requirement for minimum shading size, and the maximum value was set at 0.60 because too large window shading would affect the amount of natural lighting entering the building as well as will require extra structural support. The effect of insulation will be discussed separately in subsection 3.3.2 D.

Table 1 Design parameter values

Parameter	Values*
Window size (WWR)	**10%**, 20%, 30%, 40% and 50%
Window shading (projection factor)	**0.00**, 0.15, 0.30, 0.45 and 0.60
Ventilation (window operable rate)	**25%**, 50%, 75% and 100%
Thermal mass (RE wall thickness)	**200mm**, 250mm, 300mm, 350mm and 400mm

* Bold values correspond to “basic model house” (subsection 3.1)

3.3 Simulation and results

For the simulation, it was assumed that there is daytime occupancy and cooking heat gains are included. Full details of other assumptions for the simulation (such as window opening schedule, weather data and infiltration) have been presented elsewhere by Dong et al. (Dong, et al., 2014).

While *AccuRate* is usually used to ‘rate’ a building design based on the predictions of heating and cooling loads, the software can also be used to predict indoor temperatures when heating and cooling are not employed by running the simulation in the ‘non-rating’ mode. In *AccuRate* the predicted indoor temperatures is a mixture of both indoor air temperature and radiant temperature, which is very similar to operative temperature (CSIRO, 2004), therefore it is reasonable to compare the indoor temperatures derived from *AccuRate* to the adaptive comfort zone model.

It should be pointed out at this point that the thermal comfort standard in ASHRAE 55 was developed from work conducted using a mean outdoor temperature range between 5^o and 33^oC; however, de Dear and Brager (de Dear and Brager, 1998) argued that this standard was valid for a mean outdoor temperature range of between 10^o and 33^oC as 5^oC was too extreme for the lower end. In the current study, the upper and lower limits of the acceptable indoor operative temperatures have been extended horizontally for mean outdoor temperatures between 5^oC and 10^oC as shown in Figure 3, which gives an example of the adaptive comfort zone for Adelaide, Australia, based on the outdoor long term average database over a 12-month period provided by *AccuRate* software (CSIRO, 2004). For a mean outdoor temperature greater than 33^oC or less than 5^oC, the corresponding indoor operative temperatures were defined as uncomfortable (explanation is given in §3.3.1).

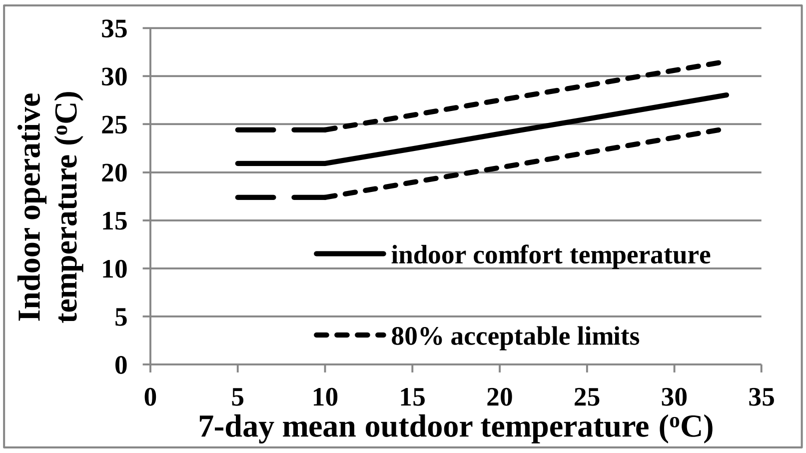


Figure 3 Acceptable indoor temperatures for naturally ventilated buildings (warm temperate climate)

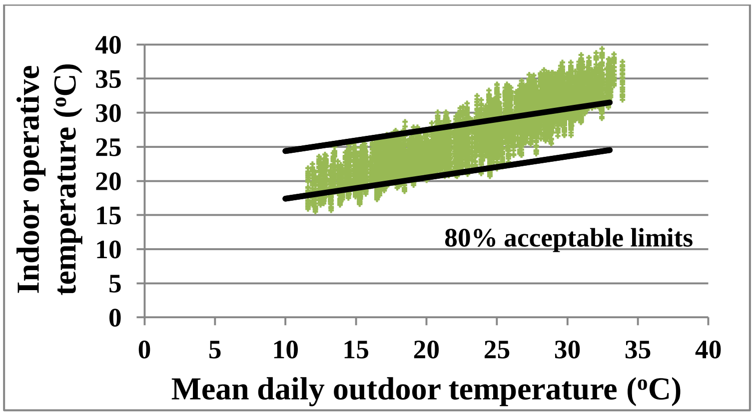
In order to investigate the influence of climate on the indoor temperatures, the analysis was conducted using three different Australian climate zones– 3, 5 and 7 – representing a semi-arid climate (Bsh), hot Mediterranean climate (Csb) and moderate oceanic climate (Cfb) in the Koppen climate classification system, respectively (Kottek, et al., 2006; McBoyle, 1971). Information about each climate is summarised in Table 2.

Table 2 Details of three climate zones

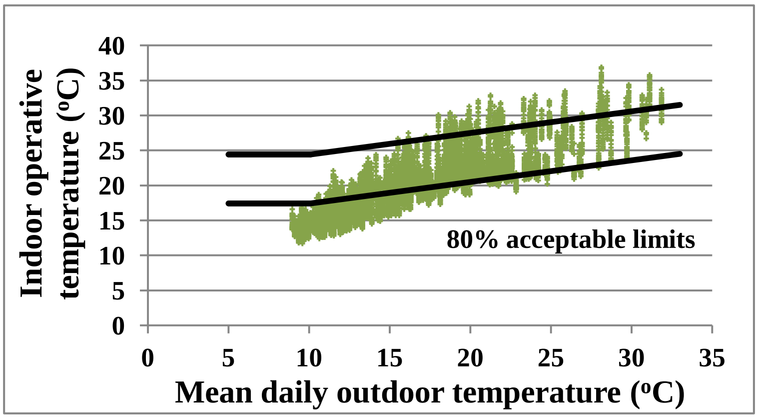
	Climate zone 3 (Bsh)	Climate zone 5 (Csb)	Climate zone 7 (Cfb)
Climate type	Hot arid	Warm temperate	Cool temperate
Summer characteristics	Hot dry	Warm	Mild to warm
Winter characteristics	Warm	Cool	Cold
Summer temperature range	22.5—36.7	16.6—28.6	10.6—24.2
Winter temperature range	9.3—26.6	8.5—17.0	3.9—11.8
Typical city in Australia	Longreach	Adelaide	Ballarat

3.3.1 Results for the basic model house

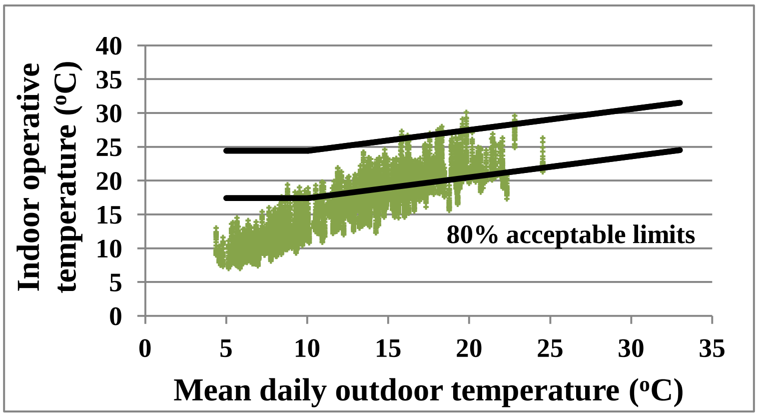
The indoor temperatures of the basic model house in each climate over a whole year period were simulated. The coincidences of predicted indoor temperatures and the adaptive comfort zone (between the upper and lower 80% acceptable limits) are shown in Figure 4.



(a) Longreach (hot arid climate, climate zone 3)



(b) Adelaide (warm temperate climate, climate zone 5)



(c) Ballarat (cool temperate climate, climate zone 7)

Figure 4 Coincidence of simulated indoor temperatures with adaptive comfort zone

According to the results shown in Figure 4, in Longreach, for considerable amount (37%) of the time the indoor operative temperatures of the basic model house were fallen outside of the adaptive comfort zone, normally because they were too hot. In Adelaide, uncomfortable indoor operative temperatures accounted for almost half of the time beyond both of the upper and lower acceptability limits. In Ballarat, for over 70% of the time the indoor operative temperatures were below the lower 80% acceptability limit. It should be noted that for the cases with a mean outdoor temperature greater than 33^{o}C (in climate zone 3) or less than 5^{o}C (in climate zone 7), the corresponding indoor operative temperatures were defined as uncomfortable as they were normally too hot (over 32^{o}C) as shown in Figure 4(a) or too cold (below 13^{o}C) as shown in Figure 4(c). The simulation results indicate that uninsulated rammed earth wall houses cannot provide sufficient comfortable indoor conditions if the other building features are not well designed, especially in locations that experience cool to cold winter.

3.3.2 Results for model houses with different design parameters

A): Effect of window size

In order to evaluate the effect of window size on the indoor temperatures, the window size of each wall was modified one by one from 10% to 50%. The percentage of predicted indoor temperatures that fell inside the adaptive comfort zone considering difference window sizes are reported in Table 3, where it can be seen that in Longreach (hot arid climate), small windows (but not necessarily the smallest to be tested) in each wall resulted in more comfortable indoor temperatures because overheating was a common problem in a hot arid climate, and minimizing solar heat was achieved by implementing smaller windows.

In Adelaide (warm temperate climate) and Ballarat (cool temperate climate), however, the percentage of comfortable indoor temperatures increased as window size increased. This is because in these cities, most of the uncomfortable indoor operative temperatures fell outside the lower acceptability limit. Larger windows would therefore allow greater solar heat gains to warm the house.

Table 3 Effects of window size on thermal comfort

Window size (WWR)		Percentage of indoor temperatures inside adaptive comfort zone		
		Longreach	Adelaide	Ballarat
North window	10%	63.0%	50.7%	27.1%
	20%	63.0%	53.9%	29.5%
	30%	62.3%	57.0%	31.8%
	40%	60.1%	59.4%	34.1%
	50%	58.5%	61.4%	36.4%
East window	10%	63.0%	50.7%	27.1%
	20%	63.2%	51.7%	28.7%
	30%	62.8%	52.8%	30.2%
	40%	62.3%	53.6%	31.9%
	50%	61.4%	54.1%	33.2%
South window	10%	63.0%	50.7%	27.1%
	20%	63.3%	51.0%	27.9%
	30%	63.1%	51.3%	28.7%
	40%	62.7%	51.6%	29.7%
	50%	62.1%	52.1%	30.4%
West window	10%	63.0%	50.7%	27.1%
	20%	62.9%	51.7%	28.6%
	30%	62.7%	52.5%	29.6%
	40%	62.3%	53.1%	30.7%
	50%	61.7%	53.9%	31.7%

B): Effect of shading, ventilation rate and thermal mass

The effects of the other three parameters on the percentage of indoor operative temperatures that fell inside the adaptive comfort zone are indicated in Table 4. In Longreach, increasing the projection factor of the window shading from 0.00 to 0.60 led to a slight increase (1.5%) in the number of hours of comfortable indoor temperatures. If the same projection factor was applied to the model houses in Adelaide and Ballarat, however, the percentage decreased by 3.3% and 3.7% respectively. This result was similar in relation to changing the window size as solar heat can be reduced by either increasing window shading or decreasing window size.

Furthermore, the degree to which a window should be opened to allow natural ventilation also influences the number of hours of comfortable temperatures. In Longreach the percentage of comfortable indoor temperatures of the model house increased by 7.6% if the windows could be fully opened, while the percentage of comfort temperatures of the model houses in Adelaide and Ballarat would fall if the windows were fully opened, with the number of comfortable indoor temperatures decreasing by 2.9% and 1.2%, respectively. This is because fully opening the windows to allow natural ventilation to cool the house, which is beneficial in hot climates, could have a negative impact in cooler climates during low outdoor temperatures.

Increasing wall thickness could increase the number of comfortable indoor operative temperatures in each of the three climates. By increasing the wall thickness from 200mm to 400mm, the percentage of indoor temperatures falling inside the adaptive comfort zone increased by 5.8%, 11.4% and 4.7% for the model houses in Longreach, Adelaide and Ballarat, respectively.

Table 4 Effects of shading, ventilation rate and thermal mass on the thermal comfort

Parameter		Percentage of indoor temperatures inside adaptive comfort zone		
		Longreach	Adelaide	Ballarat
Window shading (projection factor)	0.00	63.0%	50.7%	27.1%
	0.15	63.2%	50.2%	26.5%
	0.30	64.0%	49.4%	25.3%
	0.45	64.4%	48.3%	24.3%
	0.60	64.5%	47.4%	23.4%
Ventilation rate (window operable rate)	25%	63.0%	50.7%	27.1%
	50%	67.4%	49.2%	26.3%
	75%	69.4%	48.3%	26.0%
	100%	70.6%	47.9%	25.9%
Thermal mass (wall thickness)	200mm	63.0%	50.7%	27.1%
	250mm	65.6%	53.6%	28.8%
	300mm	66.9%	56.7%	30.1%
	350mm	67.9%	59.5%	31.0%
	400mm	68.8%	62.1%	31.8%

C): Results for multiple parameter optimisations

According to the results presented in Tables 3 and 4, it is clear that optimising one parameter can only increase the number of comfortable indoor temperatures to a limited extent. Therefore, multiple parameter optimizations were conducted. Once the optimum value of one parameter had been determined, this optimum value was applied in the investigations of the subsequent parameters until the optimum value of the last tested parameter was determined. By doing this, the optimum value of each parameter that corresponding to the fully optimised model house was obtained as shown in Table 5.

Table 5 Optimum values of design parameters

Parameter	Optimum values		
	Longreac	Adelaide	Ballarat
North WWR	10%	50%	50%
East WWR	20%	20%	50%
South WWR	20%	10%	50%
West WWR	10%	10%	50%
Projection factor	0.60	0.00	0.00
Window operable rate	100%	25%	25%
Wall thickness	400mm	400mm	400mm

The amount of comfort indoor operative temperatures for the fully optimised model houses was also simulated. In Longreach, fully optimised model house would maintain comfortable indoor temperatures for 79.2% of the time. For Adelaide and Ballarat, fully optimised model houses produced comfortable indoor temperatures for 71.1% and 46.6% of the time respectively.

D): Effect of insulation

According to the simulation results presented above, it is clear that although fully optimised, naturally ventilated houses constructed with uninsulated rammed earth walls cannot provide an adequate amount of comfortable indoor operative temperatures, especially in cold climates. Adding insulation is an effective and simple way of improving the thermal performance of rammed earth wall houses (Soebarto, 2009; Taylor, et al., 2008). For rammed earth walls, insulation is normally installed in between two rammed earth wall leaves, forming an insulated cavity rammed earth (ICRE) wall system, in order to maintain their aesthetic appearance and the thermal mass effect from the inner side rammed earth leaf (Hall and Swaney, 2005). In order to investigate the effect of each parameter on the indoor temperatures of insulated rammed earth wall houses, a new basic model house was developed based on the original basic model. The parameters of the new basic model remained the same except for the external walls which were now replaced with ICRE walls, consisting of two 150mm thick rammed earth wall leaves between which a 30mm thick polystyrene insulation layer was sandwiched. A sectional drawing of this wall system is shown in Figure 5.

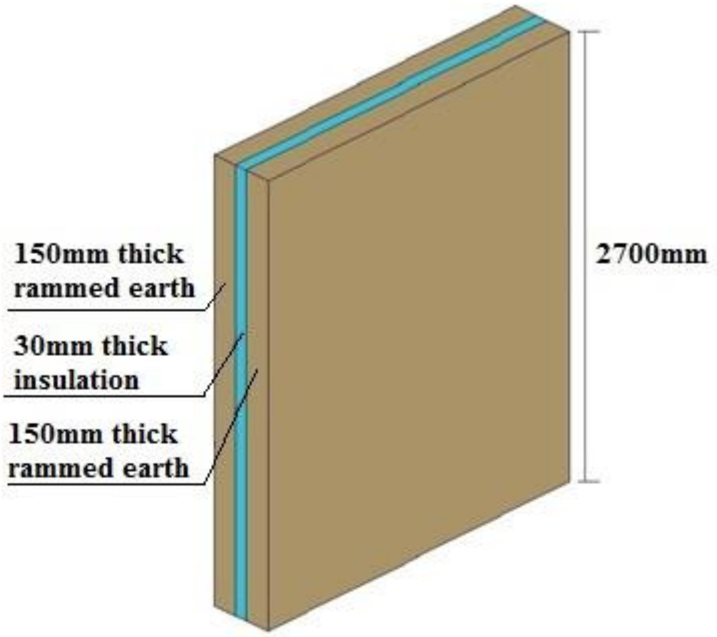


Figure 5 Insulated cavity rammed earth wall

Besides the effects of the parameters evaluated for the solid rammed earth wall house, the effect of insulation thickness was also evaluated for the new model houses by modifying the insulation thickness from 30mm to 100mm. This phase of simulations aimed to investigate the optimal thermal performance of fully optimised ICRE wall houses under naturally ventilated condition, hence only multiple parameter optimisations were conducted. Once the optimum value of a parameter was determined, it was applied in the subsequent investigations of the other parameters. The simulation results are presented in Figure 6 to 8.

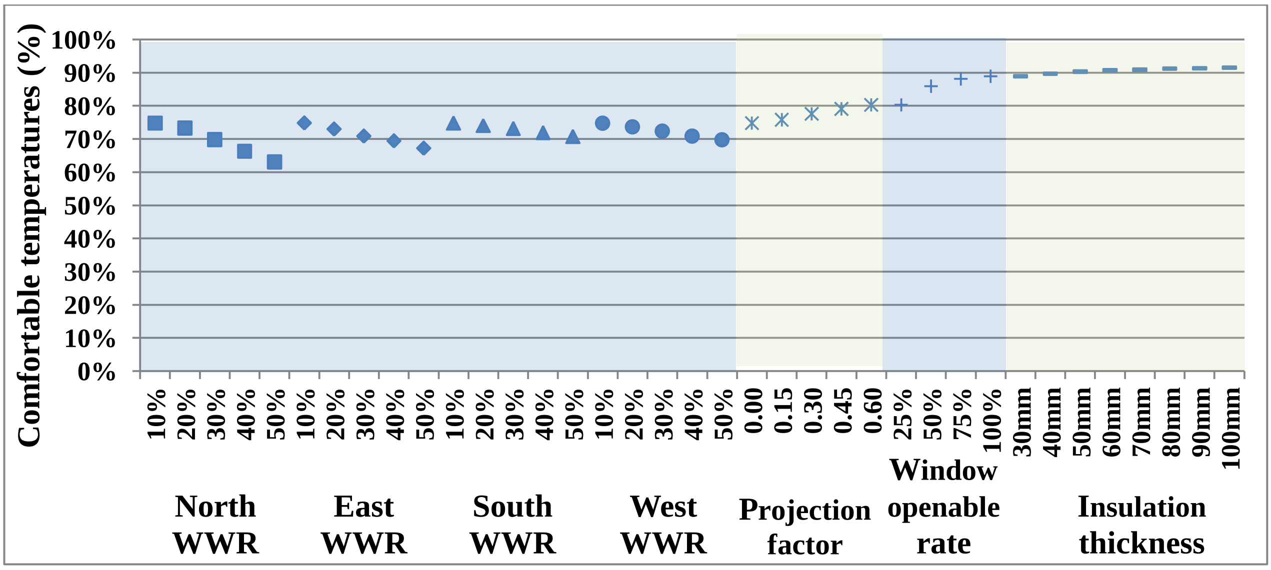


Figure 6 Effect of each parameter on the percentage of indoor temperature inside comfort zone (Longreach)

As shown in Figure 6, in Longreach, small windows in each wall were desirable. Increasing window shading and ventilation rate was effective to improve the percentage of indoor temperatures that fell inside the adaptive comfort zone. Increasing the insulation thickness from 30mm to 100mm, on the other hand, only resulted in a slight improvement (2.6%) on the amount of comfortable indoor operative temperatures.

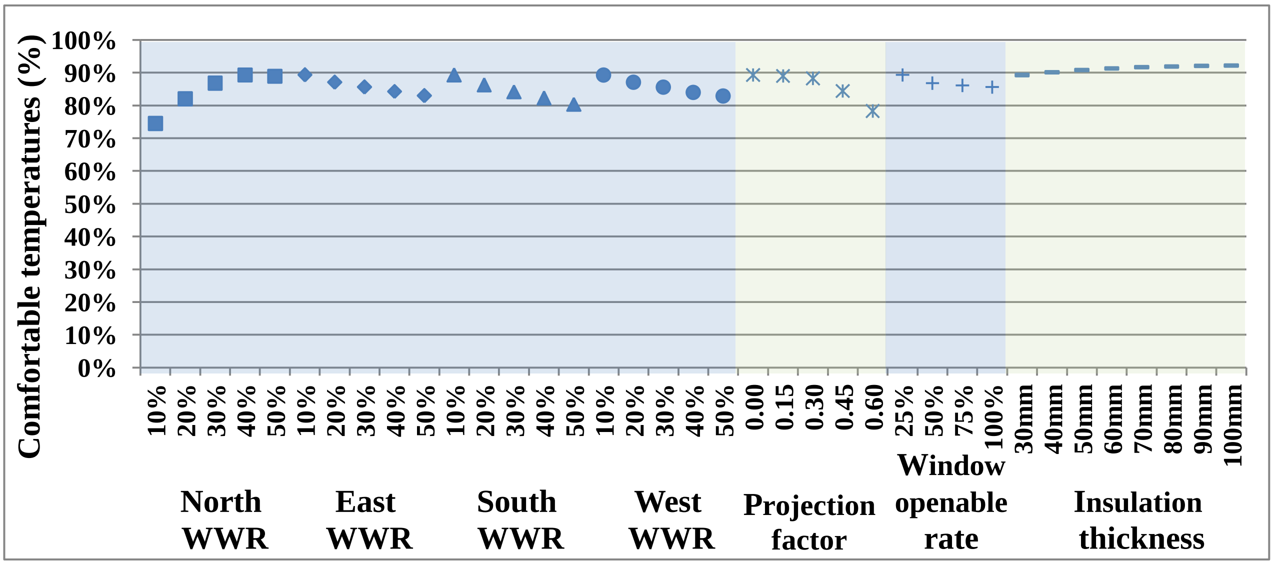


Figure 7 Effect of each parameter on the percentage of indoor temperature inside comfort zone (Adelaide)

In Adelaide (Figure 7), increasing north WWR from 10% to 40% caused an increase of the indoor operative temperatures that fell inside the adaptive comfort zone from74.5% to 89.3%. Further increasing the WWR to 50% led to a slight reduction of the percentage to 88.9%. For the other windows, small WWR led to more comfortable indoor temperatures. Increasing window shading and the ventilation rate, on the other hand, had negative effects on the indoor comfort while similar to the model house in Longreach, while increasing the insulation thickness can only slightly increase the percentage of indoor operative temperatures falling inside the adaptive comfort zone.

