ANALYSIS OF INDOOR PERFORMANCE OF HOUSES USING RAMMED EARTH WALLS

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ABSTRACT

This paper presents results of a study to investigate the thermal performance of two existing houses that use rammed earth as the sole wall material and compare it with the performance of a house using insulated rammed earth walls. Indoor temperatures of the houses were hourly monitored and the monitored data were used to calibrate the simulation models. The results show that in summer, the uninsulated rammed earth houses have similar performance to the insulated rammed earth house; however, without using any heater, the uninsulated houses could be cooler as much as 5 degrees hence potentially would use more energy.

INTRODUCTION

Rammed earth, along with other alternative materials such as mud bricks and straw bales, are often promoted as 'sustainable' building materials. One aspect that makes these materials perceived to be 'sustainable' is their embodied energy. If made locally, the embodied energy of rammed earth and mud brick is estimated to be around 0.7 MJ/kg, less than 30% of the embodied energy of clay bricks (2.5 MJ/kg) and less than 20% of the embodied energy of lightweight aerated concrete blocks (3.6 MJ/kg) (Lawson 1996). On the other hand, the thermal performance of these materials is often overly stated in many publications. A few searches in the internet reveal few misleading information about the thermal performance of rammed earth walls. For example, rammed earth walls are claimed as having "superior insulation", providing "excellent protection from extremes in climate" due to their hefty thickness (Rammed Earth Construction 2009), thus lowering heating and cooling needs (Austin Green Building Program 2009).

Rammed earth walls indeed have high thermal mass. According to the Australian Institute of Refrigeration, Air Conditioning and Heating the conductivity of 250 mm thick of rammed earth wall with a density of 1540 kg/m3 and specific heat of 1260 J/kg.K is 1.25 W/m.K (AIRAH 2000). Concrete with a density of 2240 kg/m3 will have similar conductivity (which is 1.3 W/m/K or more depending on the quartz or quartzite sand content) however the specific heat would be between 800 to 1000 J/kg.K (ASHRAE 1997a). This means rammed earth can contain or absorb more heat than concrete does even though it is less dense.

When used internally and exposed to heat source including direct and indirect solar radiation, rammed earth walls absorb and store the heat and release it when the surrounding temperature drops below the walls' temperature. When used as external walls, thick rammed earth walls provide a long thermal time lag, thus slowing down the heat transfer between the inside and outside. As a result, the internal temperature in summer will likely to be lower than the outside during the day and the peak of the internal temperature will occur several hours after the peak outside temperature occurs. This characteristic is what makes many people think that rammed earth walls will also have high insulation values.

To provide information that is more accurate the Commonwealth Science and Industry Research Organisation (CSIRO) in Australia already conducted a laboratory test on rammed earth walls in 2000. The result reveals that the overall thermal resistance of rammed earth is 0.4 $m^2.^{\circ}K/W$ (CSIRO 2000). This is comparable with the overall thermal resistance of 220 mm bricks with density of 1280 kg/m3, of 200 mm concrete blocks with density of 2210 kg/m3 and slightly better than the resistance of 250 mm concrete walls with density of 2240 kg/m3 (which is only 0.2 $m^2.^{\circ}K/W$ (ASHRAE 1997a), but obviously worse than the resistance of any insulating materials. The MABEL team from Deakin University conducted a study on the thermal performance of an unoccupied mud brick house, a material with similar thermal properties as rammed earth, and found that the "mud bricks suffers a constant heat loss" (MABEL 2005). Using the data from this study, Delsante (2006) validated the prediction of the thermal behaviour (i.e. thermal resistance, density and thickness) of mud bricks as well as the energy calculation for mud brick buildings in the simulation program AccuRate (Delsante 2005). The study confirmed AccuRate prediction, which showed that the internal temperature of a mud brick house in winter without heating could be as low as 12.6°C when the outdoor temperature was 3°C. This result showed a good agreement with measured data of 12.2°C (Delsante 2006).

Based on the thermal resistance, density and thickness, one can expect that using rammed earth walls will indeed result in good performance in summer (Delsante 2006). However, Delsante argued that such walls would have poor to moderate winter performance. In winter, the thermal time lag effect of the rammed earth walls will also slow down solar heat gains through the walls. Unless the house has good solar orientation and sufficient sun-facing glazed windows as well as some space heating, using only rammed earth as external walls may not be as good as claimed or perceived. Even if the walls absorb solar and internal heat during the day, without any insulating material externally, the rammed earth walls will also lose the stored heat at nighttime.