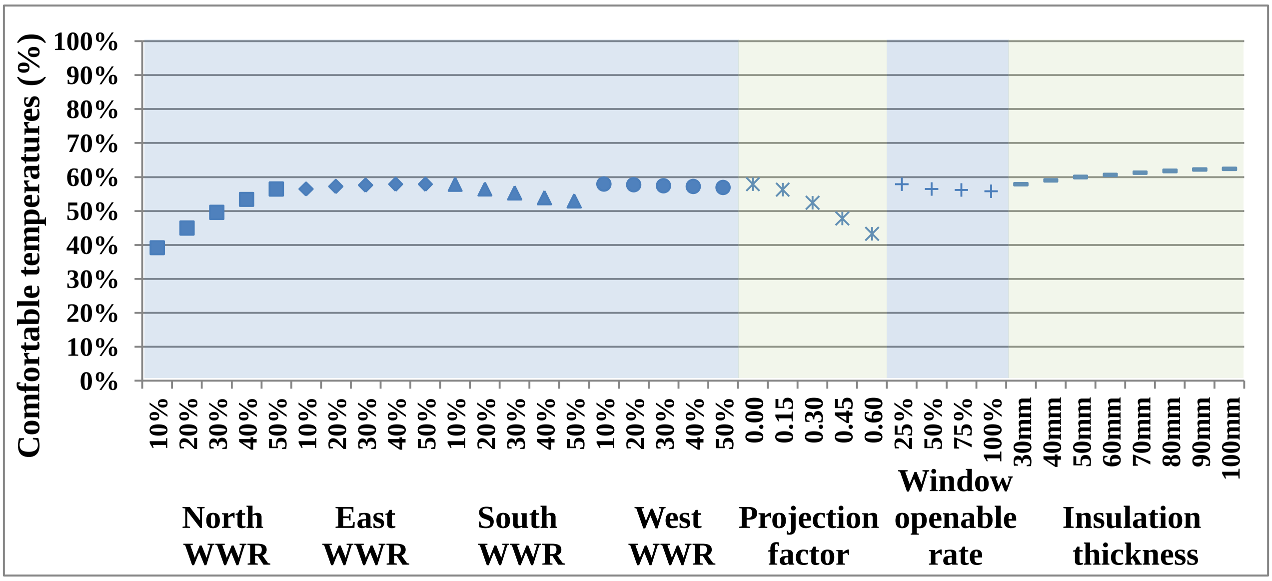


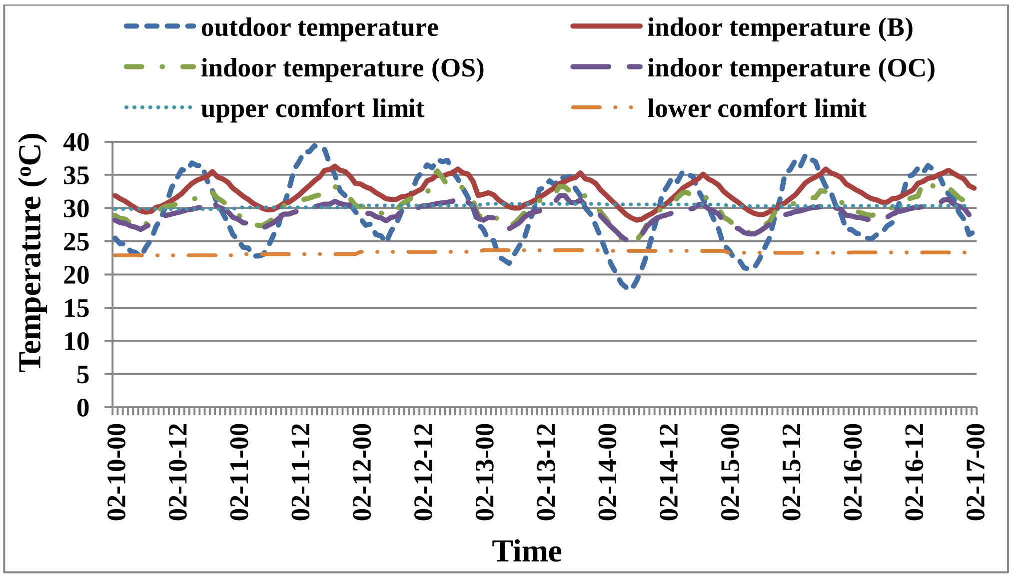
Figure 8 Effect of each parameter on the percentage of indoor temperature inside comfort zone (Ballarat)

For Ballarat (Figure 8), the percentage of indoor temperatures that fell inside the adaptive comfort zone increased from 39.2% to 56.5% as the north WWR increased from 10% to 50%. This value reached 57.9% by increasing the east WWR to 50%. Increasing the other window areas had negative effect on the indoor temperatures while the effects of window shading, ventilation rate and insulation thickness on the indoor temperature were similar to the model houses in Adelaide.

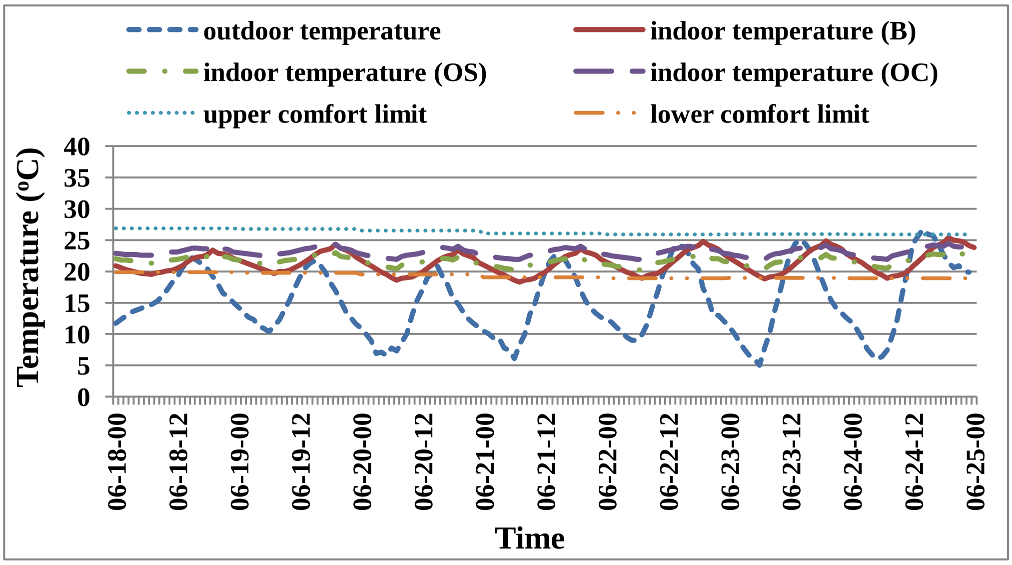
4. Further analysis

4.1 Indoor temperatures of model houses in a typical summer/winter week

For each climate, the indoor temperatures in the model houses during a typical summer week (from 10 February to 16 February) and a winter week (from 18 June to 24 June) were simulated, including the basic model house (B), the fully optimised model house built with solid rammed earth walls (OS) and the fully optimised model house built with ICRE walls (OC). The results are reported in Figures 9-11.



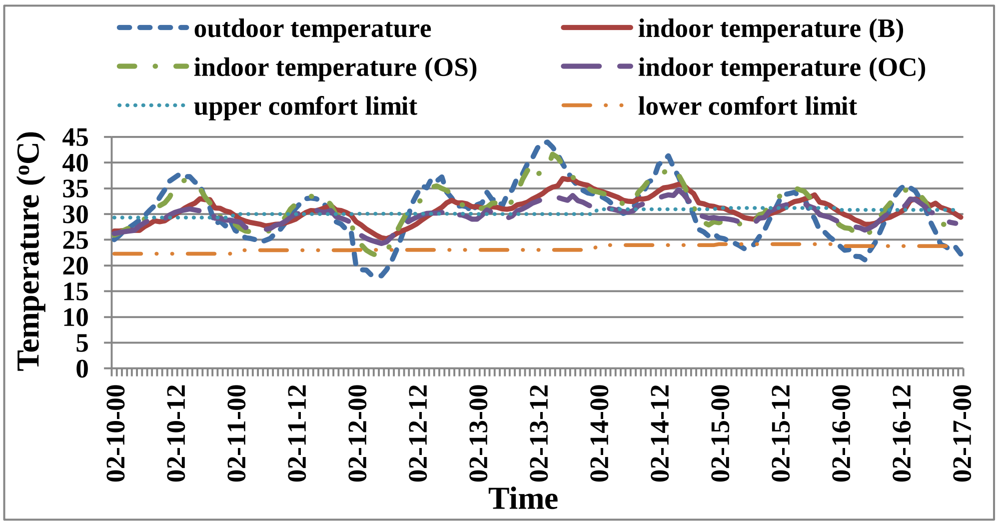
(a)



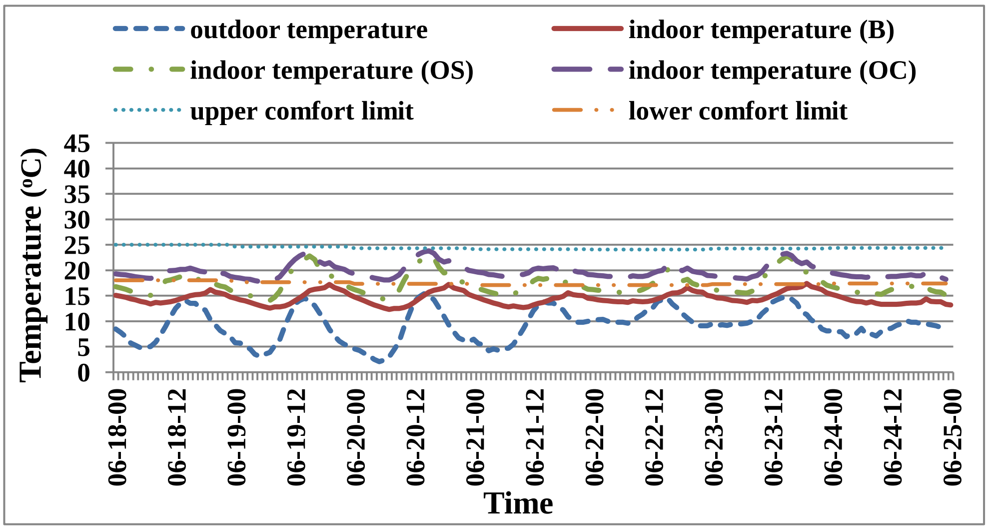
(b)

Figure 9 Indoor temperatures in a typical summer (a) and winter (b) week (Longreach)

In a hot arid climate (Longreach) as shown in Figure 9, during the typical winter week, the outdoor temperatures varied between 5.0^{o}C and 26.7^{o}C. Model house B provided an indoor operative temperatures ranging between 18.3^{o}C and 25.4^{o}C, which can be considered comfortable as they fell within the lower and upper limits. For model house OS, the indoor temperatures were kept between 20.1°C and 23.2°C, while model house OC had slightly warmer indoor temperatures, which varied from 21.9°C to 24.5°C. In the typical summer week, with outdoor temperatures ranged between 17.7°C and 39.4°C, the indoor temperatures of model houses B, OS and OC were from 28.2°C to 36.3°C, 24.6°C to 35.6°C and 24.9°C to 32.0°C, respectively, meaning that each model house overheated on hot summer days. Model house OC had the best performance.



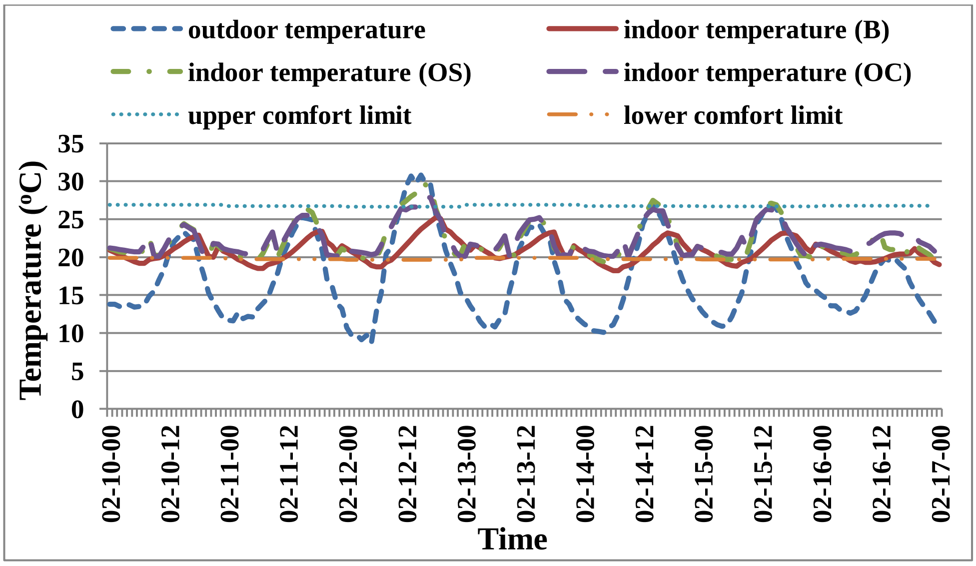
(a)



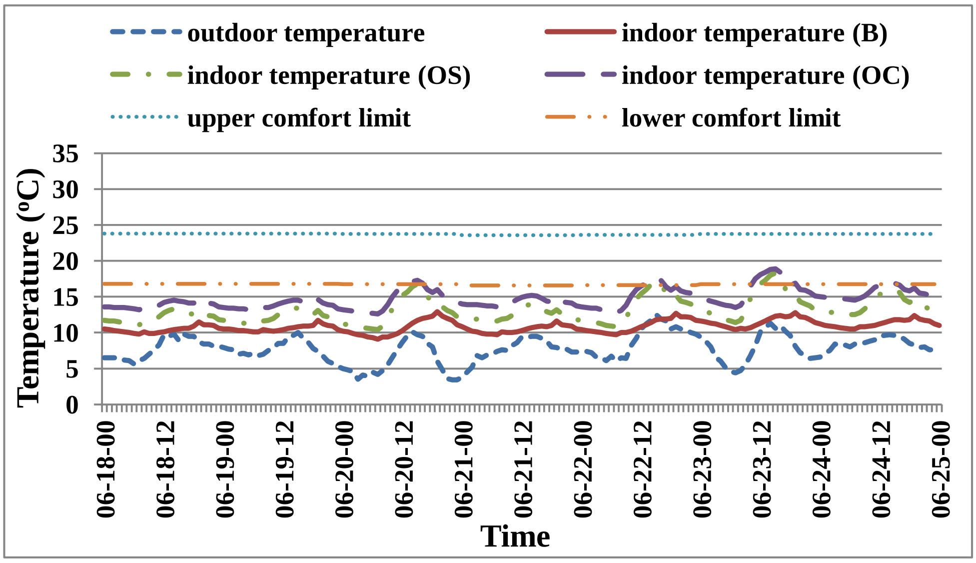
(b)

Figure 10 Indoor temperatures in a typical summer (a) and winter (b) week (Adelaide)

In a warm temperate climate (Adelaide) as shown in Figure 10, during the typical winter week, when the outdoor temperatures ranged between 2.1°C and 15.4°C, the indoor temperatures of model house B ranged from 12.3°C to17.4°C, which could be considered too cold for the home occupants as they mostly fell below the lower acceptability limits. With design parameters optimised, model house OS provided a better indoor operative temperature range of 14.1-23.0°C; however, the minimum indoor operative temperature was still too low (only 14.1°C). Model house OC provided the best indoor operative temperatures, which varied between 17.7°C and 23.8°C, which can be deemed acceptable as they fell within the acceptability limits. In the typical summer week, when the mean outdoor temperatures ranged between 18.0°C and 44.0°C, the indoor operative temperatures of model houses B, OS and OC ranged from 25.2°C to 36.9°C, 21.7°C to 41.6°C and 24.3°C to 34.7°C, respectively, meaning that the house would overheat, in particular model house OS when the mean outdoor temperature rose above 33°C. This may be due to the fact that the optimised value of each parameters was determined based on the whole year thermal performance, and a relatively larger portion of the uncomfortable indoor temperatures were experienced in cold days rather than hot days in this climate, therefore strategies that are able to reduce the amount of cold indoor temperatures are priorities, such as minimising some of the window areas, window shading and window operable rate. Doing so, however, may cause overheating in summer days.



(a)



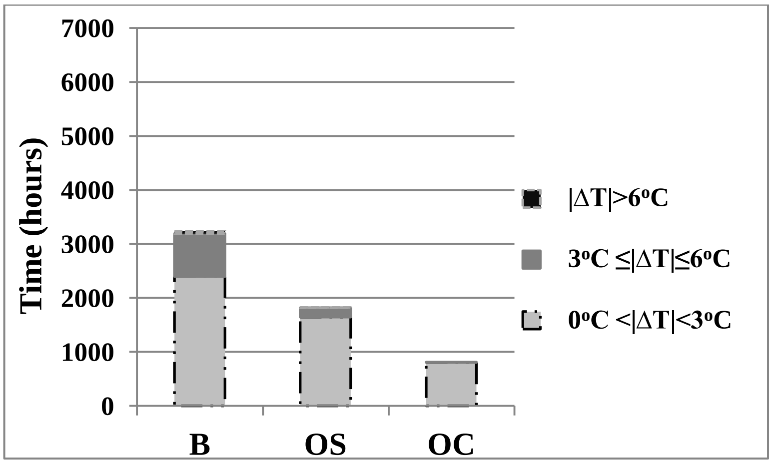
(b)

Figure 11 Indoor temperatures in a typical summer (a) and winter (b) week (Ballarat)

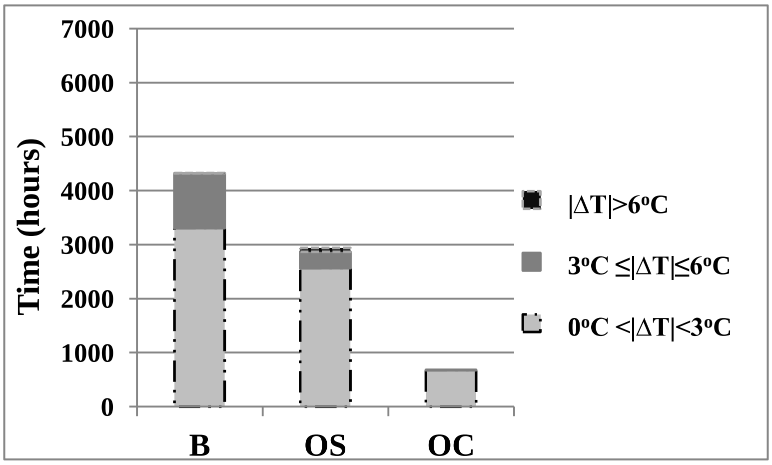
Figure 11 shows that in a cool temperate climate (Ballarat) the outdoor temperatures ranged between 3.4^{o}C and 12.5^{o}C in the typical winter week. Each model house performed unacceptably in the typical winter week, with indoor operative temperatures in model houses B, OS and OC ranging from 9.1^{o}C to12.9^{o}C, 10.4^{o}C to18.3^{o}C and 12.6^{o}C to18.9^{o}C, respectively. In the typical summer week, with outdoor temperatures ranging from 8.7^{o}C to 30.8^{o}C, the indoor temperatures of model house B ranged from 18.2^{o}C to 25.2^{o}C, which can be considered fairly comfortable as they fell within the acceptability limits. Model house OS and OC had indoor temperature ranges of 19.2-30.0^{o}C and 20.0-28.0^{o}C, respectively, which are more acceptable.

4.2 Indoor temperatures falling outside the adaptive comfort zone

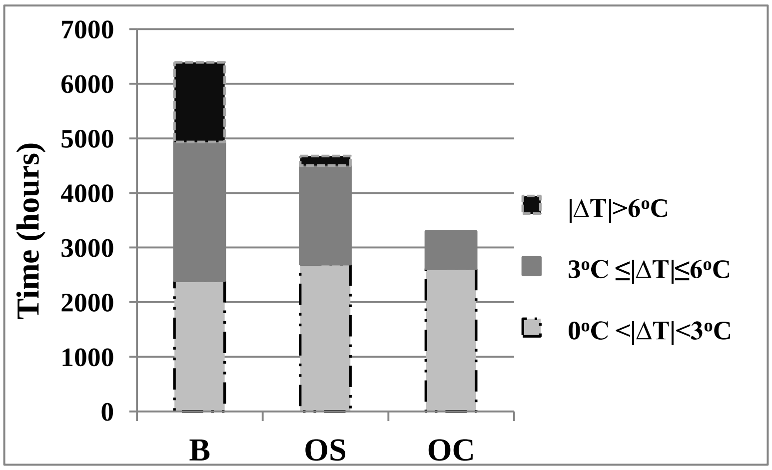
For each climate zone, the number of indoor temperatures falling outside the adaptive comfort zone was calculated and reported in Figure 12.



(Longreach)



(Adelaide)



(Ballarat)

Figure 12 Indoor temperatures that are outside the comfort zone a): Hot arid climate

For model house B in a hot arid climate (Longreach), there were 3241 hours of indoor operative temperatures that fell outside the acceptability limits and most of them (2397 hours) were over the upper comfort limit or below the lower comfort limit by less than 3°C (category $0^oC<|\Delta T|<3^oC$). Temperatures over the upper limit or below the lower limit by 3-6°C accounted for a much smaller portion (797 hours) of total uncomfortable temperatures (category $3^oC \leq|\Delta T|\leq 6^oC$). Only 47 hours of indoor temperatures were over the upper limit or below the lower limit by more than 6°C (category $|\Delta T|>6^oC$).

For model house OS, the overall amount of uncomfortable indoor temperatures was 1818 hours which was 56.1% of the number for model house B. Among all the uncomfortable indoor temperatures, 90.1% of them were over the upper comfort limit or below the lower comfort limit by less than 3°C, and almost all the rest of the uncomfortable indoor temperatures were over the upper comfort limit or below the lower comfort limit by 3-6°C. For model house OC, which experienced the least amount of uncomfortable indoor temperatures (only 813 hours), 99% of the uncomfortable temperatures were over the upper comfort limit or below the lower comfort limit by less than 3°C.

b): Warm temperate climate

In a warm temperate climate (Adelaide), the model houses performed similarly to those in Longreach, except that model house OS experienced some more extreme indoor temperatures than the other two model houses.

c): Cool temperate climate

The three model houses located in a cool temperate climate (Ballarat) had similar amounts of uncomfortable indoor temperatures which were over the upper comfort limit or below the lower comfort limit by less than 3°C. Model house B experienced indoor temperatures outside the range of comfort by 3-6°C for 2540 hours, while model houses OS and OC recorded 1805 and 675 hours of uncomfortable hours in this category, respectively. The number of uncomfortable indoor temperatures in category $|\Delta T|>6^oC$ for model house B was 1453 hours. All of these extreme indoor temperatures were below the lower comfort limit, meaning that it was too cold living in model house B in this climate. Model house OS had only 173 hours of indoor temperatures in this category and no extreme indoor temperatures were found in this category for model house OC.

To sum up, for each climate, the optimised model house with cavity insulated rammed earth walls had better performance than the other two model houses. In Longreach and Adelaide, only 813 and 683 hours of indoor temperatures fell outside the adaptive comfort zone and most of them were over the upper comfort limit or below the lower comfort limit by less than 3°C, meaning that it is possible for occupants to obtain thermal comfort by adjusting their clothing or using fans, while air-conditioning may not be necessarily applied at all. In Ballarat, however, there were a considerable amount (3293 hours) of indoor temperatures fell outside the adaptive comfort zone for model house OC and 675 hours of them were over the upper comfort limit or below the lower comfort limit by 3-6°C, meaning that in a cold climate, even with insulation applied and the other parameters optimised, heating may need to be applied for better thermal comfort even in rammed earth houses.

4.3 Considering different time period

Table 5 reports the percentage of indoor temperatures that fell inside the adaptive comfort zone for different time periods. The time period “9am-5pm” represents work time when occupants are normally outside the house, while time period “5pm-9am” indicates a time period when occupants are usually at home.

Table 5 Percentage of indoor temperatures inside adaptive comfort zone in different periods

Time period		Percentage of indoor temperatures inside adaptive comfort zone		
		Model house B	Model house OS	Model house OC
Longreach	9am-5pm	61.2%	48.4%	93.0%
	5pm-9am	63.9%	70.2%	90.8%
	In total	63.0%	62.9%	91.5%
Adelaide	9am-5pm	51.4%	77.5%	89.3%
	5pm-9am	50.3%	71.4%	93.7%
	In total	50.7%	73.5%	92.2%
Ballarat	9am-5pm	27.3%	59.4%	71.4%
	5pm-9am	27.0%	42.7%	57.9%
	In total	27.1%	48.3%	62.4%

The data presented in Figure 5 show that in Longreach, the time of day had no significant effect on the percentage of indoor temperatures inside the comfort zone for model houses B and OC. For model house OS, only 48.4% of the indoor temperatures were comfortable between 9am and 4pm, while 70.2% of indoor temperatures were comfortable between 5pm to 8am, which suits occupants who are not at home during the daytime. In Adelaide, the number of hours falling inside the comfort zone varied little with the time of day for each model house. In Ballarat, the time of day had no significant effect on the percentage of indoor temperatures that fell inside the comfort zone in model house B. For model houses OS and OC, much more comfortable hours were found from 9am to 4pm than from 5pm to 8am, which suits occupants who work outside the house at night.

5. Conclusions

This study finds that thermal comfort in naturally ventilated rammed earth houses can be improved by appropriate control of a set of design parameters relating to external walls, in particular by adding insulation. In order to achieve high level of occupant satisfaction on thermal comfort, these parameters should be wisely optimised by taking into account the influence of local climates. The main recommendations are summarised as follows for designs of naturally ventilated rammed earth houses:

In a hot arid climate such as in Longreach, over 77% of the time acceptable indoor operative temperatures can be achieved in a house built with typical 300mm thick solid rammed earth walls, as long as several key design parameters including window size, window shading and window openable rate are optimised. In this climate, overheating is the main problem, thus controls that can reduce the indoor temperatures are preferred, such as using small windows (in particular the north facing window) and large window shadings, by which the solar heat that enters the house through windows can be minimised. If large windows are preferred, they are better to be installed in the east or south wall, as they have less effect on the thermal comfort. In addition, the amount of operable window area should be as much as possible to allow natural ventilation. Increasing the wall thickness is also an effective solution to improve thermal comfort; however, it should be noted that increasing wall thickness will reduce the useable living area. If more thermal satisfaction is desired, installing 30mm of polystyrene insulation to external walls will result in comfortable indoor temperatures for 89% of the time, and almost all of the unacceptable indoor operative temperatures are over the upper comfort limit or below the lower comfort limit within 3^{o}C.

In a warm temperate climate such as in Adelaide, a house built with typical 300mm thick rammed earth walls can achieve acceptable indoor operative temperatures for 68% of the time. Most of the uncomfortable temperatures are below the lower comfort limit, meaning that the house may be considered too cold in winter. To achieve better performance, the north facing window should account for as much as 50% of the wall area to allow solar heat entering the house. Window sizes in other walls are recommended to be smaller as the heat loss through these windows may outweigh the heat gains through them. Window shadings are not necessary or should be kept as small as possible. Natural ventilation for passive cooling is less important than it is in hot climates, hence a large proportion of the window can be designed as inoperable to save the cost. As the case in the hot arid climate, the amount of comfort indoor temperatures can increase to 90% of the time when the rammed earth walls are insulated by 30mm thick polystyrene insulation and nearly all uncomfortable indoor temperatures are over/below the comfort limits by less than 3^{o}C.

In a cool temperate climate such as in Ballarat, in order to maximise passive solar heat sources, the window size in each wall of a rammed earth house should be maximised and the window shading be minimised. Operable window area can be minimised as long as it can comply with the NCC requirement for fresh air, which is 5% of the floor area. In a house with 300mm thick walls, even if the other key parameters are optimised, the acceptable indoor operative temperatures can only be achieved for 45% of the time. This means occupants will experience uncomfortable indoor environment for over half of the time year around. The number of comfortable temperatures can be improved by 13% if 30mm insulation is installed to the external rammed earth walls. Even if thicker insulation is added, for example 100mm, the acceptable indoor operative temperatures would only increase to 62% of the time, meaning that there are 3293 hours of unacceptable indoor operative temperatures year around and for 675 hours the temperatures are beyond the comfort limit by over 3^{o}C. In this climate using a heater may still be necessary for occupants of rammed earth houses to obtain thermal comfort.

In summary, this study proves that rammed earth has a great potential to be used for construction of naturally ventilated houses in hot arid and warm temperate climates. Adequate thermal comfort (approximately 90%) can be guaranteed as long as the house is designed following the recommendations presented in this study. Most of the uncomfortable temperatures are found to be within 3^{o}C beyond the comfortable limits, meaning that air-conditioning may not be necessary to be installed and occupants can achieve thermal comfort by simply adjusting their clothing or using ceiling fans. In cool temperate climates, naturally ventilated rammed earth houses are unable to provide satisfactory thermal comfort without space heating; however, the design recommendations reported in the study are still valuable to reduce the heating energy load.

References

[1] Reddy BV, Kumar PP. Embodied energy in cement stabilised rammed earth walls. Energy and Buildings. 2010;42:380-5.

[2] Treloar GJ, Owen C, Fay R. Environmental assessment of rammed earth construction systems. Structural survey. 2001;19:99-106.

[3] Morel J, Mesbah A, Oggero M, Walker P. Building houses with local materials: means to drastically reduce the environmental impact of construction. Building and Environment. 2001;36:1119-26.

[4] Venkatarama Reddy B, Leuzinger G, Sreeram V. Low embodied energy cement stabilised rammed earth building—A case study. Energy and Buildings. 2014;68:541-6.

[5] Zabalza Bribián I, Valero Capilla A, Aranda Usón A. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and Environment. 2011;46:1133-40.

[6] Blengini GA. Life cycleofbuildings,demolitionandrecyclingpotential: A casestudyinTurin,Italy. Building and Environment. 2009;44:319-30.

[7] Soebarto V. Analysis of indoor performance of houses using rammed earth walls. The Eleventh International IBPSA Conference. Glasgow, Scotland. 2009:1530-7.

[8] Hall M, Djerbib Y. Rammed earth sample production: context, recommendations and consistency. Construction and Building Materials. 2004;18:281-6.

[9] Taylor P, Luther M. Evaluating rammed earth walls: a case study. Solar Energy. 2004;76:79-84.

[10] Baggs SA, Baggs JC, Baggs DW. Australian earth-covered building. New ed. ed. Kensington, N.S.W. Australia: New South Wales University Press; 1991.

[11] Jaber S, Ajib S. Optimum, technical and energy efficiency design of residential building in Mediterranean region. Energy and Buildings. 2011;43:1829-34.

[12] Givoni B. Characteristics, design implications, and applicability of passive solar heating systems for buildings. Solar Energy. 1991;47:425-35.

[13] Paul WL, Taylor PA. A comparison of occupant comfort and satisfaction between a green building and a conventional building. Building and Environment. 2008;43:1858-70.

[14] Taylor P, Fuller R, Luther M. Energy use and thermal comfort in a rammed earth office building. Energy and Buildings. 2008;40:793-800.

[15] Liu J, Hu R, Wang R, Yang L. Regeneration of vernacular architecture: new rammed earth houses on the upper reaches of the Yangtze River. Frontiers of Energy and Power Engineering in China. 2010;4:93-9.

[16] Baggs D, Mortensen N. Thermal Mass in Building Design. BDP Environmental Design Guide. 2006.

[17] ASHRAE. ANSI/ASHRAE Standard 55-2013. Thermal environmental conditions for human occupancy. Antlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc; 2013.

[18] Fanger PO. How to apply models predicting thermal sensation and discomfort in practice. In: Oseland NA, Humphreys MA, editors: Thermal comfort: past, present and future. BRE Report; 1994.

[19] de Dear R, Brager GS. Developing an adaptive model of thermal comfort and preference. ASHRAE Transaction. 1998;104:145-67.

[20] de Dear RJ, Brager GS. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and Buildings. 2002;34:549-61.

[21] Standard ASHRAE. Standard 55-2004. Thermal environmental conditions for human occupancy. 2004.

[22] McCartney KJ, Nicol JF. Developing an adaptive control algorithm for Europe. Energy and Buildings. 2002;34:623-35.

[23] Indraganti M. Behavioural adaptation and the use of environmental controls in summer for thermal comfort in apartments in India. Energy and buildings. 2010;42:1019-25.

[24] Indraganti M, Ooka R, Rijal HB, Brager GS. Adaptive model of thermal comfort for offices in hot and humid climates of India. Building and Environment. 2014;74:39-53.

[25] Indraganti M, Rao KD. Effect of age, gender, economic group and tenure on thermal comfort: a field study in residential buildings in hot and dry climate with seasonal variations. Energy and buildings. 2010;42:273-81.

[26] Cândido C, De Dear R, Lamberts R, Bittencourt L. Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone. Building and Environment. 2010;45:222-9.

[27] Goto T, Mitamura T, Yoshino H, Tamura A, Inomata E. Long-term field survey on thermal adaptation in office buildings in Japan. Building and Environment. 2007;42:3944-54.

[28] Zhong K, Fu H, Kang Y, Peng X. Indoor thermal conditions and the potential of energy conservation of naturally ventilated rooms in summer, China. Energy and Buildings. 2012;55:183-8.

[29] Saman W, Boland J, Pullen S, de Dear RJ, Soebarto V, Miller WF, et al. A framework for adaptation of Australian households to heat waves. 2013.

[30] Soebarto V, Bennetts H. Thermal comfort and occupant responses during summer in a low to middle income housing development in South Australia. Building and Environment. 2014;75:19-29.

[31] de Dear R. Adaptive thermal comfort in building management and performance. Proceedings of the Healthy Buildings. 2006;1:31-5.

[32] de Dear R. Recent enhancements to the adaptive comfort standard in ASHRAE 55-2010. Proceedings of the 45th annual conference of the Architectural Science Association. Sydney, Australia. 2011.

[33] CSIRO. AccuRate Manual: Australian Commonwealth Scientific and Industrial Research Organisation; 2004.

[34] Walsh P, Delsante A. Calculation of the thermal behaviour of multi-zone buildings. Energy and Buildings. 1983;5:231-42.

[35] Delsante A. An Empirical Validation of CHENATH, The National Home Energy Rating Scheme Simulation Engine (DBCE Doc. 95/78 (M)). Melbourne: CSIRO, Division of Building Construction and Engineering; 1995.

[36] Delsante A. A Validation of the AccuRate Simulation Engine Using BESTEST. Report to the Australian Greenhouse Office CSIRO Manufacturing & Infrastructure Technology report, CMIT (C)-2004-152. 2004.

[37] Daniel L, Soebarto V, Williamson T. Evaluating the suitability of the AccuRate engine for simulation of massive construction elements. 46th Annual Conference of the Architectural Science Association (ANZAScA). Queensland, Australia. 2012.

[38] Delsante A. A comparison of 'accurate' predictions with measured data from a mud brick house. Proceedings of IBPSA Australasia Conference. Adelaide, Australia. 2006:96-103.

[39] Wang L, Wong NH. Coupled simulations for naturally ventilated rooms between building simulation (BS) and computational fluid dynamics (CFD) for better prediction of indoor thermal environment. Building and Environment. 2009;44:95-112.

[40] Walker P, Standards Australia. The Australian Earth Building Handbook. Sydney, Australia: Standards Australia; 2002.

[41] Stabilised Earth. Rammed Earth ready to go; http://www.stabilisedearth.com.au/product_service.html. Accessed on August 30, 2013.

[42] Australian Building Codes Board. National Construction Code Canberra: Standards Australia; 2013.

[43] Dong X, Soebarto V, Griffith M. Strategies for reducing heating and cooling loads of uninsulated rammed earth wall houses. Energy and Buildings. 2014;77:323-31.

[44] McBoyle G. Climatic classification of Australia by computer. Australian Geographical Studies. 1971;9:1-14.

[45] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World map of the Koppen-Geiger climate classification updated. Meteorologische Zeitschrift. 2006;15:259-64.

[46] Hall M, Swaney B. Stabilised rammed earth(SRE) wall construction-now available in the UK. Building Engineer. 2005;80:12-5.

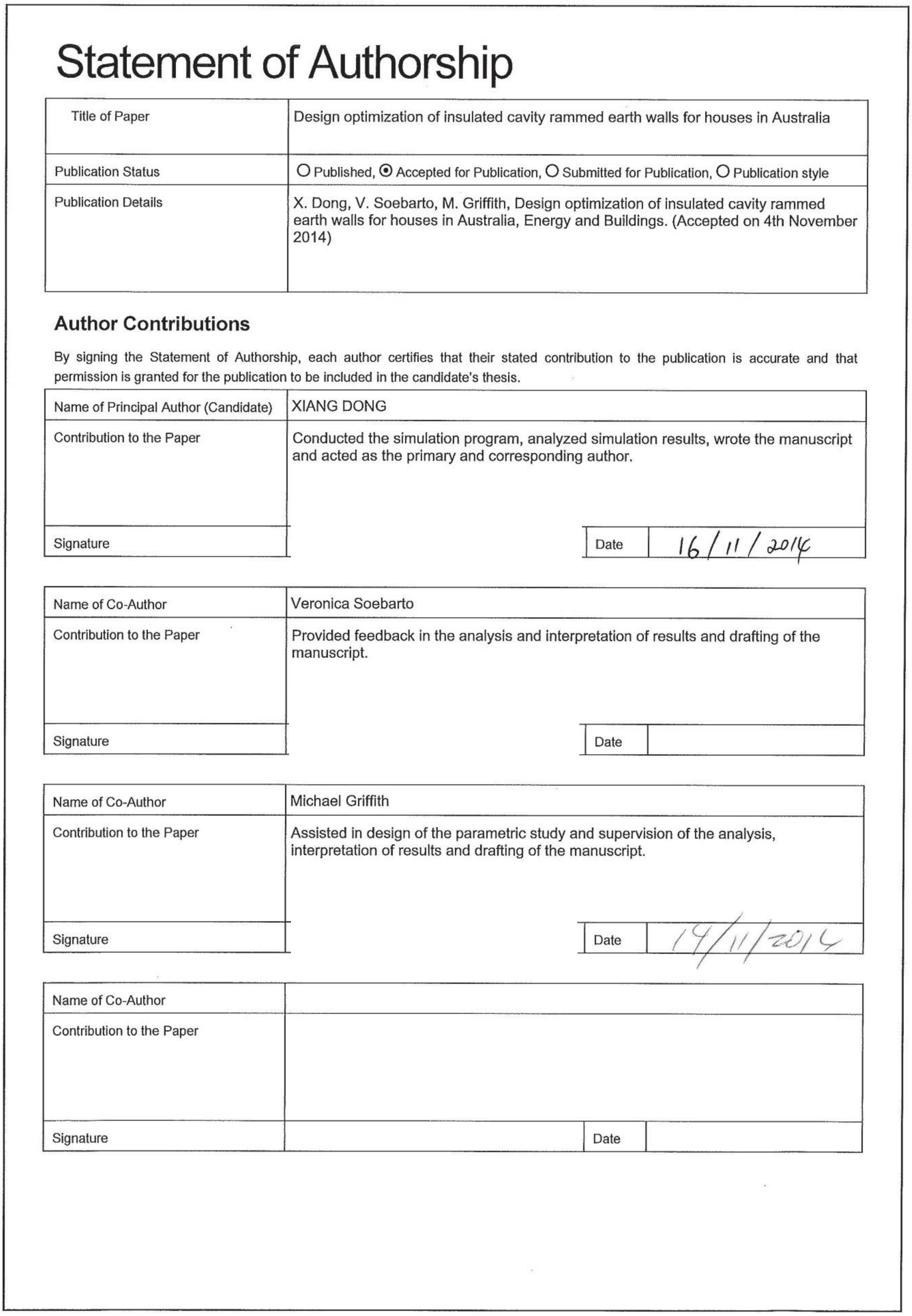
Chapter 7 Prediction of Thermal performance of Air-Conditioned Rammed Earth Wall Houses

Introduction

According to the study in Chapter 6, adding insulation to RE walls can significantly improve the thermal comfort, meaning that the energy loads (running cost) for space heating and cooling in RE wall houses can be reduced. In general, the more insulation is added, the more running cost can be saved. Adding insulation, however, will considerably increase the initial construction cost and the more insulation is added, the more initial cost will be increased. This chapter conducted a study on optimization of energy loads and total life-cycle cost of ICRE wall houses by optimizing insulation thickness and some other key design parameters including window size, window shading and RE wall thickness. The optimization study was conducted in three different Australian climates namely hot arid climate, warm temperate climate and cool temperate climate.

List of Manuscript

X. Dong, V. Soebarto, M. Griffith, Design optimization of insulated cavity rammed earth walls for houses in Australia, Energy and Buildings, 86 (2015) 852-863.



Statement of Authorship

Title of Paper	Design optimization of insulated cavity rammed earth walls for houses in Australia
Publication Status	○ Published, ● Accepted for Publication, ○ Submitted for Publication, ○ Publication style
Publication Details	X. Dong, V. Soebarto, M. Griffith, Design optimization of insulated cavity rammed earth walls for houses in Australia, Energy and Buildings. (Accepted on 4th November 2014)

Author Contributions

By signing the Statement of Authorship, each author certifies that their stated contribution to the publication is accurate and that permission is granted for the publication to be included in the candidate's thesis.

Name of Principal Author (Candidate)	XIANG DONG		
Contribution to the Paper	Conducted the simulation program, analyzed simulation results, wrote the manuscript and acted as the primary and corresponding author.		
Signature		Date	16/11/2014

Name of Co-Author	Veronica Soebarto		
Contribution to the Paper	Provided feedback in the analysis and interpretation of results and drafting of the manuscript.		
Signature		Date	

Name of Co-Author	Michael Griffith		
Contribution to the Paper	Assisted in design of the parametric study and supervision of the analysis, interpretation of results and drafting of the manuscript.		
Signature		Date	19/11/2014

Name of Co-Author			
Contribution to the Paper			
Signature		Date	

Design optimization of insulated cavity rammed earth walls for houses in Australia

Xiang Dong , Veronica Soebarto , Michael Griffith

Abstract This paper presents an optimization study of the design parameters for houses using rammed earth walls, including window sizes, window shading, the amount of thermal mass and the amount of insulation in the external walls. The optimization is based on two objectives: (1) energy use reduction and (2) life-cycle cost minimization. It was found that, in general, the thicker the walls/insulation was applied, the less the energy load, but the higher the life-cycle cost. In hot arid climates, small windows and large window shadings lead to a lower energy load while the minimum life-cycle cost was achieved with the smallest window and window shading. In warm temperate climates, the optimum size of north facing window was 30% and 40% of the wall area to achieve the minimum energy load and life-cycle cost while the sizes of the windows on the other walls as well as the window shading needed to be as small as possible. In cool temperate climates, small south facing windows and large windows in the other walls would result in the lowest energy load; however, to achieve the minimum life-cycle cost, all the windows and window shadings should be as small as possible.

Keywords: rammed earth, parameter optimization, energy load, life-cycle cost, Australia climates

1. Introduction

Buildings in Australia, including residential premises, are important contributors to greenhouse gas emissions and climate change (Centre for International Economics, 2007; Morrissey and Horne, 2011) where the residential sector (in 2006-07) consumes 8% of the total energy use (Australian Bureau of Statistics, 2009a) and more than 40% of this consumption is used for space heating and cooling (Australian Bureau of Statistics, 2009b). Therefore, the development of residences containing low embodied energy and which require little energy for space heating and cooling is of prime interest to architects and builders.

Rammed earth (RE) wall houses are perceived to be sustainable as they carry extremely low embodied energy, in particular when locally available material is used (Morel, et al., 2001; Reddy and Kumar, 2010b; Treloar, et al., 2001). In addition, with their large thermal mass, RE wall houses are assumed to perform in a thermally desirable manner because the mass can effectively delay the heat transmission through the external walls, particularly in summer when peak indoor temperatures are delayed by a long thermal time lag. In a relatively mild climate without extended periods of heat or cold, energy conservation can be achieved and temperature smoothed out (Li, et al., 2012; Soebarto, 2009; Taylor, et al., 2008). Moreover, a study conducted by Allinson and Hall (Allinson and Hall, 2010) indicated that RE walls can potentially save the energy for indoor humidification.

Such perceptions of RE walls mean that their construction has attracted increasing interest recently as architects develop greater interest in sustainability principles. Considered more realistically, the smoothing of the temperature in mild climates is offset by the fact that when summer and winter are more extreme (hot and cold for long periods), the low thermal resistance (R-Value) of RE could result in poor thermal performance. Once the interior space is warm during several hot days, it is difficult to cool unless night-time ventilation is applied. In cold days the earthen material does not effectively prevent heat draining from the inside to the outside of the house, which means that a large amount of energy may be required for space heating. Because of this behaviour, it is currently difficult for house designs using only RE walls to satisfy the Deemed-to-Satisfy provisions of the Building Code of Australia within the Australian National Construction Code (NCC) (Australian Building Codes Board, 2013), which require a minimum R-value for external walls of 2.8m^{2}K/W for Class 1 buildings (detached residential) for all climatic zones in Australia except the Alpine zone, where the minimum requirement is 3.8m^{2}K/W. According to previous studies (Hall and Allinson, 2009; Taylor and Luther, 2004; Walker and Standards Australia, 2002; Yan, et al., 2005), a typical 300mm thick RE wall has an R-Value of only 0.27-0.70m^{2}K/W. The NCC has an alternative requirement for external walls with a surface density greater than 220kg/m^2, which states that an equivalent wall insulation with an R-Value of 0.5 to 1.0m^{2}K/W (depending on other design parameters) shall be added. A typical 300mm thick RE wall has a surface density much greater than 220kg/m^2 (usually between 540 and 660kg/m^2 (Taylor and Luther, 2004)). Thus insulation with an R-Value of 0.5 to 1.0m^{2}K/W is required for solid RE walls in all climate zones except for the Alpine zone.

2. Insulated cavity RE walls

For RE, rigid insulation (extruded polystyrene or polyisocyanurate) can be inserted in the middle of the wall to preserve the aesthetics of the wall surfaces (Hall and Swaney, 2005). Extruded polystyrene (XPS) with a thickness of 1m has an R-Value of 28.6-40.0m^{2}K/W (Papadopoulos, 2005). If the average value of 34.3m^{2}K/W is applied, a solid RE wall would need to be insulated by XPS with a thickness of 15 to 30mm, in order to satisfy the minimum R-value requirement of the NCC.

Although adding 15mm to 30mm thick XPS insulation enables RE wall houses to meet the minimum R-Value requirement of the BCA, it does not guarantee satisfactory thermal performance without taking into account the other design parameters including window size, window shading, insulation thickness and the amount of thermal mass (Baggs and Mortensen, 2006). The effects of insulation as well as these other design parameters on thermal performance are discussed in the following sections of this paper.

3. Star rating requirement and methods for reducing energy load

There is another option for Class 1 buildings (residential) to satisfying the requirement of BCA (Australian Building Codes Board, 2011): the Energy Efficiency requirement, also known as the star rating method. There are 10 star ratings (1 to 10) in the Nationwide House Energy Rating Scheme (NatHERS), where more stars correspond to less energy loads. Note, in the BCA, the star rating is based on predicted space heating and cooling loads only, hence the star rating bands vary according to climatic regions. Other energy demands such as domestic hot water (DHW) are not included. According to the NatHERS, Australia is divided into 69 climate regions of similar climate; each is represented by a city with typical local climate condition. For example, in Adelaide (climate region 16: warm temperate climate), the 6-star rating corresponds to a maximum energy load of 96MJ/m^2 per annum, while in Ballarat (climate region 66: cool temperate climate) the 6-star rating corresponds to an energy load of 197MJ/m^2 per annum. By comparing the predicted energy loads for heating and cooling in order to maintain indoor thermal comfort to the reference value for each star rating load, a building design can be assigned a star rating. Starting from 2010, new residential buildings have been required to meet a 6-star rating as a minimum. In other words, the total predicted energy load for heating and cooling of the building must be equal to or less than the maximum allowed for each climate region for a 6-star rating.