The main purpose of the work presented in this paper is to provide more data on the thermal performance of houses using rammed earth as the sole wall material in both summer and winter based on simulation supported by monitored data. The performance of the rammed earth houses are also compared to that of a house, which also uses rammed earth however it is insulated externally. The latter is often called 'reverse masonry veneer' construction. This is not a typical construction in the area (the typical house construction is masonry or brick veneer); however it was chosen as a comparison to see whether insulating the rammed earth walls externally would have a significant effect on the indoor environment of a rammed earth house.

METHODOLOGY

Two occupied rammed earth houses were selected for the study, as there was no unoccupied house available. These two were chosen due to their close proximity to each other and similarity in size; however, they do have different floor plans. One has a typical 'solar house' plan. It is rectangular in its floor plan with the main spaces and openings facing the sun which is on the north side (as the location is in the southern hemisphere), and the other one is slightly square although the main spaces and openings are also facing the sun. The intention of choosing houses with different floor plans was to see whether the effect of using rammed earth walls would be similar regardless of the floor plan. The third house is larger, but it was selected as it was the only one in the area that is insulated externally and has the main spaces facing the sun. Despite the differences, the focus of the study is the living room and one bedroom on the south side of each house, and they are all comparable in size.

The houses were modelled using an hourly thermal simulation program, ENERWIN©, specifically ENERWIN-EC (Degelman 2007). Features of this program have been discussed in previous publications (Degelman and Soebarto 1995, Soebarto and Degelman 1998, Degelman 1991, 1970). As these are existing houses, hourly monitored data of the internal temperatures of the living room and bedroom were used to calibrate the simulation model to ensure that the model represented the actual house within an acceptable discrepancy. The occupants of the houses were also interviewed to gather information on occupancy or house use patterns.

First, the houses were modelled as is and the results in terms of the internal temperatures were examined. Subsequently a wall insulation and external cladding were added to the external walls of the first two houses so that their wall construction was similar to that of the third house, and the "new" performance of these houses were examined and compared to the original ones. With the same idea, the wall insulation and external cladding of the third house were removed in the subsequent simulation to see how the house would perform had it only had rammed earth for its external walls.

As these are existing houses, recorded hourly weather data were embedded into the simulation program. However, due to the budget constraint of the project, only hourly external temperature and humidity were measured. Data on wind speed and direction as well as solar radiation were obtained from the Bureau of Meteorology for a nearby site.

HOUSE DETAILS

The houses are located in Willunga, about 50 km south of Adelaide in South Australia (35°16'SL, 138°55' EL, 258 m altitude). The mean minimum temperature in summer, which is December to February, is 11°C while the mean maximum is 25°C with 41°C as the highest temperature. In winter (June to August), the mean minimum temperature is 4.5°C, mean maximum is 13.4°C, and occasionally the temperature goes below 0°C and reaches -5°C. Relative humidity ranges from 44 to 60% in summer and 70 to 85% in winter. Mean daily solar radiation ranges from 7.3 MJ/m^2 in winter to 26 MJ/m^2 in summer (Bureau of Meteorology 2008).

The first house is 104 m^2 and was occupied by one to two people during the monitoring period particularly at night times and on weekends. External walls are constructed of 220 mm rammed earth blocks while all internal walls are of 110 mm rammed earth bricks. The floor is polished concrete and the roof is clad with corrugated metal sheet with ceiling insulation of R2 (thermal resistance of 2 m^2.°K/W). The window glazing (single pane) of the north wall of the living room is 24% of the floor area and 31% of the north wall area, while the window of the south bedroom is 16% of the floor area and 20% of the south wall area. This room also has a west facing window. The house has no mechanical cooling and a portable heater was used in the living room and bedroom occassionally.

The second house is a 96 m^2 house and occupied by one person. Similar to the first house only a small percentage of the windows were opened during the day. Rammed earth blocks of 330 mm and 220 mm are used for external and internal walls respectively.

Parqutry is applied on the concrete slab floor. The roof construction is similar to that of the first house although this house has steeper sloping roof and ceiling. The single pane window glazing of the living room is 13% of the floor area and 27% of the north wall area, while in the south bedroom the south facing window is 15% of the floor area and 20% of the south wall area. A west-facing window also exists in this bedroom. The house has no mechanical cooling and a gas heater exists in the living room though it was only occassionally used during the monitoring period.

The third house is 175 m^2 and occupied by five people. During the day at least one person was in the house. External walls are constructed of 110 rammed earth bricks exposed internally and clad externally with a fibre cement sheet, an R2 insulation and a 25 mm air gap in between. The floor slab is tiled while the roof is also clad with corrugated metal sheet with a ceiling insulation of R3. The living room has window glazing of 28% of the floor area and 47% of the north wall area, while the south bedroom has window glazing of 16% of the floor area and 20% of the south wall area. There is a hybrid heating system in which solar heat is collected on the roof, stored in a heat storage and ducted to the rooms on the southern side of the house. No mechanical cooling exists and occassionally a portable heater was used in the living room during the monitoring period. Figures 1 to 3 show the floor plans of the three houses.