Passive design strategies such as direct solar gain for passive heating and natural ventilation for passive cooling are effective to reduce the heating and cooling loads, respectively (Givoni, 1991; Jaber and Ajib, 2011). The direct gain strategy requires a large amount of thermal mass to absorb and store solar heat that comes through the windows during the day and to release this stored energy slowly during the night (Givoni, 1991). Natural ventilation (for example opening windows when the outdoor temperatures are lower than indoors) helps to cool a house and reduces the cooling load (Jaber and Ajib, 2011). In order to effectively implement these passive strategies, the windows must be sized accordingly as a large amount of heat flow between the inside and outside of a building as well as the natural ventilation in a building is transferred through windows. Window shading should also be taken into account as it controls the amount of solar gain through the windows. In summary, many researchers have confirmed that substantial energy saving on space heating and cooling can be obtained through optimised window design (Özkan and Onan, 2011; Persson, et al., 2006) and proper use of thermal mass and insulation (Aktacir, et al., 2010; Dombaycı, et al., 2006; Kalogirou, et al., 2002).

4. Investigations

The study aims to investigate the relationships between each parameter and the energy loads as well as total life-cycle cost, thus providing information for designers and house owners to make strategic design decisions. For example, small window areas in some climates can result in low energy loads; however, the occupants may prefer large windows for better natural light or frame view. With the information provided by this study, occupants can make more informed decisions by balancing the advantages and costs of increasing window size. It should be noted that the recommendations provided from this study are for residential buildings. For other building types (such as office buildings), the basic model as well as the assumptions of the simulation should be modified accordingly. In order to achieve this aim, the following objectives need to be fulfilled:

a) Quantify the effects of four design parameters on the heating and cooling loads of hypothetical RE houses. They are: (1) the size of each window in relation to the walls (window to wall area ratio, WWR); (2) the window shading (expressed as the projection factor, which is the ratio between the width of window shading and the distance between the bottom of the window shading and the window sill, as shown in Figure 1); (3) the amount of thermal mass (RE wall thickness); and (4) the amount of external wall insulation (insulation thickness); and

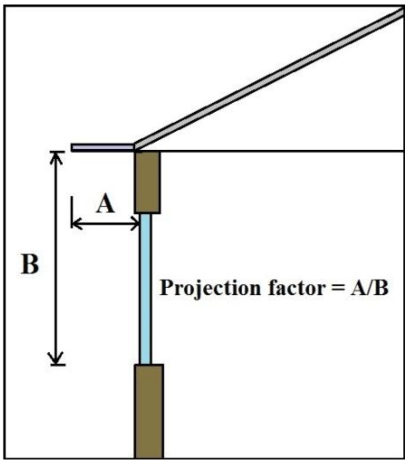


Figure 1 Calculation of projection factor

b) Evaluate the effect of each parameter on the total life-cycle costs which comprise the initial cost for construction (including air conditioner/heater) and the running cost (for space heating and cooling).

The options for each parameter were:

- *Window to wall ratio:* Five options of the WWR were evaluated – 10%, 20%, 30%, 40% and 50%. The minimum value 10% was selected considering that the house needs some natural light and ventilation. The maximum value 50% is restricted by the wall length as the window area was determined by the window width which is limited by wall length. The window sill and height were kept constant.

- *Projection factor:* the window shading was assumed to be 0.2m above the top of window. Five options for window shading (projection factor) were considered, from no window shading (projection factor 0, corresponding to an eave width of 0.00m) to large window shading (projection factor 0.60, corresponding to an eave width of 1.00m), incrementing by 0.15 (corresponding to an increment of eave width of 0.25m). Larger window shadings were not considered as it would prevent the house from obtaining sufficient daylight.

- *RE wall leaf thickness:* Four thicknesses were considered for each RE wall. The thicknesses ranged from 150mm to 225mm, incrementing by 25mm, as according to local builders it is difficult to construct wall leaves thinner than 150mm nor wall leaves thicker than 225mm are not usually applied for insulated cavity RE houses due to the fact that overly thick RE walls are not economical and will sacrifice the usable floor area. When investigating the effect of internal or external wall thickness, the other wall leaf thickness (150mm) and the insulation thickness (30mm) were kept constant as shown in Figure 2.

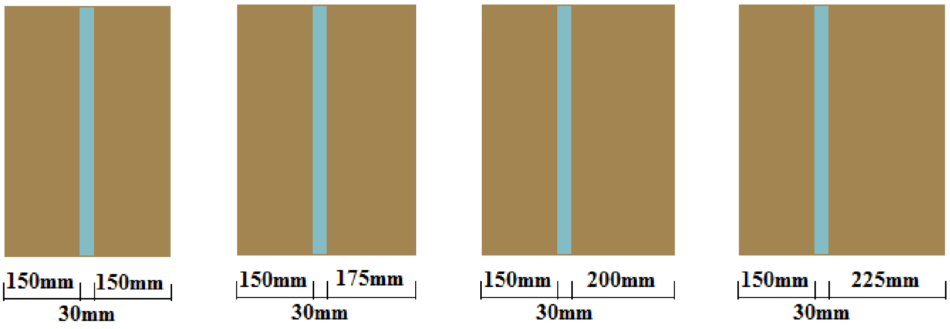


Figure 2 Increasing of wall leaf thickness

- *Insulation thickness:* Eight options of insulation thickness were considered, ranging from 30mm to 100mm, incrementing by 10mm. A 30mm polystyrene insulation gives an R-Value of approximately 1.0m^{2}K/W which is the minimum requirement for added insulation of external walls with surface density over 220kg/m^2 and insulation thicker than 100mm are not practical according to local builders. When investigating the effect of insulation thickness, the internal and external RE wall leaf thicknesses (150mm) were kept constant as shown in Figure 3.

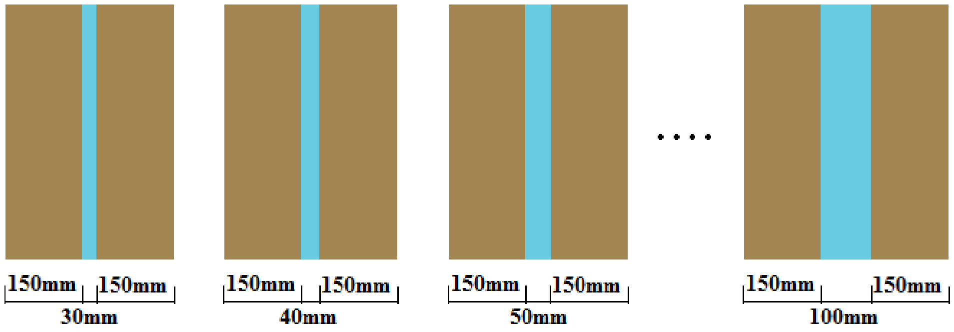


Figure 3 Increasing of insulation thickness

5. Methods

The heating and cooling load was simulated using the energy rating software *AccuRate* (CSIRO, 2004). *Accurate* calculates the annual heating and cooling energy loads required to maintain thermal comfort in a model building, taking into account the building parameters, location and assumed usage of the building. The software was developed by CSIRO and is accredited for use in NatHERS. The accuracy of this software has been validated both empirically and through intermodal comparisons (Daniel, et al., 2012b; Delsante, 2006; Delsante, 1995; Delsante, 2004). The mathematical basis of this energy rating tool can be found in the work of researchers such as Walsh and Delsante (Walsh and Delsante, 1983), and the detailed assumptions embedded in this software about weather data, internal gains, infiltration, use of heating and cooling and the window opening schedule are explained by the authors in a previous article (Dong, et al., 2014).

Life-cycle costing in the current study was a combination of the initial cost of construction (including the cost for air conditioner) and the running costs (for space heating and cooling). The detailed calculations are presented in Section 5.3.

5.1 “Base case” model house

This study uses a one-zone building as it is common to analyze and simulate thermal performance of houses using simplified models (Daniel, et al., 2012b; Delsante, 2004). Table 1 lists the characteristics for the base case house of an insulated cavity RE wall house. The results for this base case house will be the reference point for comparing the effect of changes to design parameters. A diagram of the base case house is shown in Figure 4 where it can be seen that the base case house was a north facing single zone house with no window shading. WWR of 10% for each direction was applied. It should be noted that according to NCC, the minimum required glazed area for habitable rooms is 10% of the floor area. For the base case house in this study, the overall glazed/window area was 10.8m^2, which was more than 10% of the floor area of 96m^2. The pitched roofs had an angle of 30^o. Extruded polystyrene was selected as insulating material of the walls. The other design parameters of the basic model are simplified (e.g. highly insulated ceilings and standard concrete floor) so that effects of these components are minimized.

Similarly, no partition walls (commonly constructed by lightweight materials) were applied in the base case house as their impact on the optimization analysis of external walls is minimal as they only affect the heat transfer between two adjacent zones and not the heat exchange between the inside and outside of a house. Moreover, in practice, internal or partition walls may be placed anywhere depending on different designs while the zone types vary according to the designer and house owners (e.g. the living room may not necessarily be planned on the north side).

A test simulation has been conducted to investigate the effect of internal walls on the energy loads of a model house. The result showed that internal walls had little impact. For example, in Adelaide, the single zone basic model house has an energy load of 275.0MJ/m^2 per annum, while a 3-zone model house with the same floor area (internal wall type: brickwork) has a similar energy load of 280.1MJ/m^2 per annum, as long as all the other factors were the same.

With *AccuRate*, a factor that would affect the energy loads of multi-zone houses was the heating thermostat setting, which varies according to the zone type (the cooling thermostat was independent on zone type). In other words, it was actually the zone type instead of the application of partition walls that affects the energy loads of houses. In this study the zone type was assumed to be Living/kitchen (which is required for one-zone model analysis by *AccuRate* program as internal heat gains from occupants and equipment can be considered in this zone type) and the heating thermostat setting for this zone type is 20^{o}C.

The test simulations however found that the optimum values of the design parameters were independent of the thermostat settings. It can therefore be concluded that the simple model house can be used to conduct the parametric study in this research.

Table 1 Characteristics of the base case house

Parameters	**Descriptions**
Floor area	96m^2 $(12m \times 8m)$
External wall height	2.7m
External wall thickness	330mm (150mm RE+30mm insulation+150mm RE)
Cement stabilised rammed earth[*]	Thermal resistance (1m thick): 0.8m^2 K/W, heat capacity: 1940kJ/m^3 K
Extruded polystyrene[*]	Thermal resistance (1m thick): 35.7m^2 K/W, heat capacity: 10.9kJ/m^3 K
Concrete floor	100mm thick, R-Value=0.07m^2 K/W
Ceiling	R 3.0 glass fibre batt + 10mm thick plasterboard
Pitched roof	R 1.0 glass fibre batt insulation + 1mm steel sheet
Window to wall ratio	10% for each direction
Window type	Single-glazed clear glass window with timber frame (50% openable, Overall Heat Transfer Coefficient=5.75W/m^2 K, Solar Heat Gain Coefficient =0.69)
Window location	1.0m above floor, with a fixed window height of 1.5m
Window shading	Simple wooden frames + 1mm thick steel sheets

[*] The thermal properties of the material are selected as the default value from the software *AccuRate.*

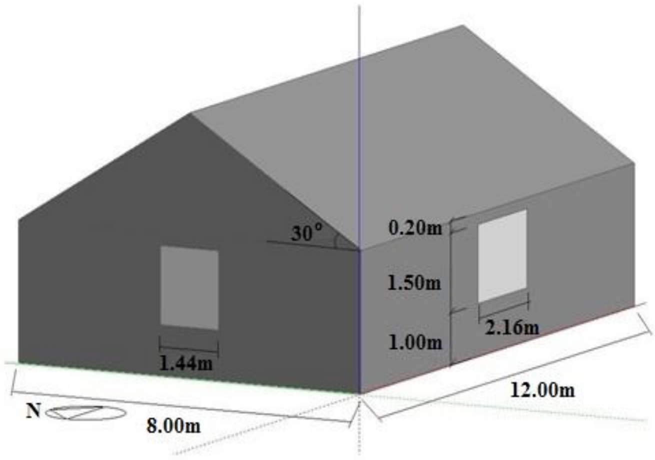


Figure 4 Basic model house

5.2 Australian climate zones

For the analysis, three locations were considered – Longreach, Adelaide and Ballarat– covering Australia climate zones 3, 5 and 7 (as shown in Figure 5), corresponding to semi-arid climate (Bsh), hot Mediterranean climate (Csb) and moderate oceanic climate (Cfb) in the Koppen climate classification system, respectively. Detailed information about these climate zones is available from the NCC (Australian Building Codes Board, 2013) which is summarized in Table 2. The maximum energy load demand to satisfy the 6-star rating requirements of the NCC (Australian Building Codes Board, 2013) is presented in Table 2 for each of these locations.

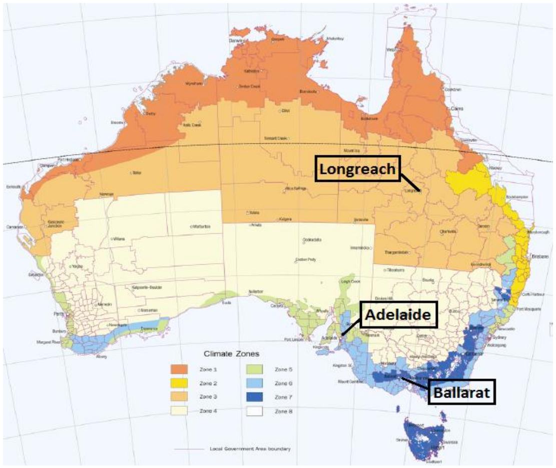


Figure 5 Selected cities in different climate zones

Table 2 Details of three climate zones

	Climate zone 3	Climate zone 5	Climate zone 7
Climate type	Hot arid	Warm temperate	Cool temperate
Summer characteristics	Hot dry	Warm	Mild to warm
Winter characteristics	Warm	Cool	Cold
Summer temperature range (^oC)	22.5—36.7	16.6—28.6	10.6—24.2
Winter temperature range (^oC)	9.3—26.6	8.5—17.0	3.9—11.8
Typical city	Longreach	Adelaide	Ballarat
Heating thermostat settings (^oC)	20	20	20
Cooling thermostat settings (^oC)	27	25	23.5
6 star energy rating (MJ/m^2 p. a)	141(maximum)	96 (maximum)	197 (maximum)

5.3 Life-cycle cost analysis

5.3.1 Initial cost

The price of constructing RE walls (maximum storey height of 3m) is commonly calculated by wall area according to contractors who were consulted during the current study. In real life situations, the labour component will be built-in. For the purposes of the current study, this labour cost was assumed to be independent of the wall thickness so that only the quantity of the materials was responsible for any price differences in the study calculations. The price of each building parameter was provided by the contractors or derived from quotes provided by Rawlinson's Quantity Surveyors and Construction Cost Consultants (Rawlingsons quantity surveyors and construction cost consultants, 2013). The standard construction costs in Adelaide, South Australia, were used for all calculations (as shown in Table 3); whereas the price of some building parameters in Longreach and

Ballarat were not available. The prices of building parameters in different cities will not affect the investigation of this research. The inflation rate (2.75%) and interest rate (4.75%) used in this analysis was the average value of Australia inflation rate for the last 10 years (2004-2013) (Trading Ecnomics, 2013a; Trading Ecnomics, 2013b).

Data for the air conditioner modelling in the current study were obtained from standard reverse cycle machines which have extremely high efficiency. Reverse cycle air conditioning was selected for the heating/cooling system as it was the most popular system for cooling and heating (reverse cycle heat pump system) in Australia according to a 2012 survey (Australian Bureau of Statistics, 2012). Its size was based on the peak heating and cooling load and the price reflected the machine's capacity to cool or heat. Prices of common reverse cycle air-conditioners and their capacity were obtained from local market, which can also be obtained online (Get Price, 2013). The relationship between the capacity and price of a reverse cycle air conditioner is illustrated in Figure 6 where the cooling capacity ranged from 2.0kW to 12.5kW and the while heating capacity ranged from 2.7kW to 14.0kW). The equations presented in Figure 6 are polynomial equations for the trend lines of the selected data. The symbol '$' represents the Australian Dollar.

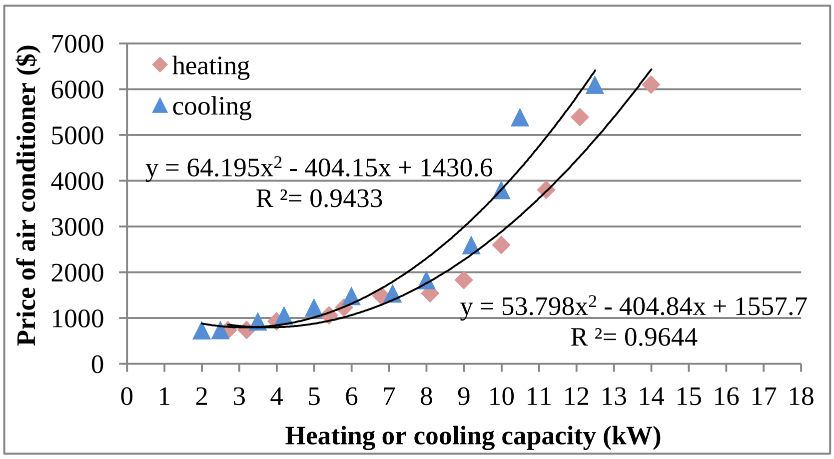


Figure 6 Relationship between heating and cooling capacity and the price of air conditioner

The initial cost of construction of the model houses ($\mathrm{C_{IC}}$) consisted of the cost of constructing the RE walls ($\mathrm{C_{RE}}$), the cost of insulation materials ($\mathrm{C_I}$), the cost of windows ($\mathrm{C_W}$), the cost of window shading ($\mathrm{C_S}$) and the cost of air conditioning ($\mathrm{C_{AC}}$), which can be computed as: $C_{IC} = C_{RE} + C_I + C_W + C_S + C_{AC}$.

The cost of window eaves and windows were based on their dimensions. Once the windows were sized, the volume of RE and insulating material could be determined based on the net wall area and wall thickness, and then the cost of RE walling and insulation material could be determined. For each model, the peak heating and cooling load was determined using *Accurate*. Based on the peak load, a virtual air conditioner was devised and its price was then derived from the relationship given in Figure 3.

5.3.2 Running cost for heating and cooling

Running cost ($\mathrm{C_R}$) depends on the cost of heating ($\mathrm{C_H}$) and cooling ($\mathrm{C_C}$), which can be expressed as: $C_R = C_H + C_C$; the annual cost for heating/cooling of a house can therefore be calculated as: $C_H = N \times \mathrm{P_H}/\mathrm{E_H}$ and $C_C = N \times \mathrm{P_C}/\mathrm{E_C}$, where N= the amount of energy consumed for heating or cooling annually; $\mathrm{P_H}, \mathrm{P_C}$ = the unit price of electricity for heating (in winters) and cooling (in summers), respectively; $\mathrm{E_H}, \mathrm{E_C}$ = the heating coefficient of the performance and cooling energy efficiency of the reverse cycle air conditioner, respectively. The actual (present) value ($\mathrm{C_a}$) of C during the life-cycle of the building can be calculated by (Dombaycı, et al., 2006; Hasan, 1999; Mearig, et al., 1999): $C_a = C \times (1 + \mathrm{g}) \times [1 - (1 + \mathrm{g})^{\mathrm{n}}/(1 + \mathrm{i})^{\mathrm{n}}]/(\mathrm{i} - \mathrm{g})$ (if i>g), where g = the inflation rate; i = the interest rate; n = the assumed life-time of the building (assumed to be 20 years).

For each model house with given input data, the annual heating and cooling load were calculated and the annual cost of heating and cooling was determined. As a result, the running cost of the model house over its life-cycle could be calculated. Values of the parameters used in the calculation, based on local market conditions, are provided in Table 3.

Table 3 Values of parameters

Parameter	Value
Unit price of electricity for heating, P_H	0.31AUD/kWh
Unit price of electricity for cooling, P_C	0.35AUD/kWh
Heating coefficient of performance, E_H	3.7
Cooling energy efficiency rating, E_C	3.1
Interest rate, i	4.75%
Inflation rate, g	2.75%
Life time period, n	20 years
Rammed earth walling	1133AUD/ m^3
Extruded polystyrene	801AUD/ m^3
Window	410AUD/ m^2
Window eave	45AUD/ m^2

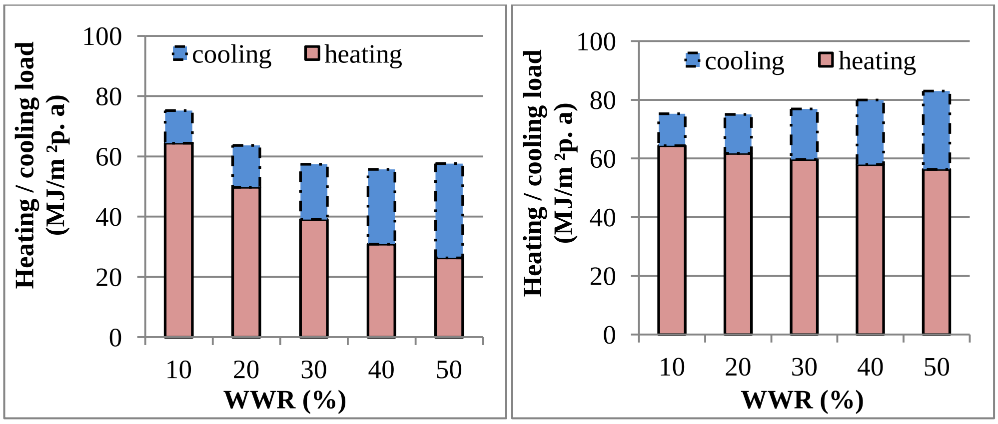
6. Simulation results

The simulation results show that the dwelling in warm temperate climates (Australian climate zone 5) required both cooling and heating. In hot arid climates (Australian climate zone 3), however, space heating was hardly required; almost all the energy was consumed for space cooling. In cool temperate climates (Australian climate zone 7), space cooling accounted for a very small proportion of the total load (always less than 3%) and space heating consumed most of the energy.

6.1 Warm temperate climates (such as Australian climate zone 5: Adelaide)

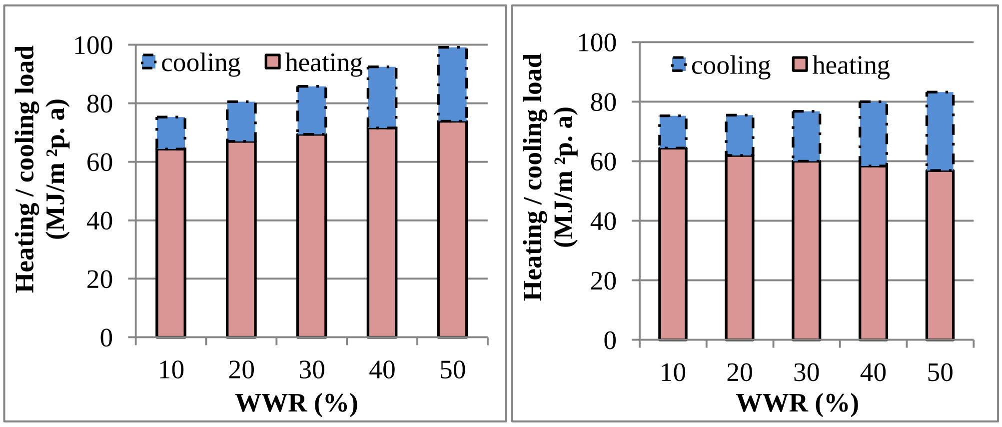
6.1.1 Effect of window size

As illustrated in Figure 7, increasing the size of the north window decreased the heating load considerably as the north facing window was able to collect solar heat in winter. This, however, would increase the cooling load in summers with heat entering the house through the large north windows. The minimum total load over the year was achieved when the north window size was 40% of the wall area. East and west window sizes had similar effects on the energy loads as shown in Figure 7b and 7d. Increasing the size of these two windows lowered the heating load and raised the cooling load with the total load also being increased because the cooling load increase outweighed the drop in the heating load. Enlarging the south window (Figure 7c) increased both the heating and cooling loads particularly due to the increase in cooling due to the heat gains late in the afternoon when the sun could still reach the south-facing windows.



(a) North window

(b) East window



(c) South window

(d) West window

Figure 7 Effect of each window size on the heating and cooling load (Adelaide)

6.1.2 Effect of window shading

Figure 8 shows that increasing the projection factor of window shading resulted in a considerable increase in heating load and a small reduction in cooling load. As the projection factor increased from 0 to 0.60, the total energy load increased from 75.3 to 92.9MJ/m^2 per annum due to an increased heating load.

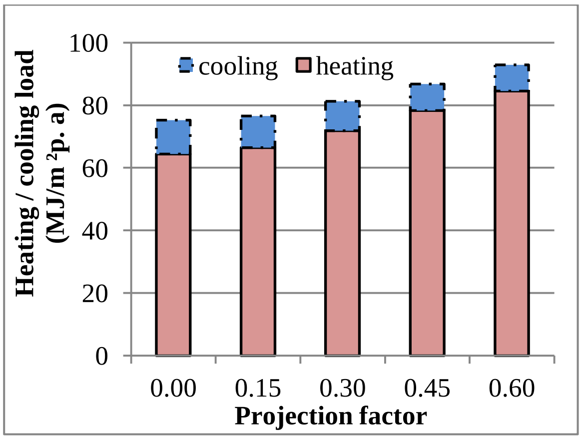
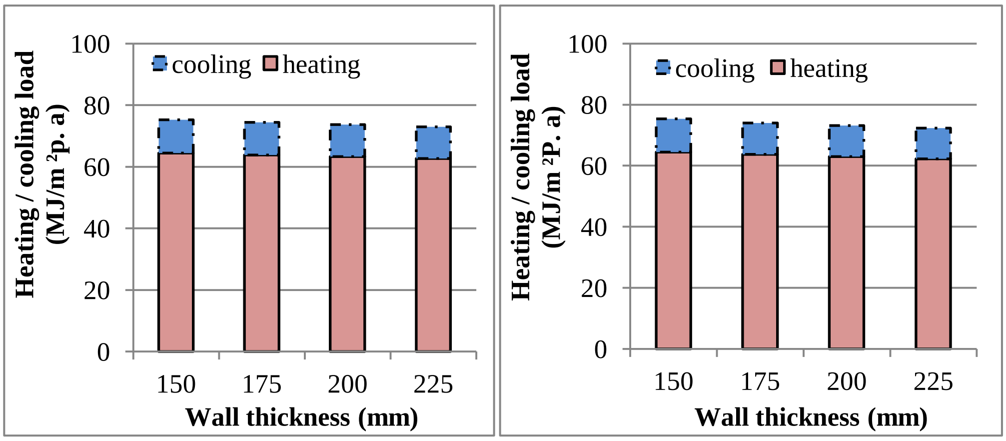


Figure 8 Effect of window shading on the heating and cooling load (Adelaide)

6.1.3 Effect of RE wall thickness

As illustrated in Figure 9, only a slight reduction in the total energy load (less than 4%) was achieved by increasing either the external or internal RE wall leaf thickness from 150mm to 225mm as the total thermal property of the original walls only changed slightly with an increase by 75mm of thermal mass. Despite the claims that RE walls provide excellent thermal mass effect, this investigation found that the benefit of having thicker RE walls is small.



(a) External wall (b) Internal wall

Figure 9 Effect of wall leaf thickness on the heating and cooling load (Adelaide)

6.1.4 Effect of insulation thickness

As shown in Figure 10, increasing the insulation thickness for the hypothetical house in Adelaide (Australian climate zone 5) from 30mm to 100mm reduced both the heating and the cooling load, and the total energy load dropped by 36% from 75.3 to 48.4MJ/m^2 per annum as the increased thermal resistance that can effectively reduce the heating load.

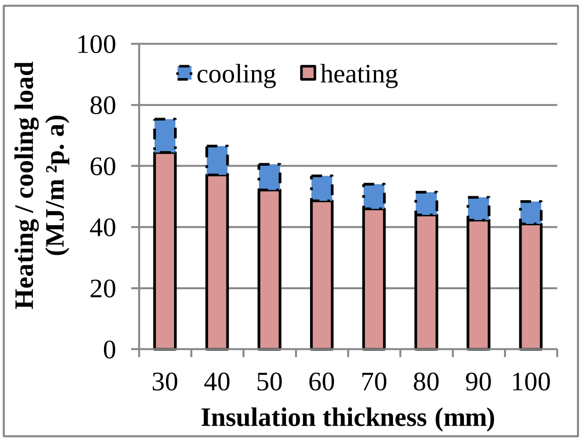


Figure 10 Effect of insulation thickness on the heating and cooling load (Adelaide)

6.1.5 Meeting the 6-star requirement

In summary, in a warm temperate climate (Australian climate zone 5) where space heating consumes more energy than space cooling, strategies which can effectively reduce the heating load are desirable, such as applying large north windows and small other facing windows, minimising the eave width and maximising the insulation thickness. Increasing wall thickness can only slightly reduce the energy load thus it is not recommended to reduce energy loads by constructing very thick walls.

It should be noted that the energy loads presented in Figures 7 to 10 were calculated value. The star rating was assigned based on the area-adjusted load, which was calculated by adjusting the total load in proportion to the total building surface area to floor area ratios of a range of dwellings in a particular

Climate Zone (NatHERS National Administrator, 2012). From the data presented above, the maximum total energy load of 99.2MJ/m^2 per annum occurred when the WWR for the south window was 50%. The area-adjusted load for this calculated value was 80.8MJ/m^2 per annum, which was lower than the maximum demand of 6-star rating (96MJ/m^2 per annum) for this climate. This means that for the base case house, each option of these four parameters investigated in this study can be applied in this climate.

6.2 Hot arid climate (such as Australian climate zone 3: Longreach) and cool temperate climate (such as Australian climate zone 7: Ballarat)

6.2.1 Effect of each parameter on the total energy loads

Since the heating load in hot arid climates (Australian climate zone 3) and the cooling load in cool temperate climates (Australian climate zone 7) accounts for a very small part of the total energy load, only the total energy load was analysed as shown in Figure 11.

In hot arid climates (Australian climate zone 3); the window size in each direction has a similar effect on the total energy load. Increasing the WWR from 10% to 50% caused in all instances a significant rise in the total energy load from 89.0 to approximately 140.0MJ/m^2 per annum. Increasing the projection factor is an effective way to reduce the total energy load in hot arid climates, whereas when the projection factor increased from 0 to 0.60, the total energy load dropped by 16% from 89.0 to 74.9MJ/m^2 per annum due to the fact that in this climate zone, space heating is rarely required and large window shading can effectively reduce the cooling load. RE wall thickness had only small effect on the total energy load, while an increase of insulation thickness from 30mm to 100mm reduced the energy load by 16%.

In cool temperate climates (Australian climate zone 7), the east and west window sizes had only a very slight effect on the total energy load. Increasing the WWR of the north facing window from 10% to 50% led to a substantial drop (by 18%) in the total energy load, while increasing the WWR of south facing window resulted in a considerable increase (by 12%) in the total energy load. Increasing the projection factor from 0 to 0.60 resulted in a rise of the total energy load by 14% from 268.0 to 306.1MJ/m^2 per annum due to the fact that in this climate most of the total energy load was used for space heating and larger shadings reduced the amount of solar heat entering the house hence the increased the heating load. The efffect of RE wall thickness on the total energy load in this climate was similar to that in hot arid climates. Insulation thickness, however, had greater effect in cool temperate climates (an increase from 30mm to 100mm reduced the energy load by 26%) than that in hot arid climates.

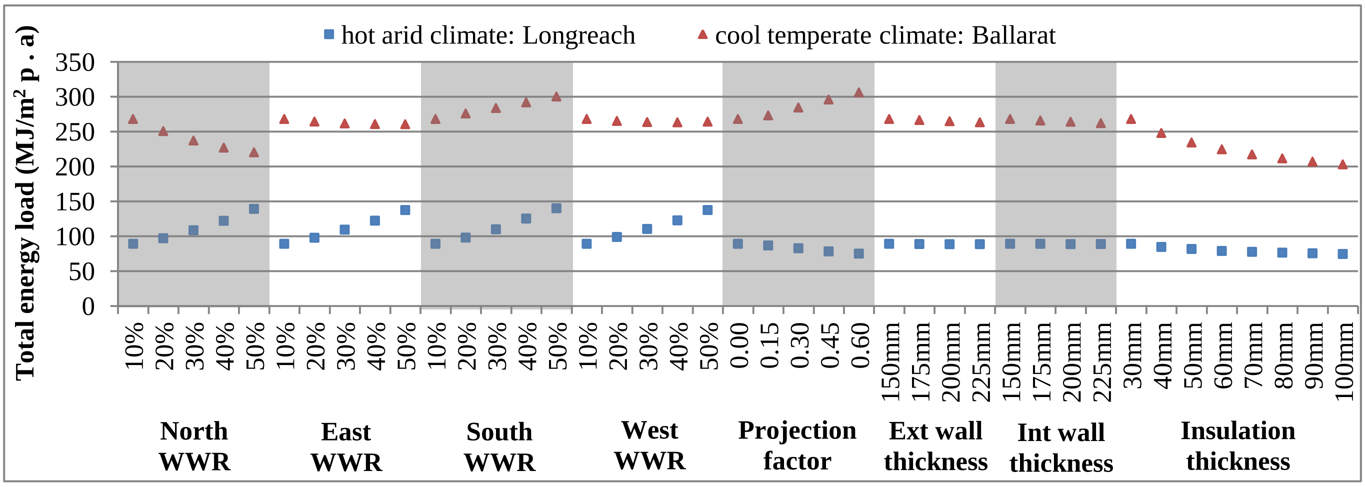


Figure 11 Effect of each parameter on the total energy load (Longreach and Ballarat)

6.2.2 Meeting the 6-star requirement

In summary, in a hot arid climate (Australian climate zone 3), considering all changes investigated in this study, the maximum calculated energy loads of the base case house (140.0MJ/m^2 per annum) was achieved when the WWR of the east facing window was 50%. The area-adjusted load for this calculated value was 119.9MJ/m^2 per annum, which was still lower than the maximum demand of 6-star rating (141.0MJ/m^2 per annum) for this climate, meaning that for the base case house, all the changes investigated in the study can be applied.

In a cool temperate climate (Australian climate zone 7), however, the base case house can achieve the 6-star rating requirements only when the WWR of the north facing window was 30% or above, or when the insulation thickness was 50mm or more. Changing the values of the other parameters, individually, however, cannot help the base case model to meet the 6-star rating requirements unless some of the other parameters were also changed. For example, if the WWR of the north facing window is smaller than 30% (which makes the base case model fail to meet the 6-star rating requirements), the base case house can still meet the 6-star rating requirements if the insulation thickness is changed to be more than 30mm.

7. Effect of each parameter on the total life-cycle cost

In order to reduce the total energy load or to meet the 6-star rating requirements, the design parameters must be optimized; however, changing the value of the parameters may results in an increase of total life-cycle cost. For example, increased insulation thickness will reduce the total energy load and therefore the running cost for heating and cooling, but doing so will increase the cost of insulation material. If the increase in the material cost outweighs the reduction in the running cost, the total life-cycle cost will increase. Hence in order to minimize the total life-cycle cost, the effect of each parameter on the total life-cycle cost has to be investigated. For example, in hot arid climates, small windows on each wall will result in lower energy loads, but in practice large windows are commonly favoured by the occupants in order to capture natural light, to frame views and to augment heating. Increasing the window size may however increase the total energy load, but as long as the total energy load can be kept under the maximum allowable for a 6-star house by changing other parameters (for example increasing the insulation thickness), then large windows are acceptable. In this case, what designers will be more interested to know is the implication of increasing the window size/insulation thickness on the total life-cycle cost. If the increase in the window size and insulation thickness will only result in a small increase of the total life-cycle cost then large windows may be chosen.

7.1 Warm temperate climates (such as Australian climate zone 5: Adelaide)

Figure 12 shows an example of the effect of a design parameter (north window size) on the economic costs of rammed earth houses in climate zone 5. In general, the initial cost of construction and air conditioning has the most significant impact on the total life-cycle cost, while the cost for heating and cooling only accounts for a small portion of the total life-cycle cost due to the fact that reverse cycle air conditioners have very high efficiency.

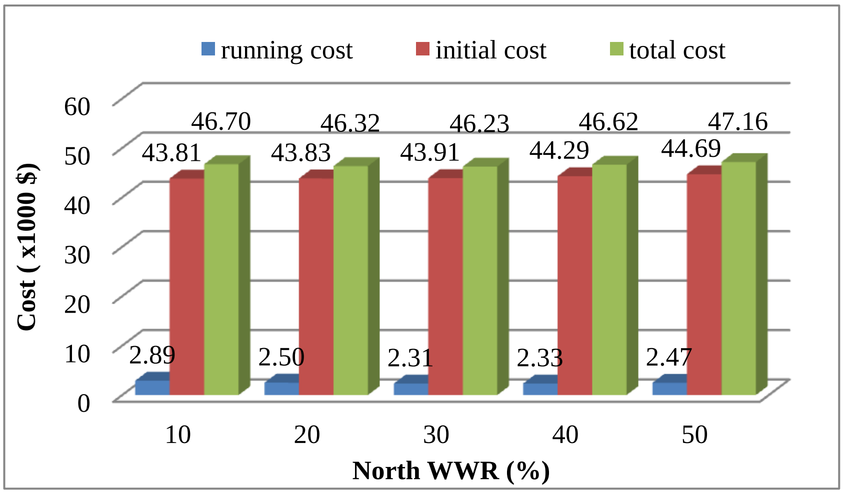


Figure 12 Effect of north window size on the costs (Adelaide)

It can be seen from Figure 12 that the minimum life-cycle cost occurs when the north window size is 30% of the wall area. The effects of the other three window sizes and window shading on the economic costs are reported in Table 4. For the east, south and west windows, the smallest window size (WWR=10%) gave the minimum life-cycle cost although the life-cycle cost did not increase considerably (no more than $620) when the window sizes (east, south and west) increased from 10% to 30%. This means having larger windows in these walls does not have much of an impact on the total life-cycle cost of the house. Increased window shading (expressed in the projection factor) resulted in an increase in energy load, and therefore increased running costs (21%). The initial cost also increased because of the larger eaves. Hence the total life-cycle cost of the building increased due to the increase in both running and initial costs.

The effects of RE wall leaf and insulation thickness on the costs are presented in Table 5 where it can be seen that the external and internal RE wall leaf thicknesses had only a small effect on the running cost. For example, increasing the external wall thickness from 150 to 225 mm only reduced the running cost by 3%. The life-cycle cost, however, increased by 18% as each wall thickness increased from 150 to 225mm. Hence thinner RE wall leaves are recommended as long as they can fulfil the building's structural strength requirements (Standards Australia, 2001; Walker and Standards Australia, 2002). The running cost decreased by $1028 (36%) while the total life-cycle cost increased by $4390 (9%) with the gradual increase in thickness from 30mm to 100mm because the increase in the initial cost due to the extra insulation was more than the decrease in the present value of the running cost.

Table 4 Effects of window size and shading on the costs (warm temperate climate)

Parameter	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
East WWR (%)			
Base case	2890	43815	46704
20	2909(+1%)	43842(0%)	46752(0%)
30	3019(+4%)	43942(0%)	46961(+1%)
40	3187(+10%)	44261(+1%)	47448(+2%)
50	3349(+16%)	44834(+2%)	48183(+3%)
South WWR (%)			
Base case	2890	43815	46704
20	3115(+8%)	43899(0%)	47014(+1%)
30	3337(+15%)	43984(0%)	47321(+1%)
40	3634(+26%)	44216(+1%)	47850(+2%)
50	3930(+36%)	44376(+1%)	48306(+3%)
West WWR (%)			
Base case	2890	43815	46704
20	2926(+1%)	43842(0%)	46769(0%)
30	3011(+4%)	44087(+1%)	47098(+1%)
40	3183(+10%)	44492(+2%)	47675(+2%)
50	3353(+16%)	44513(+2%)	47866(+2%)
Projection factor			
Base case	2890	43815	46704
0.15	2929(+1%)	43863(0%)	46792(0%)
0.30	3093(+7%)	43985(0%)	47079(+1%)
0.45	3285(+14%)	43960(0%)	47246(+1%)
0.60	3507(+21%)	44233(1%)	47740(+2%)

"+" and "-" stand for increase and decrease, respectively.

Table 5 Effects of wall leaf and insulation thickness on the costs (warm temperate climate)

Parameter	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
External wall thickness (mm)			
Base case	2890	43815	46704
175	2853(-1%)	46659(+6%)	49512(+6%)
200	2825(-2%)	49576(+13%)	52401(+12%)
225	2799(-3%)	52347(+19%)	55145(+18%)
Internal wall thickness (mm)			
Base case	2890	43815	46704
175	2835(-2%)	46732(+7%)	49567(+6%)
200	2805(-3%)	49431(+13%)	52236(+2%)
225	2769(-4%)	52347(+19%)	55116(+18%)
Insulation thickness (mm)			
Base case	2890	43815	46704
40	2550(-12%)	44842(+2%)	47392(+1%)
50	2318(-20%)	45571(+4%)	47889(+3%)
60	2180(-25%)	46227(+6%)	48407(+4%)
70	2074(-28%)	46889(+7%)	48964(+5%)
80	1972(-32%)	47764(+9%)	49736(+6%)
90	1910(-34%)	48498(+11%)	50407(+8%)
100	1862(-36%)	49233(+12%)	51094(+9%)

7.2 Hot arid climates (such as Australian climate zone 3: Longreach) and cool temperate climates (such as Australian climate zone 7: Ballarat)

7.2.1 Effect of window size

In hot arid climates (Australian climate zone 3), increasing the size of each window led to both greater initial costs and greater running costs, meaning an increased life-cycle cost for the building as shown in Table 6. As the WWR increased from 10% to 50% for north, east, south and west windows, respectively, the life-cycle cost increased by $2527, $2720, $2677 and $3051, respectively. In cool temperate climates (Australian climate zone 7), however, increasing the north WWR up to 50% would slightly decrease the total life-cycle cost, and increasing east or west WWR up to 30% (50%) will only increase the total life-cycle cost by 1% (2%). What is important to note, however, is that in order to meet the 6-star requirements, the WWR of the north facing window of the base case house should be no less than 30%, and the larger the better.

Table 6 Effects of window size on the costs (hot arid and cool temperate climates)

WWR (%)	Hot arid climates (Australian climate zone 3)			Cool temperate climates (Australian climate zone 7)		
	Running cost ($)	Initial cost ($)	Life-cycle cost ($)	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
North window						
10	4270	46350	50620	9856	41989	51845
20	4654(+9%)	46220(0%)	50874(+1%)	9229(-6%)	42613(+1%)	51842(0%)
30	5201(+22%)	46199(0%)	51400(+2%)	8746(-11%)	42837(+1%)	51583(-1%)
40	5853(+37%)	46389(0%)	52242(+3%)	8385(-15%)	43290(+1%)	51675(0%)
50	6674(+56%)	46473(0%)	53147(+5%)	8163(-17%)	43374(+1%)	51537(-1%)
East window						
10	4270	46350	50620	9856	41989	51845
20	4687(+10%)	46449(0%)	51137(+1%)	9729(-1%)	42585(+1%)	52314(+1%)
30	5244(+23%)	46549(0%)	51793(+2%)	9637(-2%)	42728(+1%)	52365(+1%)
40	5863(+37%)	46541(0%)	52403(+4%)	9615(-2%)	43015(+1%)	52360(+2%)
50	6592(+54%)	46748(+1%)	53340(+5%)	9621(-2%)	43165(+1%)	52786(+2%)
South window						
10	4270	46350	50620	9856	41989	51845
20	4697(+10%)	46654(+1%)	51351(+1%)	10156(+3%)	42658(+1%)	52814(+2%)
30	5268(+23%)	46411(0%)	51679(+2%)	10446(+6%)	42837(+1%)	53282(+3%)
40	6007(+41%)	46823(+1%)	52829(+4%)	10757(+9%)	42970(+1%)	53726(+4%)
50	6717(+57%)	46580(0%)	53296(+5%)	11081(+12%)	43054(+1%)	54135(+4%)
West window						
10	4270	46350	50620	9856	41989	51845
20	4740(+11%)	46342(0%)	51082(+1%)	9761(-1%)	42501(+1%)	52262(+1%)
30	5292(+24%)	46549(0%)	51841(+2%)	9709(-1%)	42642(+1%)	52351(+1%)
40	5882(+38%)	47093(+2%)	52975(+5%)	9704(-2%)	43015(+1%)	52719(+2%)
50	6592(+54%)	47079(+2%)	53671(+6%)	9759(-1%)	43165(+1%)	52924(+2%)

7.2.2 Effect of window shading

As can be seen from Table 7, in hot arid climates (Australian climate zone 3), increasing the projection factor from 0 to 0.60 resulted in a 16% reduction in running cost. The minimum initial cost and life-cycle cost were achieved at a projection factor of 0.45. In climate zone 7, however, increasing the projection factor increased both the initial cost and the running cost because the shading would reduce the amount of solar radiation into the space in winter, hence increasing the heating energy. Life-cycle cost increased by $1722 as the projection factor increased from 0 to 0.60.

Table 7 Effect of projection factor on the costs (hot arid and cool temperate climates)

Projection factor	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
Hot arid climates (Australian climate zone 3)			
base case	4270	46350	50620
0.15	4155(-3%)	46323(-0%)	50478(-0%)
0.30	3963(-7%)	46297(-0%)	50260(-1%)
0.45	3752(-12%)	45110(-3%)	48861(-3%)
0.60	3594(-16%)	45280(-2%)	48874(-3%)
Cool temperate climates (Australian climate zone 7)			
base case	9856	41989	51845
0.15	10046(+2%)	42070(+0%)	52116(+1%)
0.30	10458(+6%)	42151(+0%)	52609(+1%)
0.45	10880(+10%)	42232(+1%)	53112(+2%)
0.60	11254(+14%)	42313(+1%)	53567(+3%)

7.2.3 Effect of wall leaf thickness

Running costs could not be reduced to any great degree by increasing either the external or the internal wall thickness whereas increasing the wall thickness significantly raised the initial cost. Consequently, in hot arid climates, the total life-cycle cost increased by 17% (14%) when exterior (interior) wall leaf thickness increased from 150mm to 225mm as shown in Table 8 and Table 9. In cool temperate climates (Australian climate zone 7), similar results were observed with total life-cycle costs increased by16% when each of the wall leaf increased from 150mm to 225mm.

Table 8 Effect of external wall thickness on costs (hot arid and cool temperate climates)

External wall thickness (mm)	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
Hot arid climates (Australian climate zone 3)			
base case	4270	46350	50620
175	4256(0%)	49086(+6%)	53342(+5%)
200	4246(-1%)	51930(+12%)	56176(+11%)
225	4246(-1%)	54774(+18%)	59020(+17%)
Cool temperate climates (Australian climate zone 7)			
base case	9856	41989	51845
175	9801(-1%)	44811(+7%)	54612(+5%)
200	9739(-1%)	47655(+13%)	57394(+11%)
225	9683(-2%)	50500(+20%)	60183(+16%)

Table 9 Effect of internal wall thickness on costs (hot arid and cool temperate climates)

Internal wall thickness (mm)	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
Hot arid climates (Australian climate zone 3)			
base case	4270	46350	50620
175	4270(0%)	49086(+6%)	53356(+5%)
200	4251(0%)	50736(+9%)	54987(+9%)
225	4256(0%)	53580(+16%)	57835(+14%)
Cool temperate climates (Australian climate zone 7)			
base case	9856	41989	51845
175	9775(-1%)	44811(+7%)	54587(+5%)
200	9709(-1%)	47655(+13%)	57365(+11%)
225	9635(-2%)	50500(+20%)	60134(+16%)

7.2.4 Effect of insulation thickness

Table 10 shows that in hot arid climates (Australian climate zone 3), increasing the insulation thickness from 30mm to 100mm can reduce the running cost by 16%, while the initial cost and total life-cycle cost were minimized at an insulation thickness of 40mm. In cool temperate climates (Australian climate zone 7), it is clear that increasing the thickness of the insulation from 30 to 100mm also led to a steady drop in running costs (up to 24%) but raised the initial and total life-cycle costs by 13% and 6% respectively. It is important to note that insulation with a sufficient thickness (50mm for the base case house) must be applied in order to meet the 6-star rating requirements. Although increasing the insulation thickness will result in an increase of total life-cycle cost, the total energy load can be considerably reduced while the cost penalty from increasing insulation thickness is not significant (the total life-cycle cost will only increase by approximately 1% for every 10mm increase in insulation thickness). Hence if the total energy load of a house exceeds the maximum value for 6-star rating requirements, it is recommended that insulation thickness be increased in order to reduce the energy load (to a value that is lower than the maximum allowance for 6-star requirements).

Table 10 Effect of insulation thickness on the costs (hot arid and cool temperate climates)

Insulation thickness (mm)	Running cost ($)	Initial cost ($)	Life-cycle cost ($)
Hot arid climates (Australian climate zone 3)			
base case	4270	46350	50620
40	4054(-5%)	45582(-2%)	49636(-2%)
50	3915(-8%)	46565(0%)	50480(0%)
60	3776(-12%)	47279(+2%)	51055(+1%)
70	3718(-13%)	48084(+4%)	51802(+2%)
80	3661(-14%)	48799(+5%)	52460(+4%)
90	3617(-15%)	49516(+7%)	53134(+5%)
100	3570(-16%)	50320(+9%)	53890(+6%)
Cool temperate climates (Australian climate zone 7)			
base case	9856	41989	51845
40	9116(-8%)	42732(+2%)	51848(+0%)
50	8618(-13%)	43501(+4%)	52119(+1%)
60	8256(-16%)	44289(+5%)	52546(+1%)
70	7989(-19%)	45079(+7%)	53068(+2%)
80	7780(-21%)	45869(+9%)	53649(+3%)
90	7607(-23%)	46661(+11%)	54268(+5%)
100	7464(-24%)	47465(+13%)	54929(+6%)

8 Multiple parameter study

Multiple parameter study was conducted to investigate the optimal thermal performance of fully optimised ICRE wall houses. To achieve this aim, once the optimum value (in terms of total energy load) of a parameter was determined, it was applied in the subsequent investigations of the other parameters. The results show that the optimum value of each parameter for the multiple parameter study was the same as that for single parameter study; except for the east and west window size for model house in cool temperate climate (for multiple parameter study, the optimum value of both east and west window size was 10% of the wall area, whereas for single parameter study, the optimum values for east and west window size was 50% and 40% of the wall area, respectively).

In terms of the life-cycle cost, the optimum value of each parameter for multiple parameter study was the same as that for single parameter study. In general, small value of each parameter results in low life-cycle parameter. It should be noted that in order to meet the 6-star rating requirement, in cool temperate climate, the north window size should be no less than 30% of the wall area, or the insulation thickness should be larger than 50mm, or the external walls of the house was insulated with 40mm insulation with a north window size larger than 20% of the wall area. Among these three options, having large north window (more than 30% of the wall area) lead to the minimum life-cycle cost.

9 Conclusions

The present study aims to provide the relationship between each parameter and energy loads/life-cycle cost, so that designers and house owners can make more informed decisions by balancing personal preferences with the cost of implementing them. In order to achieved this aim, an analysis of the energy efficiency and economic costs of RE houses was conducted by examining different options for the design parameters across a range of climate zones (from hot arid to cool temperate). The optimum value of each design parameter (from the minimum energy load/total life-cycle cost point of view) was determined with reference to the base case house developed for this study. This means that when the design parameters for the base case house were changed, the optimum values of each parameter will change. Also, the optimum value of each parameter determined in this study was restricted by the selected options of each parameter (range and increment). For example, the optimum wall thickness corresponding to minimum life-cycle cost may be calculated to be 108mm; however, it is unrealistic to construct a RE wall with such precision (to the nearest millimetre). The increments for each parameter studied in this project were reasonable values in ranges recommended by experienced local builders.

In summary, each parameter in combination with the other parameters has different effects on the energy load and total life-cycle cost in different climates. It should be noted that the calculation of life-cycle cost is based on reverse cycle air conditioner only, and the result is sensitive to the type of heating/cooling system used. The effect of using other heating/cooling systems on the life-cycle cost will be different; however, this is beyond the scope of this study. The main contribution of this research is to provide recommendations for smart designs based on the relationship between each parameter and the energy load/life-cycle cost of a RE house. With the results presented in this study, designers and home owners will be able to make more informed decisions.

References

[1] Centre for International Economics, Capitalising on the building sector's potential to lessen the costs of a broad based GHG emissions cut. Research report prepared for ASBEC Climate Change Task Group, http://www.thecie.com.au/, Accessed on August 22, 2013.

[2] J. Morrissey, R. Horne, Life cycle cost implications of energy efficiency measures in new residential buildings, Energy and Buildings, 43 (4) (2011) 915-924.

[3] Australian Bureau of Statistics, Are Households Using Renewable Energy?, http://www.abs.gov.au/, Accessed on August 22, 2013.

[4] Australian Bureau of Statistics, Feature article: heating and cooling, http://www.abs.gov.au/, Accessed on October 12, 2013.

[5] B.V. Reddy, P.P. Kumar, Embodied energy in cement stabilised rammed earth walls, Energy and Buildings, 42 (3) (2010) 380-385.

[6] G.J. Treloar, C. Owen, R. Fay, Environmental assessment of rammed earth construction systems, Structural survey, 19 (2) (2001) 99-106.

[7] J. Morel, A. Mesbah, M. Oggero, P. Walker, Building houses with local materials: means to drastically reduce the environmental impact of construction, Building and Environment, 36 (10) (2001) 1119-1126.

[8] Q. Li, X. Sun, C. Chen, X. Yang, Characterizing the household energy consumption in heritage Nanjing Tulou buildings, China: A comparative field survey study, Energy and Buildings, 49 (0) (2012) 317-326.

[9] P. Taylor, R. Fuller, M. Luther, Energy use and thermal comfort in a rammed earth office building, Energy and Buildings, 40 (5) (2008) 793-800.

[10] V. Soebarto, Analysis of indoor performance of houses using rammed earth walls, The Eleventh International IBPSA Conference, Glasgow, Scotland, (2009) 1530-1537.

[11] D. Allinson, M. Hall, Hygrothermal analysis of a stabilised rammed earth test building in the UK, Energy and Buildings, 42 (6) (2010) 845-852.

[12] Australian Building Codes Board, National Construction Code Standards Australia, Canberra, 2013.

[13] P. Walker, Standards Australia, The Australian Earth Building Handbook, Standards Australia, Sydney, Australia, 2002.

[14] M. Hall, D. Allinson, Assessing the effects of soil grading on the moisture content-dependent thermal conductivity of stabilised rammed earth materials, Applied Thermal Engineering, 29 (4) (2009) 740-747.

[15] Z. Yan, J.C. Lam, J. Liu, Experimental studies on the thermal and moisture properties of rammed earth used in adobe buildings in China, Architectural Science Review, 48 (1) (2005) 55-60.

[16] P. Taylor, M. Luther, Evaluating rammed earth walls: a case study, Solar Energy, 76 (1) (2004) 79-84.

[17] M. Hall, B. Swaney, Stabilised rammed earth(SRE) wall construction-now available in the UK, Building Engineer, 80 (9) (2005) 12-15.

[18] A. Papadopoulos, State of the art in thermal insulation materials and aims for future developments, Energy and Buildings, 37 (1) (2005) 77-86.

[19] D. Baggs, N. Mortensen, Thermal Mass in Building Design, BDP Environmental Design Guide, (2006).

[20] Australian Building Codes Board, National Construction Code Standards Australia, Canberra, 2011.

[21] S. Jaber, S. Ajib, Optimum, technical and energy efficiency design of residential building in Mediterranean region, Energy and Buildings, 43 (8) (2011) 1829-1834.

[22] B. Givoni, Characteristics, design implications, and applicability of passive solar heating systems for buildings, Solar Energy, 47 (6) (1991) 425-435.

[23] M.-L. Persson, A. Roos, M. Wall, Influence of window size on the energy balance of low energy houses, Energy and Buildings, 38 (3) (2006) 181-188.

[24] D.B. Özkan, C. Onan, Optimization of insulation thickness for different glazing areas in buildings for various climatic regions in Turkey, Applied Energy, 88 (4) (2011) 1331-1342.

[25] S.A. Kalogirou, G. Florides, S. Tassou, Energy analysis of buildings employing thermal mass in Cyprus, Renewable Energy, 27 (3) (2002) 353-368.

[26] M.A. Aktacir, O. Büyükalaca, T. Yılmaz, A case study for influence of building thermal insulation on cooling load and air-conditioning system in the hot and humid regions, Applied Energy, 87 (2) (2010) 599-607.

[27] Ö.A. Dombaycı, M. Gölcü, Y. Pancar, Optimization of insulation thickness for external walls using different energy-sources, Applied Energy, 83 (9) (2006) 921-928.

[28] CSIRO, AccuRate Manual, Australian Commonwealth Scientific and Industrial Research Organisation, 2004.

[29] A. Delsante, An Empirical Validation of CHENATH, The National Home Energy Rating Scheme Simulation Engine (DBCE Doc. 95/78 (M)), Melbourne: CSIRO, Division of Building Construction and Engineering, 1995.

[30] A. Delsante, A Validation of the AccuRate Simulation Engine Using BESTEST, Report to the Australian Greenhouse Office. CSIRO Manufacturing & Infrastructure Technology report, CMIT (C)-2004-152, (2004).

[31] A. Delsante, A comparison of 'accurate' predictions with measured data from a mud brick house, Proceedings of IBPSA Australasia Conference, Adelaide, Australia, (2006) 96-103.

[32] L. Daniel, V. Soebarto, T. Williamson, Evaluating the suitability of the AccuRate engine for simulation of massive construction elements, 46th Annual Conference of the Architectural Science Association (ANZAScA), Queensland, Australia, (2012).

[33] P. Walsh, A. Delsante, Calculation of the thermal behaviour of multi-zone buildings, Energy and Buildings, 5 (4) (1983) 231-242.

[34] X. Dong, V. Soebarto, M. Griffith, Strategies for reducing heating and cooling loads of uninsulated rammed earth wall houses, Energy and Buildings, 77 (2014) 323-331.

[35] Rawlingsons quantity surveyors and construction cost consultants, Rawlingsons Australian construction handbook, 31 ed., Rawlinsons Publishing, Perth, Western Australia, 2013.

[36] Trading Ecnomics, Australia Inflation Rate, http://www.tradingeconomics.com/australia/inflation-cpi, Accessed on March 10, 2013.

[37] Trading Ecnomics, Australia Interest Rates, http://www.tradingeconomics.com/australia/interest-rate, Accessed on March 10, 2013.

[38] Australian Bureau of Statistics, Household Energy Consumption Survey, http://www.abs.gov.au/, Accessed on August 23, 2013.

[39] Get Price, Mitsubishi Air Conditioners, http://www.getprice.com.au/mitsubishi-air-conditioners.htm, Accessed on August 10, 2013.

[40] A. Hasan, Optimizing insulation thickness for buildings using life cycle cost, Applied Energy, 63 (2) (1999) 115-124.

[41] T. Mearig, N. Coffee, M. Morgan, Life cycle cost analysis handbook: draft, State of Alaska, Department of Education and Early Development, Education Support Services/Facilities, 1999.

[42] NatHERS National Administrator, Nationwide House Energy Rating (NatHERS) – Software Accreditation Protocol, Commonwealth Department of Climate Change and Energy Efficiency (Ed.), NatHERS, Canberra, Australia, 2012.

[43] Standards Australia, AS 3700-2001: Masonry Structures, Standards Australia, Sydney, Australia, 2001.

Chapter 8 Discussions and Closing Remarks

The work presented in this thesis has proposed some contributions for structural and sustainable design of RE wall houses. With the outcomes of this research, designers and house owners will be able to make informed design decisions for safety and cost effective RE wall houses in Australian with satisfactory thermal comfort.

8.1 Research outcomes

The main outcomes of this research are outlined below:

Chapter 4 presented results of an experimental program on the structural performance of RE walls, including the material properties (compressive strength, Young's modulus, stress-strain relationship and flexural tensile strength) and flexural behavior of full-scale RE walls, considering the effect of insulation in the middle. Test results showed that Insulated Cavity Rammed Earth (ICRE) walls can meet the structural design requirements in *Australian earth building handbook* and *Australian Standard AS3700*.

Chapter 5 presented a parametric study on the effect of key design parameters on the energy loads of solid RE wall houses by simulation. The study provided a set of recommendations for uninsulated RE wall houses to reduce the energy input for heating and cooling under different climate conditions. The simulation results also proposed the limitations of using uninsulated RE walls to build houses in cold climate, where adding insulation to RE walls is recommended.

Chapter 6 outlined a number of recommendations for the design of naturally ventilated houses using RE walls. Design parameters were optimized for maximum thermal comfort. The design parameters include window size, window shading, ventilation rate, the amount of thermal mass and insulation. With the recommendations, designers and house owners can build a house with rammed earth walls that will provide adequate thermal comfort without heating and cooling in hot arid and warm temperate climates, in particular when insulation is added. In cool temperate climates, however, satisfactory thermal comfort cannot be achieved only by optimizing design parameters even if insulation is added, meaning that space heating is necessary to maintain comfortable indoor environment.

Chapter 7 outlined another group of recommendations for designs of RE wall houses. Life-cycle cost assessment was performed to compare the cost of a certain design decision to its alternatives. The most cost effective designs were therefore obtained. The study proposed suggestions for designers and house owners to build a house with minimum life cycle cost. In addition, with the presented results, they are able to know the cost of a certain design, hence special personal designs can be made with valuable information.

8.2 Recommendations for future work

During the course of this research, several questions have been raised which represent opportunities for future research. These include:

1. The material properties of RE were derived from testing of a relatively small sample size and all specimens were from one batch of material. Future research should include a wider variety of commonly used soil types and a larger sample size.

2. The flexural behavior of full-scale walls was obtained by testing only one wall for each type. The full-scale Insulated Cavity Rammed Earth (ICRE wall specimen tested in this study may not be representative as there was a solid RE section at the top. Future research should test more representative full-scale walls to obtain a comprehensive understanding of the wall behavior under out-of-plane vertical bending.

3. The behavior of thin RE walls (for example 100mm) under compression and out-of-plane lateral loading was not evaluated. Future research should focus on thin RE walls as according to this research, thin RE walls have adequate compressive and flexural strengths for single storey houses.

4. The similarity of structural properties between RE walls and traditional masonry, such as brick and block walls, requires further validation; in order to investigate whether standards for brick masonry can be applied to RE since currently no standards are available for RE buildings in Australian.

5. Parametric studies have been conducted to investigate the effect of a set of key design parameters on the thermal comfort and energy load as well as the life-cycle cost of RE wall houses by simulation. The presented simulation program had important limitations: (1) the simulation results were not validated by monitored data due to limitations in resources and available real project/buildings with ICRE walls that can be tested; and (2) the effect of other types of air-conditioning and energy source were not considered. Future modelling should include more complex situations, such as different types of air-conditioning and energy sources. In addition, the simulation results should be compared with monitored results of real RE houses.

References (excluding those in papers)

ASHRAE (2013). "ANSI/ASHRAE Standard 55-2013. Thermal environmental conditions for human occupancy." American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, Antlanta.

ASHRAE (2004). "Standard 55-2004." *Thermal environmental conditions for human occupancy*.

Australian Building Codes Board (2013). "National Construction Code ", Standards Australia, Canberra.

Australian Bureau of Statistics (2009a). "Are Households Using Renewable Energy?", <http://www.abs.gov.au/>. (Accessed on August 22, 2013).

Australian Bureau of Statistics (2010). "Australian Social Trends." <http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/4102.0Main+Features20Jun+2010>. (Accessed on October 9, 2014).

Australian Bureau of Statistics (2009b). "Feature article: heating and cooling." <http://www.abs.gov.au/>. (Accessed on October 12, 2013).

Baggs, D., and Mortensen, N. (2006). "Thermal Mass in Building Design." *BDP Environmental Design Guide*.

Baggs, S.,Baggs, D. W., and Baggs, J. C. (1991). *Australian Earth-Covered Buildings*, New South Wales University Press.

Bahar, R.,Benazzoug, M., and Kenai, S. (2004). "Performance of compacted cement-stabilised soil." *Cement and concrete composites*, 26(7), 811-820.

Balaras, C. (1996). "The role of thermal mass on the cooling load of buildings. An overview of computational methods." *Energy and Buildings*, 24(1), 1-10.

Brown, R. H., and Elling, R. E. "Lateral load distribution in cavity walls." The Brick Institute of American, Washington, DC, 351.

Centre for International Economics (2007). "Capitalising on the building sector's potential to lessen the costs of a broad based GHG emissions cut. Research report prepared for ASBEC Climate Change Task Group." <http://www.thecie.com.au/>. (Accessed on August 22, 2013).

Ciancio, D., and Gibbings, J. (2012). "Experimental investigation on the compressive strength of cored and molded cement-stabilized rammed earth samples." *Construction and Building Materials,* 28(1), 294-304.

Çomaklı, K., and Yüksel, B. (2003). "Optimum insulation thickness of external walls for energy saving." *Applied Thermal Engineering*, 23(4), 473-479.

Crawley, D. B.,Hand, J. W.,Kummert, M., and Griffith, B. T. (2008). "Contrasting the capabilities of building energy performance simulation programs." *Building and environment*, 43(4), 661-673.

CSIRO (2004). *AccuRate Manual*, Australian Commonwealth Scientific and Industrial Research Organisation.

Daniel, L.,Soebarto, V., and Williamson, T. (2012). "Evaluating the suitability of the AccuRate engine for simulation of massive construction elements." *46th Annual Conference of the Architectural Science Association (ANZAScA)*Queensland, Australia.

de Dear, R. "Adaptive thermal comfort in building management and performance." *Proc., Proceedings of the Healthy Buildings*, 31-35.

de Dear, R. "Recent enhancements to the adaptive comfort standard in ASHRAE 55-2010." *Proc., Proceedings of the 45th annual conference of the Architectural Science Association. Sydney, Australia: ANZAScA*.

de Dear, R., and Brager, G. S. (1998). "Developing an adaptive model of thermal comfort and preference." *ASHRAE Transaction*, 104(1a), 145-167.

de Dear, R. J., and Brager, G. S. (2002). "Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55." *Energy and Buildings*, 34(6), 549-561.

Degelman, L. O., and Soebarto, V. I. "Software description for ENER-WIN: A visual interface model for hourly energy simulation in buildings." *Proc., Proceedings of Building Simulation, International Building Performance Simulation Association (IBPSA) Conference, Madison, WI*, 692-696.

Delgado, M. C., Jiménez , and Guerrero, I. C. (2007). "The selection of soils for unstabilised earth building: A normative review." *Construction and Building Materials*, 21(2), 237-251.

Delsante, A. "A comparison of 'accurate' predictions with measured data from a mud brick house." 96-103.

Delsante, A. (2004). "A Validation of the AccuRate Simulation Engine Using BESTEST." *Report to the Australian Greenhouse Office. CSIRO Manufacturing & Infrastructure Technology report, CMIT (C)-2004-152*.

Doherty, K.,Griffith, M. C.,Lam, N., and Wilson, J. (2002). "Displacement-based seismic analysis for out-of-plane bending of unreinforced masonry walls." *Earthquake engineering & structural dynamics*, 31(4), 833-850.

Easton, D. (2007). *The rammed earth house*, Chelsea Green Publishing.

Givoni, B. (1991). "Characteristics, design implications, and applicability of passive solar heating systems for buildings." *Solar Energy*, 47(6), 425-435.

Gregory, K.,Moghtaderi, B.,Sugo, H., and Page, A. (2008). "Effect of thermal mass on the thermal performance of various Australian residential constructions systems." *Energy and Buildings*, 40(4), 459-465.

Griffith, M. C.,Lam, N. T.,Wilson, J. L., and Doherty, K. (2004). "Experimental investigation of unreinforced brick masonry walls in flexure." *Journal of Structural Engineering*, 130(3), 423-432.

Griffith, M. C.,Magenes, G.,Melis, G., and Picchi, L. (2003). "Evaluation of out-of-plane stability of unreinforced masonry walls subjected to seismic excitation." *Journal of Earthquake Engineering*, 7(S1), 141-169.

Hall, M., and Allinson, D. (2009). "Assessing the effects of soil grading on the moisture content-dependent thermal conductivity of stabilised rammed earth materials." *Applied Thermal Engineering*, 29(4), 740-747.

Hall, M., and Djerbib, Y. (2004). "Rammed earth sample production: context, recommendations and consistency." *Construction and Building Materials*, 18(4), 281-286.

Hall, M., and Swaney, B. (2005). "Stabilised rammed earth(SRE) wall construction- now available in the UK." *Building Engineer*, 80(9), 12-15.

Hasan, A. (1999). "Optimizing insulation thickness for buildings using life cycle cost." *Applied Energy*, 63(2), 115-124.

Jaquin, P.,Augarde, C.,Gallipoli, D., and Toll, D. (2009). "The strength of unstabilised rammed earth materials." *Géotechnique.*, 59(5), 487-490.

Jayasinghe, C. (1999). "Alternative building material and methods for Sri Lanka." Ph.D., University of Moratuwa, Sri Lanka, Sri Lanka.

Jayasinghe, C., and Kamaladasa, N. (2007). "Compressive strength characteristics of cement stabilized rammed earth walls." *Construction and Building Materials*, 21(11), 1971-1976.

Jayasinghe, C., and Mallawaarachchi, R. (2009). "Flexural strength of compressed stabilized earth masonry materials." *Materials & Design*, 30(9), 3859-3868.

Kaynakli, O. (2008). "A study on residential heating energy requirement and optimum insulation thickness." *Renewable Energy*, 33(6), 1164-1172.

Kneifel, J. (2010). "Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings." *Energy and Buildings*, 42(3), 333-340.

Kottek, M.,Grieser, J.,Beck, C.,Rudolf, B., and Rubel, F. (2006). "World map of the Koppen-Geiger climate classification updated." *Meteorologische Zeitschrift*, 15(3), 259-264.

McBoyle, G. (1971). "Climatic classification of Australia by computer." *Australian Geographical Studies*, 9(1), 1-14.

Memari, A. M.,Burnett, E. F., and Kozy, B. M. (2002). "Seismic response of a new type of masonry tie used in brick veneer walls." *Construction and Building Materials*, 16(7), 397-407.

Middleton, G. F., and Schneider, L. M. (1992). *Earth-wall construction*, CSIRO Division of Building. Construction and Engineering.

Morel, J.-C.,Pkla, A., and Walker, P. (2007). "Compressive strength testing of compressed earth blocks." *Construction and Building Materials*, 21(2), 303-309.

Morel, J.,Mesbah, A.,Oggero, M., and Walker, P. (2001). "Building houses with local materials: means to drastically reduce the environmental impact of construction." *Building and Environment*, 36(10), 1119-1126.

Morris, H.,Walker, R., and Drupsteen, T. (2011). "Modern and historic earth buildings: Observations of the 4th September 2010 Darfield earthquake." Building and Earthquake-Resilient Society, Auckland, New Zealand, 133-142.

Morris, H.,Walker, R., and Drupsteen, T. (2010). "Observations of the performance of earth buildings following the September 2010 Darfield earthquake." *Bulletin of the New Zealand Society for Earthquake Engineering*, 43(4), 393.

Morrissey, J., and Horne, R. (2011). "Life cycle cost implications of energy efficiency measures in new residential buildings." *Energy and Buildings*, 43(4), 915-924.

NatHERS National Administrator (2012). "Nationwide House Energy Rating (NatHERS) – Software Accreditation Protocol." Commonwealth Department of Climate Change and Energy Efficiency, ed., NatHERS, Canberra, Australia.

Neymark, J., and Judkoff, R. "International energy agency building energy simulation test (BESTEST) and diagnostic method." *Proc., National Renewable Energy Laboratory*, Citeseer.

Ngowi, A. B. (1997). "Improving the traditional earth construction: a case study of Botswana." *Construction and Building Materials*, 11(1), 1-7.

Page, A. W.,Kleeman, P. W., and Kautto, J. (1996). *A Design Procedure for Cavity and Veneer Wall Ties*, Department of Civil Engineering and Surveying, The University of Newcastle.

Page, A. W.,Simundic, G., and Masia, M. (2007). "Wall tie behavior in cavity and veneer wall systems." The Masonry Society, Missouri. USA, 323-334.

Papadopoulos, A. (2005). "State of the art in thermal insulation materials and aims for future developments." *Energy and Buildings*, 37(1), 77-86.

Paul, W. L., and Taylor, P. A. (2008). "A comparison of occupant comfort and satisfaction between a green building and a conventional building." *Building and Environment*, 43(11), 1858-1870.

Reddy, B., and Jagadish, K. (2003). "Embodied energy of common and alternative building materials and technologies." *Energy and buildings*, 35(2), 129-137.

Reddy, B., and Kumar, P. (2010a). "Structural Behavior of Story-High Cement-Stabilized Rammed-Earth Walls under Compression." *Journal of Materials in Civil Engineering*, 23(3), 240-247.

Reddy, B.,Lal, R., and Nanjunda Rao, K. (2007a). "Optimum soil grading for the soil-cement blocks." *Journal of Materials in Civil Engineering*, 19(2), 139-148.

Reddy, B.,Leuzinger, G., and Sreeram, V. (2014). "Low embodied energy cement stabilised rammed earth building—A case study." *Energy and Buildings*, 68, 541-546.

Reddy, B. V., and Gupta, A. (2005). "Characteristics of soil-cement blocks using highly sandy soils." *Materials and structures*, 38(6), 651-658.

Reddy, B. V., and Kumar, P. P. (2011a). "Cement stabilised rammed earth. Part A: compaction characteristics and physical properties of compacted cement stabilised soils." *Materials and structures*, 44(3), 681-693.

Reddy, B. V., and Kumar, P. P. (2011b). "Cement stabilised rammed earth. Part B: compressive strength and stress–strain characteristics." *Materials and structures*, 44(3), 695-707.

Reddy, B. V., and Kumar, P. P. (2010b). "Embodied energy in cement stabilised rammed earth walls." *Energy and Buildings*, 42(3), 380-385.

Reddy, B. V., and Kumar, P. P. (2010c). "Structural Behavior of Story-High Cement-Stabilized Rammed-Earth Walls under Compression." *Journal of Materials in Civil Engineering*, 23(3), 240-247.

Reddy, B. V.,Lal, R., and Nanjunda Rao, K. (2007b). "Optimum Soil Grading for the Soil-Cement Blocks." *Journal of Materials in Civil Engineering*, 19(2), 139-148.

Shaviv, E.,Yezioro, A., and Capeluto, I. G. (2001). "Thermal mass and night ventilation as passive cooling design strategy." *Renewable Energy*, 24(3), 445-452.

Soebarto, V. (2009). "Analysis of indoor performance of houses using rammed earth walls." *The Eleventh International IBPSA Conference*Glasgow, Scotland, 1530-1537.

Standards Australia (2001). "AS 3700-2001: Masonry Structures." Standards Australia, Sydney, Australia.

Standards New Zealand (2000). "AS/NZS 2699.1 Built-in components in masonry construction. Part 1: Wall ties."Wellington, New Zealand.

Standards New Zealand (1998a). "NZS 4297, Engineering Design of Earth Buildings." Standards New Zealand, Wellington, New Zealand.

Standards New Zealand (1998b). "NZS 4298, Materials and Workmanship for Earth Buildings." Standards New Zealand, Wellington, New Zealand.

Standards New Zealand (1998c). "NZS 4299, Earth Building not Requiring Specific Design." Standards New Zealand, Wellington, New Zealand.

Taylor, P.,Fuller, R., and Luther, M. (2008). "Energy use and thermal comfort in a rammed earth office building." *Energy and Buildings*, 40(5), 793-800.

Taylor, P., and Luther, M. (2004). "Evaluating rammed earth walls: a case study." *Solar Energy*, 76(1), 79-84.

Treloar, G. J.,Owen, C., and Fay, R. (2001). "Environmental assessment of rammed earth construction systems." *Structural survey*, 19(2), 99-106.

Walker, P. (1995). "Strength, durability and shrinkage characteristics of cement stabilised soil blocks." *Cement and Concrete Composites*, 17(4), 301-310.

Walker, P., and Standards Australia (2002). "The Australian Earth Building Handbook." Standards Australia, Sydney, Australia.

Walsh, P., and Delsante, A. (1983). "Calculation of the thermal behaviour of multi-zone buildings." *Energy and Buildings*, 5(4), 231-242.

Wang, R.,Elwi, A., and Hatzinikolas, M. (1997a). "Numerical study of tall masonry cavity walls subjected to eccentric loads." *Journal of Structural Engineering*, 123(10), 1287-1294.

Wang, R.,Elwi, A.,Hatzinikolas, M., and Warwaruk, J. (1997b). "Tests of tall cavity walls subjected to eccentric loading." *Journal of Structural Engineering*, 123(7), 912-919.

West, H.,Hodgkinson, H., and de Vekey, R. "The Lateral Resistance of Cavity Walls with Different Types of Wall-ties." The Brick Institute of American, 387.

West, H.,Hodgkinson, H., and Haseltine, B. (1977). "The resistance of brickwork to lateral loading." *Journal of the Institution of Structural Engineers*, 55(10), 411-421.

Yamin, L. E.,Phillips, C. A.,Reyes, J. C., and Ruiz, D. M. (2004). "Seismic behavior and rehabilitation alternatives for adobe and rammed earth buildings." *13th World Conference on Earthquake Engineering*Vancouver, BC, Canada, Paper No. 2942.

Yan, Z.,Lam, J. C., and Liu, J. (2005). "Experimental studies on the thermal and moisture properties of rammed earth used in adobe buildings in China." *Architectural Science Review*, 48(1), 55-60.

Zhou, T.,Mu, J., and Yang, H. (2010). "Application and practice of a new earthquake resistance rammed earth dwelling in the post-disaster reconstruction." *World Earthquake Engineering*, 26(3), 145-150.

Zmavc, R. (1991). "Simplified analysis of shear-connected cavity walls." Master of Science, University of Manitoba, Winnipeg, Manitoba, Canada.

Appendix A: Material test results

1. Molded material test specimens

Using the same batch of material that used for constructing the solid wall, material test specimens were made in molds, including six molded cubic specimens MC (side length 100mm), six molded cylindrical specimens MCy (100mm diameter by 200mm tall) and six molded beam specimens MB (nominal 100mm by 100mm by 500mm long) as shown in Figure 1. The material test specimens were constructed using a smaller jackhammer as is indicated in Figure 2. During the construction of material test specimens, some extremely large aggregates were excluded by builders.

Figure 1 Material test specimens

Figure 2 Construction of material test specimens

2. Cut/cored material test specimens

After the full-scale wall specimens were tested, four cubes and four small beams were cut from the edges of the top half of the wall, and three cylindrical specimens were cored vertically as shown in Figure 3 in order to investigate the material properties of the tested wall at a manageable scale. The dimensions of specimens taken from the full-scale tested walls are shown in Table 1.

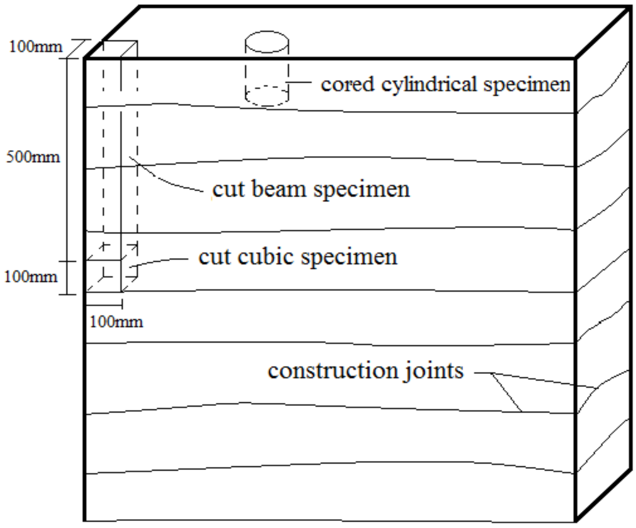


Figure 3 Orientation of cut specimens from full-scale solid walls

Table 1 Dimensions of specimens taken from tested walls

Specimens	*Dimensions (mm)		Specimens	*Dimensions (mm)	
Cut Cube from solid wall (CCS)	#1	101×100×99	Cut Cube from cavity wall (CCC)	#1	101×100×99
	#2	101×98×100		#2	101×101×97
	#3	101×101×102		#3	102×102×98
	#4	101×101×99		#4	101×101×100
Cut beam from solid wall (CBS)	#1	499×99×101	Cut beam from cavity wall (CBC)	#1	497×98×101
	#2	501×97×100		#2	495×101×100
	#3	498×102×101		#3	488×104×100
	#4	499×100×101		#4	500×103×101
Cored cylinder from solid wall (CCyS)	#1	59×116	Cored cylinder from cavity wall (CCyC)	#1	106×206
	#2	59×118		#2	107×211
	#3	58×118		#3	107×205

*Dimension: Length×Width×Height (cube and beam); Diameter× Height (cylinder)

3 Curing of specimens

The molded material test specimens were removed from molds seven days after they were made and then covered with moist cloth and left to dry in the laboratory. For cored and cut specimens, they were left to dry in the laboratory before being tested. The curing time of each specimen before test was recorded and is given in Table 2.

Table 2 Curing time of material test specimens

Specimen type	Curing time (day)	Specimen type	Curing time (day)
MC1-3	52	CCS1-4	120
MC4-6	66	CCC1-4	120
MB1-3	52	CBS1-4	86
MB4-6	66	CBC1-4	86
MCy1	112	CCyC1	127
MCy2	113	CCyC2	140
MCy3	120	CCyC3	141
		CCyS1-3	156

4 Testing program and results

4. 1 Compression tests

4.1.1. Cubic specimens

Compression tests were carried out to determine the compressive strength f_{mc}, Young's modulus E and stress-strain relationship of RE material. There were four types of specimens used for compressive strength test namely molded cubic specimen, molded cylindrical specimen, cut cubic specimen and cored cylindrical specimen.

The cubic specimens (both molded and cut from the tested walls) were tested by applying a uniaxial compressive load at a rate of 40kN/min until specimen failure. During each test, hour-glass mode cracking was always observed. The test setup and typical failure pattern are shown in Figure 4. As noted, the molded cubic specimens did not have construction joints, and in the case of the cut cubic specimens, they had been carved from a part of the wall without joints. Therefore, construction joints did not affect compression tests on either specimen. The compressive strength of the RE material was calculated by dividing the maximum applied load by the specimen's cross-sectional area. After each test, parts of the failed specimen were collected and dried in an oven at 105°C for at least 24 hours to determine their moisture content (MC) at the time of testing.

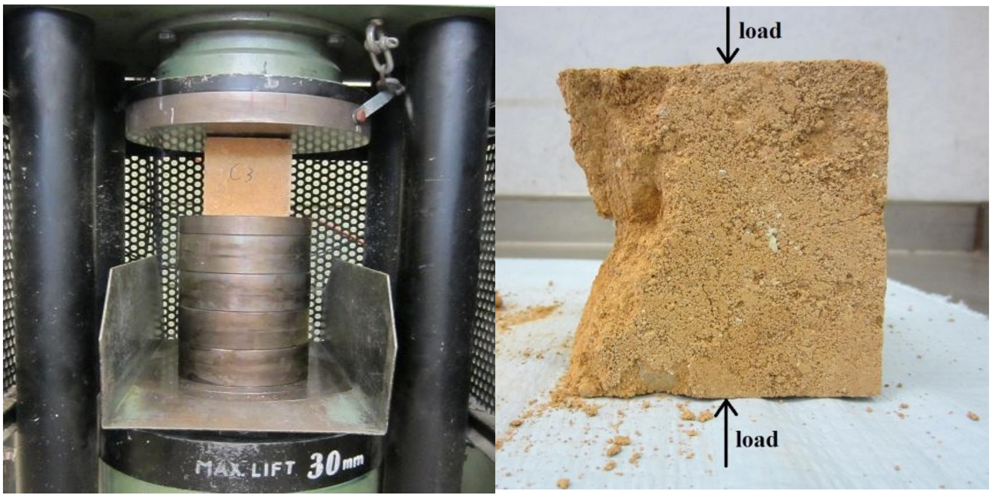


Figure 4 Compression test setup and typical failure pattern of cubic specimens

The six molded cubic specimens (MC) were tested at two different ages, MC1-MC3 were tested 52 days after casting, while MC4-MC6 were tested two weeks later (i.e., 66 days). Consequently, MC4-MC6 had lower average moisture content than MC1-MC3, however, according to a T-test (GraphPad Software), there was no statistically significant difference between the compressive strength of these two groups of specimens, so that the six specimens were treated as if they shared identical material properties.

Test results for molded cubic specimens and cut cubic specimens from solid wall are given in Table 3 where it can be seen that the six molded cubic specimens had an average compressive strength of 9.75MPa, and the four cubic specimens cut from the solid wall had a similar average compressive strength of 10.24MPa. The average dry density of the molded and cut cubic specimens was very similar to each other (1897.85kg/m^3 versus 1894.96kg/m^3). The slightly higher compressive strength recorded by the specimen from the wall can be explained by the fact that the cut cubic specimens contained less moisture than the molded cubic specimens (2.86% versus 4.72%).

Table 3 Compressive strength of molded cubic specimens and cut cubic specimens from solid wall

MC	*DD (kg/m^3)	*MC (%)	*f_c (MPa)	CCS	*DD (kg/m^3)	*MC (%)	*f_c (MPa)
MC1	1887.35	6.05	8.66	CCS 1	1876.75	2.91	11.78
MC2	1894.96	5.46	9.18	CCS 2	1900.65	2.87	9.34
MC3	1929.65	5.50	9.96	CCS 3	1922.76	3.01	9.98
MC4	1865.73	3.55	8.96	CCS 4	1879.66	2.64	9.84
MC5	1915.85	3.97	9.72	-----	-----	-----	-----
MC6	1893.57	3.81	12.02	-----	-----	-----	-----
Mean	1897.85	4.72	9.75		1894.96	2.86	10.24
St.Dev.	22.38	1.07	1.21		21.55	0.16	1.07
CoV	0.01	0.23	0.12		0.01	0.06	0.10

* DD, MC and f_c stand for dry density, moisture content and compressive strength, respectively.

The results for cut cubic specimens from cavity wall are reported in Table 4. It is clear that the dry density and moisture content of cut cubes from cavity wall were similar to those of cubes cut from solid wall; however, the average compressive strength of the cavity wall material was only 77.4% of that for solid wall material, which may be due to the fact that they were made from different batch of materials.

Table 4 Compressive strength of cut cubic specimens from cavity wall

Specimens	DD (kg/m^3)	MC (%)	f_c (MPa)
CCC 1	1781.44	2.85	7.98
CCC 2	1836.32	2.81	8.92
CCC 3	1885.57	2.80	7.54
CCC 4	1832.83	2.61	7.29
Mean	1834.04	2.77	7.93
St.Dev.	42.54	0.11	0.72
CoV	0.02	0.04	0.09

4.1.2. Cylindrical specimens

Both 100mm diameter molded cylindrical specimens and 60mm diameter cylindrical specimens cored from the wall were tested to determine their compressive strength. The size of the cored cylinders was smaller than the size of the molded ones due to the restriction of the drilling equipment, while the slenderness ratio of both types of specimens was kept at approximately 2. Before testing, each specimen was capped with dental plaster at top and bottom to achieve uniform stress distribution. The test setup is shown in Figure 5.

Figure 5 Test setup for compression test of molded cylindrical specimens

To determine the Young’s modulus, each cylinder specimen was first subjected to compression under load control at a rate of 40kN/min and stopped when the load reaches about 40% of the maximum load the specimen can resist. The maximum load was predicted from the compression test of the cube specimens. This loading process was repeated three times and then the load was changed to displacement control at a rate of 0.1mm/min until the specimen failed to determine the ultimate compressive strength and entire stress-strain relationship.

For the first two molded cylinders, two Linear Variable Differential Transformers (LVDTs) and two train gauges (20mm long) were used to obtain the strain value. The LVDTs recorded the shortened height of the whole specimen; the strain gauges were pasted at the middle part of the specimen. The data obtained from the strain gauges were mainly used to determine the Young’s modulus while the data obtained from the LVDTs were mainly used to determine the entire stress-strain relationship.

It was found that the strains recorded by LVDTs differed significantly from the strain recorded by the strain gauges. It was suspected that the Young’s modulus along the height of the specimen was not constant. Thus, for the following tests of the cylinders, six train gauges (three on each side) were used to record the strains at different part of the specimens. The size of the cylinders cored from the cavity wall was similar to the size of the molded specimens; however, the size of cylinders cored from solid wall was smaller due to the difficulty of operation. Thus the maximum load that the small specimens could resist would be much smaller; therefore, in order to avoid sudden crack damage, the loading rate for the small specimens was reduced to 10kN/min under load control and 0.05mm/min under displacement control respectively. Each specimen normally failed by crushing, some at the bottom, while most crushed at the middle, after which vertical or diagonal cracking developed from the crushed point towards the top and bottom of the specimen as shown in Figure 6.

(a) Hourglass shape failure

(b) Diagonal cracking with no cracking through ends

(c) Diagonal cracking with cracking through ends

(d) vertical cracking with no cracking through ends

Figure 6 Typical failure patterns of cylindrical specimens

A. Compressive strength

The compressive strength of molded cylinders and cylinders cored from solid RE wall (these two types of specimens were made from the same batch of material) is presented in Table 5, where it can be seen that the average compressive strength of the molded cylindrical specimens was 7.82MPa, which was 75% of the average compressive strength attained by the cylindrical specimen cored from the tested wall. The dry density and moisture content of these two types of specimens were close to each other. Therefore, the difference between the compressive strength of the molded cylinders and those cored from the solid wall can be attributed to the fact that the loading rate for the molded cylindrical specimens was faster than that for cylindrical specimens from the wall, which may have caused unexpected damage to the molded specimens before peak stress was reached.

Table 5 Compressive strength of molded cylindrical specimens and specimens cored form the solid wall

Specimen *MCy	DD (kg/m^3)	MC (%)	f_c (MPa)	Specimen *CCy	DD (kg/m^3)	MC (%)	f_c (MPa)
MCy1	1814.49	1.63	6.32	CCy1	1801.30	2.56	12.29
MCy2	1836.98	2.09	9.29	CCy2	1824.52	2.26	10.12
MCy3	1810.19	2.27	7.86	CCy3	1766.47	2.17	8.85
Mean	1820.55	2.00	7.82		1797.43	2.33	10.42
St. Dev.	14.39	0.33	1.49		29.22	0.20	1.74
CoV	0.01	0.17	0.19		0.02	0.09	0.17

*Specimen MCy and CCyS stand for molded cylindrical specimen and cored cylindrical specimen from solid wall, respectively.

The results for cut cylindrical specimens cored from the cavity wall are reported in Table 6. It is clear that the dry density and moisture content of cut cylinders from the cavity wall were similar to those of cylinders cut from the solid wall, leading to similar compressive strengths. This agreement in compressive strength does not agree with the result observed from cut cubic specimens, which showed that the cut cubes from the solid wall had a 23% stronger compressive strength than cubes cut from the cavity wall. This may reflect the nature of RE material which can vary significantly from one part of a wall to another.

Table 6 Compressive strength of cylindrical specimens cored form the cavity wall

Specimens	DD (kg/m^3)	MC (%)	f_c (MPa)
CCyC 1	1877.64	2.55	10.75
CCyC 2	1876.14	2.76	10.36
CCyC 3	1872.70	2.73	11.50
Mean	1875.49	2.68	10.87
St.Dev.	2.53	0.11	0.58
CoV	0.00	0.04	0.05

Meeting compressive strength design requirements in Australia

Assuming that the compressive stress applied to external walls is approximately 0.1MPa for single storey houses (Jayasinghe and Kamaladasa, 2007), the required characteristic compressive strength is 0.5MPa for walls with a slenderness ratio less than 18 (Standards Australia, 2001) (see subsection 2.4.1). The characteristic compressive strength of RE material tested in this study was calculated using the equation (Standards Australia, 2001):

$$f_c' = f_c - 1.65 \times St.Dev. \qquad \text{Eq1}$$

where f_c= the mean compressive strength and $St.Dev.$ = standard deviation of the test results.

The results are summarised in Table 7, where it can be seen that local RE material had adequate characteristic compressive strength to meet the design strength requirement in Australia for single storey houses, and even for two storey houses.

The minimum thickness and maximum slenderness ratio required in the *Australian earth building handbook* are 200mm and 18 (Walker and Standards Australia, 2002), respectively. These requirements seem to be too conservative. For thinner RE walls with greater slenderness ratios, for example, 100mm thick and 3.0m tall (corresponding to a slenderness ratio of 30 and consequently a reduction factor of 0.18), the minimum required characteristic compressive strength is 1.2MPa, which is still much smaller than the value derived from experimental tests.

Table 7 Characteristic compressive strength of RE

Specimen type	f_c (MPa)	*St.Dev.* (MPa)	f_c' (MPa)
MC	9.75	1.21	7.75
MCy	7.82	1.49	5.36
CCS	10.24	1.07	8.45
CCyS	10.42	1.74	7.55
CCC	7.93	0.72	6.74
CCyC	10.87	0.58	9.91

For cavity walls, each wall leaf should be assessed separately and individually; in addition the loaded wall leaf of a cavity wall should not be thinner than 100mm and the total thickness of two leaves should not less than 200mm (Standards Australia, 2001). Thus single storey houses (less than 3.0m tall) constructed using ICRE walls with two 100mm thick RE leaves can meet the structural design requirements in Australia.

B. Young's modulus

The Young's modulus was determined from the initial linear part of the stress-strain relationships. At the beginning, most of the relationships were not linear, which may due to the fact that the top or bottom surface of the specimens was not perfectly even. Therefore, the beginning part, when the corresponding stress was between 0 to 0.5MPa, was the cut off for determining the Young's modulus. Since the specimens were loaded up to the point of failure, the real ultimate strength was determined. For some specimens, the real ultimate strength was a little smaller than the predicted ultimate strength, thus the range of data was adjusted to between 0.5Mpa and 40% of real ultimate strength to determine the Young's modulus.

For each part (top, middle and bottom) of each specimen, three sets of data were recorded because the specimens were loaded three times, but the data from the first loading process were not used to determine the Young's modulus. The Young's modulus of each part was determined as the mean of the two values recorded during the last two loading processes. The Young's modulus of each specimen was determined as the mean of Young's modulus of the three parts. The Young's modulus derived from data recorded by the strain gauges and LVDTs are reported in Table 8 and Table 9, respectively.

Table 8 Young's modulus derived from data of strain gauges

Specimen type	MC (%)	DD (kg/m^3)	E (MPa) part		Mean
MCy1	2.1	1837.0	Middle	5950.1	5950.1
MCy2	1.6	1814.5	Middle	7090.1	7090.1
MCy3	2.3	1810.2	Top	8629.5	6085.1
			Middle	6817.4	
			Bottom	2808.4	
	Mean (MPa)				6375.1
	St. Dev. (MPa)				622.9
	CoV				0.10
CCyS1	2.6	1801.3	Top	5962.2	6574.4
			Middle	7723.5	
			Bottom	6037.6	
CCyS2	2.3	1824.5	Top	3680.2	3238.7
			Middle	3275.3	
			Bottom	2760.7	
CCyS3	2.2	1766.5	Top	6596.0	5004.5
			Middle	4553.0	
			Bottom	3864.6	
	Mean (MPa)				4939.2
	St. Dev. (MPa)				1668.8
	CoV				0.34
CCyC1	2.5	1877.6	Top	7190.9	6166.2
			Middle	4504.4	
			Bottom	6803.3	
CCyC2	2.8	1876.1	Top	5871.5	5678.6
			Middle	3979.8	
			Bottom	7184.5	
CCyC3	2.7	1872.7	Top	7094.2	6517.6
			Middle	4243.3	
			Bottom	8215.3	
	Mean (MPa)				6120.8
	St. Dev. (MPa)				421.3
	CoV				0.07

It is indicated from data in Table 8 that the Young's modulus of different parts of the specimens varied significantly due to the construction technique of specimens which caused different densities along the height. There were roughly two parts to each ramming layer, a dense part and a loose part. The Young's modulus of the dense part can be two to three times the Young's modulus of the loose part according to the data given in Table 8. The cored specimens usually had ramming layers about 120-140mm in height; however, the molded specimens usually have much shorter ramming layers as the height of the molds was only 200mm, and each specimen consisted of several layers.

Therefore, it is hard to obtain a representative Young's modulus for structural analysis from molded specimens. The cored specimens from the solid wall were cored from the middle part of a wall and only around 100mm in height, but a ramming layer was around 120-140mm in height. It is therefore reasonable to conclude that most of the specimens were cored from a denser part of a ramming layer or a looser part of a layer. This situation could explain why the Young's modulus of specimen CCyS2 was much smaller than that of the others. This result suggests that when determining the Young's modulus of rammed earth, the cored specimens which consist of a whole ramming layer are the most representative ones.

Table 9 Young's modulus derived from data of LVDTs

Specimen type	E (MPa)	Mean (MPa)	St. Dev. (MPa)	CoV
MCy1	2771.9	2955.3	161.2	0.05
MCy2	3019.1			
MCy3	3074.8			
CCyS1	3033.7	2557.0	506.6	0.20
CCyS2	2025.0			
CCyS3	2612.1			
CCyC1	4093.4	4198.9	293.2	0.07
CCyC2	3973.1			
CCyC3	4530.2			

Comparison was made between the test results from strain gauges and LVDTs. From Tables 8 and 9, it can be seen that the Young's modulus derived from LVDTs were smaller than those derived from strain gauges. This may be due to the fact that some strain gauges were pasted on some big aggregates which had much larger Young's modulus than the average Young's modulus of specimen. It can be seen from Table 8 that the specimens cored from the cavity wall are much larger than those of specimens cored from the solid wall, indicating that they are made from different batches of material.

C. Stress-strain relationship

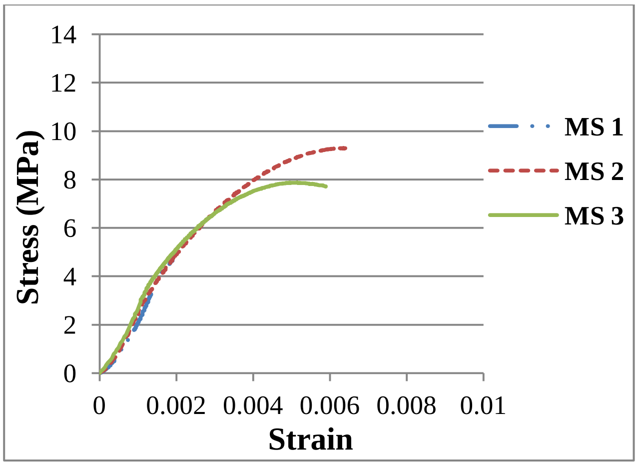
For molded cylinder specimens, the strain value was derived from the displacement of platens recorded by two LVDTs. For the three cored specimens (cored from the failed cavity wall), the LVDTs were attached to the middle part of the specimens in order to obtain the representative strain value of the middle 120mm of the specimen (which is about the height of a ramming layer). For the other three cored specimens (cored from the failed solid wall), the height was less than the height of a ramming layer. This was impossible to obtain a representative strain value of a whole ramming layer. The strain was derived from the displacement of platens recorded by the machine automatically.

It is always difficult to determine the stress-strain relationship using uniaxial compression tests, especially the part after peak load, as it is difficult to obtain reliable strain data when the specimen is crushed. The data recorded from the two LVDTs always differed significantly (in particular when the applied load exceeded the peak load) due to the unexpected bending or crushing of specimens, which put part of the specimens under a lower level of compression, invalidating the recording of LVDTs.

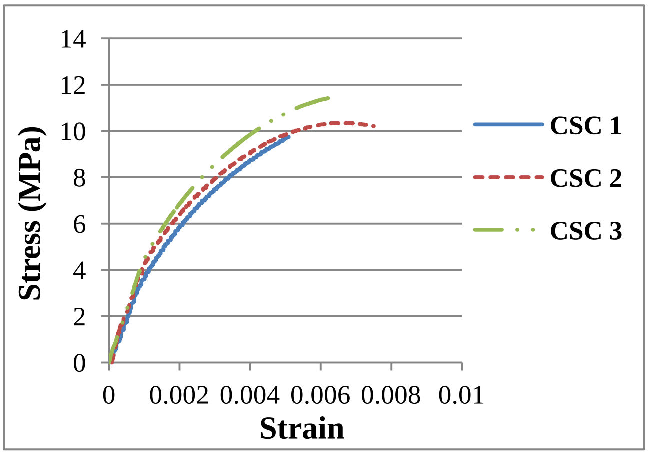
For most of the tests, the data recorded from the two LVDTs differ significantly at the beginning, which may due to the fact that the top or bottom surface of the specimen was not smooth, the crushing of small particles might result in the considerable difference of the two LVDT readings. This difference reduced gradually as the applied loading increased up to the peak load, and then the difference started to increase until the end of the test. For molded specimens, the stress-strain curve stopped once the reading from each LVDT departed more than 20% from the average of the two readings. For the specimens cored from the failed cavity wall, this difference was always a little over 20%; thus this percentage was increased to 25%, otherwise, the stress-strain curve would stop at a very small applied stress.

For specimens cored from the failed solid wall, since only platen displacement was recorded, the stress-strain curve stopped once one of the strain gauges readings started to decrease, which meant that part of the specimen was crushed and the strain reading became unreliable. The stress-strain relationships of each type of specimens are shown in Figure 7.

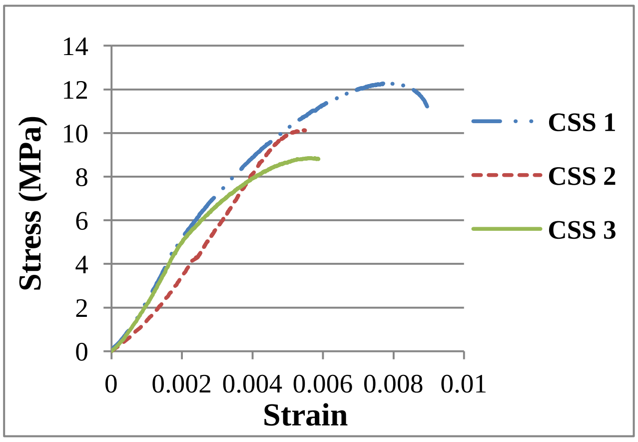
It can be seen from Figure 7 that the stress-strain curves are linear at the beginning and then become non-linear until reaching ultimate stress. Most of the curves stopped once the peak stress was reached. The shape of the curves is similar but the peak stress varies considerably for all three types of specimens. For molded specimens and specimens cored from the cavity wall, the initial part of the three stress-strain curves almost overlap, which means the Young's modulus of the specimens are similar. For cored specimens from a solid wall, the initial part of one stress-strain curve differs markedly from the other two curves, which means the Young's modulus of these specimens differs significantly as well. In general, the strain at peak stress is in the range of 0.005-0.008 for all the specimens.



(a) Stress-strain relationship of molded specimens



(b) Stress-strain relationship of cored specimens from cavity wall



(c) Stress-strain relationship of cored specimens from solid wall

Figure 7 Stress-strain relationships

4. 2 Four-point bending tests

Four-point bending tests were conducted to determine the flexural tensile strength of the molded beam specimens. The test set up is the same to that used for testing cut beams taken from full-scale walls (see Chapter 4, subsection 4.1.2). The test results of molded beams are shown in Table 10 where it can be seen that the first group of molded beams (MB) MB1-MB3 (tested 52 days after casting) had a mean flexural tensile strength of 1.65MPa, and the second group of molded beams MB4-MB6 (tested 66 days after casting) had a mean flexural tensile strength of 1.89MPa. Taken together, the six molded beam specimens recorded an average flexural tensile strength of 1.77MPa.

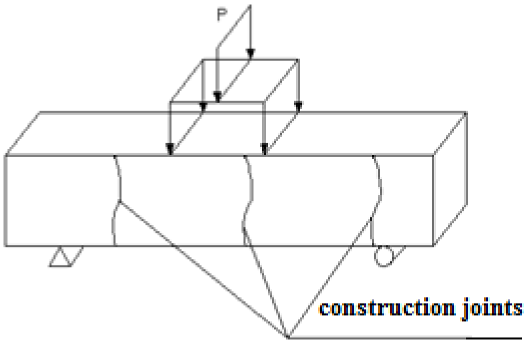
The two groups of molded specimens were made from the same batch of material and their average dry density was very close to one another (1836.67kg/m3 versus 1833.09kg/m3), thus the only factor that could influence the difference in flexural tensile strength was moisture content. It can be seen that specimens MB4-MB6 (with average moisture content of 6.61%) had a slightly smaller average flexural tensile strength than specimens MB1-MB3 (with average moisture content of 4.91%), suggesting that lower moisture content increases the flexural tensile strength.

Table 10 Flexural tensile strength of molded beam specimens

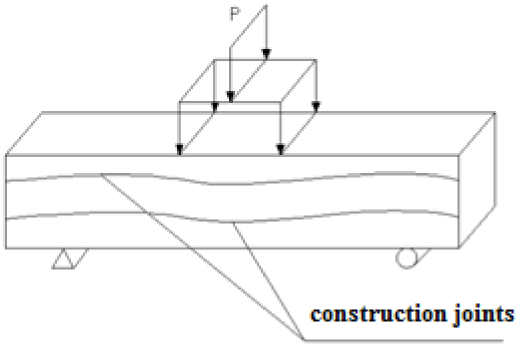
Specimen	*DD (kg/m^3)	*MC (%)	*f_t (MPa)
MB1	1805.04	6.04	1.66
MB2	1851.48	6.78	1.63
MB3	1853.50	7.01	1.65
Mean	1836.68	6.61	1.65
St.Dev.	27.41	0.51	0.02
CoV	0.01	0.08	0.01
MB4	1883.23	5.22	1.87
MB5	1789.53	4.86	1.89
MB6	1826.50	4.65	1.92
Mean	1833.09	4.91	1.89
St.Dev.	47.20	0.29	0.02
CoV	0.03	0.06	0.01

The flexural tensile strength of beams cut from the solid wall (reported in Chapter 4, subsection 4.1.2) is 0.85MPa with average moisture content of 3.50% and average dry density of 1896.58kg/m^3. Cut beams from the solid wall and molded beams were made from the same batch of material and they had similar moisture content and dry density. The average flexural strength of the molded specimens was over twice the value of the average flexural tensile strength of the cut beam specimens.

The significant difference in flexural tensile strength between the molded beam specimens and the full-scale wall/cut beam specimens was due to the fact that the loading direction for the wall and the specimens cut from the wall both initiated tensile stresses perpendicular to the construction joints (see Figure 10), which appear to create weak points in terms of tensile strength. The molded specimens, on the other hand, did not have any comparable construction joints. Furthermore, this result is consistent with the study of Jayasinghe and Mallawaarachchi (2009), who reported that the flexural strength of a RE panel with construction joints parallel to the flexural tensile stress was approximately twice the value for that of a RE panel with construction joints perpendicular to the flexural tensile stress.



(a) Cut specimens



(b) Molded specimens

Figure 10 Relationships between directions of load and ramming lines

References

Jayasinghe, C., and Kamaladasa, N. (2007). "Compressive strength characteristics of cement stabilized rammed earth walls." *Construction and Building Materials*, 21(11), 1971-1976.

Jayasinghe, C., and Mallawaarachchi, R. (2009). "Flexural strength of compressed stabilized earth masonry materials." *Materials & Design*, 30(9), 3859-3868.

Standards Australia (2001). "AS 3700-2001: Masonry Structures." Standards Australia, Sydney, Australia.

Walker, P., and Standards Australia (2002). "The Australian Earth Building Handbook." Standards Australia, Sydney, Australia

Appendix B: The Batch Files Code

(The code is written in Matlab.)

```
-----------------------------------------------------------------------------------------
function runall
%
paths=====================================================
template_file_path = 'D:\Data\AccuRate\modelling_results\other climate zones\5 adelaide 16\50% openable\adelaide cavity wall single glazed 0 eaves\batchrun\SCRATCH'; % the template file
target_file = 'C:\Users\xdong\AppData\Local\VirtualStore\Program Files (x86)\AccuRate\SCRATCH';
out_file_path = 'C:\Users\xdong\AppData\Local\VirtualStore\Program Files (x86)\AccuRate\output.txt';                    % the result file generated by running data once
result_file_path = 'D:\Data\AccuRate\modelling_results\'; % the results of multiple runs

mkdir(result_file_path)
%
% variables
load('window_width.mat');
load('wall_thickness.mat');
load('my_initial.mat');
% keywords
keywords_in2 = '2N 21EXTERNAL WALL: Rammed earth';
keywords_in1 = 'C              Height Width AzimHSSch1HSSch2VShSchScSch1ScSch2ScSch3 Curtn Blind';
keywords_in3 = 'C        No. Width        Cd    Perc      Low    HighCpIndx Type ExponAdjZonConTyp MidHtContrlLouvre';
keywords_in4 = 'C    Data type 2: Construction data';
keywords_in5 = 'C Walls';
```

```
%
=====================================================
for i = 1:size(thickness,1)
    file_name =
sprintf('%s%d_%d_%d.txt',result_file_path,thickness(i,1),thickness(i,2),thickn
ess(i,3));
    out_file = fopen(file_name,'w');
    for j = 1:size(width,1)
        new_data.width = width(j,:);
        new_data.thickness = thickness(i,:);
        % update file

carve_template_file(template_file_path,target_file,keywords_in1,keywords_in
2,keywords_in3,...
            keywords_in4,keywords_in5,new_data);
        % run on the updated file
        cd 'C:\Program Files (x86)\AccuRate';
        system('accurateengine');
        % output results
        source_file = fopen(out_file_path,'r');
        flag = 0;
        while ~feof(source_file)
            line = fgetl(source_file);
            if ~isempty(line)
                parsed = textscan(line,'%s %s %s',1);
                if strcmp(cell2mat(parsed{3}),'ENTIRE')
                    flag = 1;
                elseif flag == 1
                    parsed = textscan(line,'%s',1);
                    switch cell2mat(parsed{1})
                        case 'HEATING'
                            parsed =
textscan(line,'%s %s %s %s %s %f',1);
```

```
                            heat_eng = parsed{6};
                        case 'SENSIBLE'
                            parsed =
textscan(line,'%s %s %s %s %s %s %f',1);
                            sen_cool_eng = parsed{7};
                        case 'LATENT'
                            parsed =
textscan(line,'%s %s %s %s %s %s %f',1);
                            lat_cool_eng = parsed{7};
                        otherwise
                    end
                end
            end
        end
        temp_eng = sen_cool_eng + lat_cool_eng;
        fprintf(out_file,'%d\t%d\t%d\t%d\t%d\t%f\t%.2f\t%.2f\t%.2f\r\n', ...

j,my_initial(j,1),my_initial(j,2),my_initial(j,3),my_initial(j,4),my_initial(j,5),h
eat_eng/96,temp_eng/96,(temp_eng+heat_eng)/96);
        fclose(source_file);
    end
    fclose(out_file);
end
%++++++++++++++++++++++++++++++++++++++++++++++++++
% keyword_in1: the width
% keyword_in2: the thickness
function carve_template_file(template_file_path,target_file,keywords_in1, ...
    keywords_in2,keywords_in3,keywords_in4,keywords_in5,new_data)
file = fopen(template_file_path,'r');
file_temp = fopen(target_file,'w');
factor = 0.375;
while ~feof(file)
    line = fgetl(file);
```

```
    ans1 = strfind(line,keywords_in1);
    ans2 = strfind(line,keywords_in2);
    ans3 = strfind(line,keywords_in3);
    ans4 = strfind(line,keywords_in4);
    ans5 = strfind(line,keywords_in5);
    if ~isempty(ans1)
        fprintf(file_temp,'%s\r\n',line);
        fgetl(file);
        fgetl(file);
        fgetl(file);
        fgetl(file);
        new_line = sprintf(' 3    1    1    1.50%6.2f      %3d          2          0
0          0          0          0          6          0', ...
            new_data.width(1), 0);
        fprintf(file_temp,'%s\r\n',new_line);
        new_line = sprintf(' 3    1    1    1.50%6.2f      %3d          4          0
0          0          0          0          6          0', ...
            new_data.width(2), 90);
        fprintf(file_temp,'%s\r\n',new_line);
        new_line = sprintf(' 3    1    1    1.50%6.2f      %3d          6          0
0          0          0          0          6          0', ...
            new_data.width(3), 180);
        fprintf(file_temp,'%s\r\n',new_line);
        new_line = sprintf(' 3    1    1    1.50%6.2f      %3d          8          0
0          0          0          0          6          0', ...
            new_data.width(4), 270);
        fprintf(file_temp,'%s\r\n',new_line);
    elseif ~isempty(ans2)
        new_line = sprintf(' 2N 21EXTERNAL WALL: Rammed
earth %d+%d+%d    Area:    108.0', ...
            new_data.thickness);
        fprintf(file_temp,'%s\r\n',new_line);
        fgetl(file);
```

```
        new_line = sprintf(' 2 21       37 %d236    %d
37 %d',new_data.thickness);
        fprintf(file_temp,'%s\r\n',new_line);
    elseif ~isempty(ans3)
        fprintf(file_temp,'%s\r\n',line);
        fgetl(file);
        fgetl(file);
        fgetl(file);
        fgetl(file);
        new_line = sprintf(' 3    1301    %.2f      0.6       85    1.00    2.50
1        1     0.5         0         0', ...
            new_data.width(1)*factor);
        fprintf(file_temp,'%s\r\n', new_line);
        new_line = sprintf(' 3    1302    %.2f      0.6       85    1.00    2.50
2        1     0.5         0         0', ...
            new_data.width(2)*factor);
        fprintf(file_temp,'%s\r\n', new_line);
        new_line = sprintf(' 3    1303    %.2f      0.6       85    1.00    2.50
3        1     0.5         0         0', ...
            new_data.width(3)*factor);
        fprintf(file_temp,'%s\r\n', new_line);
        new_line = sprintf(' 3    1304    %.2f      0.6       85    1.00    2.50
4        1     0.5         0         0', ...
            new_data.width(4)*factor);
        fprintf(file_temp,'%s\r\n', new_line);
    elseif ~isempty(ans4)
        fprintf(file_temp,'%s\r\n',line);
        line = fgetl(file);
        fprintf(file_temp,'%s\r\n',line);
        line = fgetl(file);
        fprintf(file_temp,'%s\r\n',line);
        line = fgetl(file);
        fprintf(file_temp,'%s\r\n',line);
```

```
            fgetl(file);
            area =    sum(new_data.width)*1.5;
            new_line = sprintf(' 2N    1WINDOW: Generic 03: Timber/uPVC
single-glazed: clear glass: U = 5.75: SHGC = 0.69    Area:      %.1f',area);
            fprintf(file_temp,'%s\r\n',new_line);
      elseif ~isempty(ans5)
            fprintf(file_temp,'%s\r\n',line);
            line = fgetl(file);
            fprintf(file_temp,'%s\r\n',line);
            line = fgetl(file);
            parsed = textscan(line,'%d %d %d %f %f',1);
            narea = prod(cell2mat(parsed(4:5)))-new_data.width(1)*1.5;
            new_line = sprintf(' 3    1 21    2.70 12.00 %.2f         0    0.50    0.50
1.00         1          0          0          0         0\r\n', ...
                  narea);
            fprintf(file_temp,new_line);
            line = fgetl(file);
            parsed = textscan(line,'%d %d %d %f %f',1);
            narea = prod(cell2mat(parsed(4:5)))-new_data.width(2)*1.5;
            new_line = sprintf(' 3    1 21    2.70    8.00 %.2f        90    0.50
0.50    1.00         3          0          0          0         0\r\n', ...
                  narea);
            fprintf(file_temp,new_line);
            line = fgetl(file);
            parsed = textscan(line,'%d %d %d %f %f',1);
            narea = prod(cell2mat(parsed(4:5)))-new_data.width(3)*1.5;
            new_line = sprintf(' 3    1 21    2.70 12.00 %.2f      180    0.50    0.50
1.00         5          0          0          0         0\r\n', ...
                  narea);
            fprintf(file_temp,new_line);
            line = fgetl(file);
            parsed = textscan(line,'%d %d %d %f %f',1);
            narea = prod(cell2mat(parsed(4:5)))-new_data.width(4)*1.5;
```

```
        new_line = sprintf(' 3    1 21    2.70    8.00 %.2f      270    0.50
0.50    1.00          7          0          0          0          0\r\n', ...
            narea);
        fprintf(file_temp,new_line);
    else
        fprintf(file_temp,'%s\r\n',line);
    end
end
fclose(file);
fclose(file_temp);
```

Appendix C: Published Papers

List of published papers:

1. X. Dong, V. Soebarto, M. Griffith, Strategies for reducing heating and cooling loads of uninsulated rammed earth wall houses, Energy and Buildings, 77 (2014) 323-331.

2. X. Dong, V. Soebarto, M. Griffith, Achieving thermal comfort in naturally ventilated rammed earth houses, Building and Environment, 82 (2014) 588-598.

3. X. Dong, V. Soebarto, M. Griffith, Design optimization of insulated cavity rammed earth walls for houses in Australia, Energy and Building, 86 (2015) 852-863.

Dong, X., Soebarto, V. & Griffith,M. (2014). Strategies for reducing heating and cooling loads of uninsulated rammed earth wall houses,
Energy and Buildings, *v. 77, pp. 323-331*

Dong, X., Soebarto, V. & Griffith,M. (2014). Achieving thermal comfort in naturally ventilated rammed earth houses.
Building and Environment, v. 82 , pp. 588-598.

Dong, X., Soebarto, V. & Griffith,M. (2015). Design optimization of insulated cavity rammed earth walls for houses in Australia.
Energy and Buildings, v. 86, pp. 852-863.