MODELLING THE HOUSES

The building geometry of each house was modelled based on the available architectural or construction drawings, confirmed or modified based on-site measurement and observation. Existing vegetation and other shading devices such as curtains and blinds were included in the simulation models. Each house was modelled as having several zones so that the spaces being monitored could be examined separately, whereas other spaces not being monitored (such as toilets and laundry) were lumped together as long as they were in the same orientation toward the sun and had similar use patterns.

As no measurements were taken to calculate the thermal properties of the materials, they were calculated based on published data. See Table 1. Natural ventilation rate was estimated based on the amount of openings that were observed during the monitoring period and using a simplified method from ASHRAE (ASHRAE 1997b, Chapter 25.12), with the equation:

$$Q = Cv \times A \times V \quad \text{[1]}$$

where Q = airflow rate in m^3/sec

Cv = effectiveness of opening, assumed to be 0.3 for wind direction diagonal to the inlet

A = area of inlet opening in m^2, and

V = wind speed, in m^2/sec.

Natural ventilation was however not applied in simulating all three houses in winter as in reality all openings were usually closed during this period. Infiltration rate in all three houses was assumed to be 0.8 ACH.

All houses were simulated in a free-run (non heating and cooling) mode as no mechanical cooling was installed in the actual houses and only occasionally portable heaters were used. The cumulative degree hours when the houses were "too cold" and "too warm" as a result of changing the wall materials were then examined. These would indicate the need for additional heating or cooling: the lesser the need, the better the performance. Each house was simulated for the whole year however only selected results are presented in this paper.

RESULTS AND DISCUSSIONS

Calibration of the simulation models

Simulated hourly temperatures of the living room and bedroom were compared to monitored data to ensure that the model was well calibrated. It was discovered, however, that it was quite difficult to calibrate the simulation model of the houses in winter in a non air-conditioning mode as in reality portable heaters were occasionally used and there was no way to reflect this sporadic use of the heater in the simulation model. Figure 4 shows an example of this difficulty in calibrating the simulation results to monitored data.

For the summer period, the simulation models of all three houses showed close agreements with monitored data. In the living room of the first house, a correlation coefficient (R^2) of 0.987 was obtained between the simulated hourly temperature and monitored data for the period of January to March 2007. In the second and third houses, the correlation coefficients were 0.891 and 0.984 respectively. Figures 5, 6 and 7 are presented as examples of comparisons between simulated temperatures in the living room of the houses in 2 weeks of summer 2007.

The correlation coefficient between simulated and measured data in winter was only calculated for the bedroom of the second rammed earth house as no heater was ever used in this room. The calculated R^2 was 0.828, showing an acceptable correlation between the simulated and measured temperatures. The discrepancies between the simulated and measured data occurred when the outdoor temperature was above 15 degrees. As previously mentioned no natural ventilation was used in the simulation model whereas in reality the occupants occasionally opened up some windows when the outdoor air warmed up. This was not possible to be simulated as the program only allows natural ventilation to be either existing (Natural Ventilation "Yes", and a natural ventilation rate must be entered) or non-existing (Natural Ventilation "No").

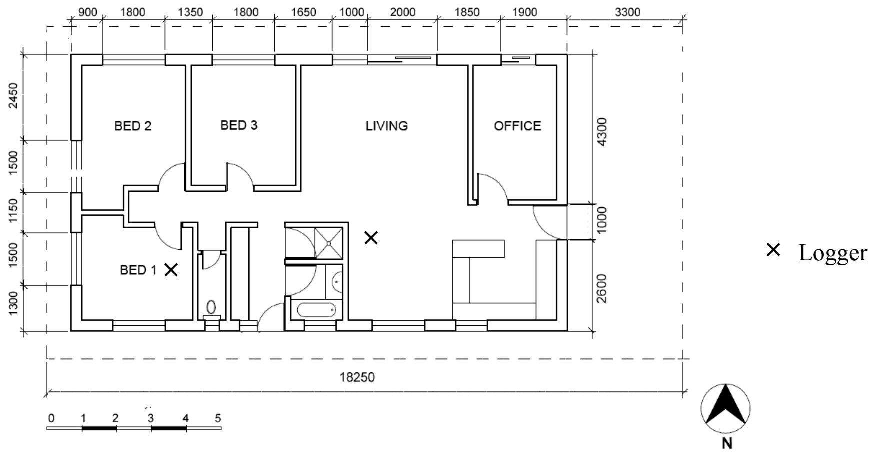

Figure 1 Floor plan of House 1

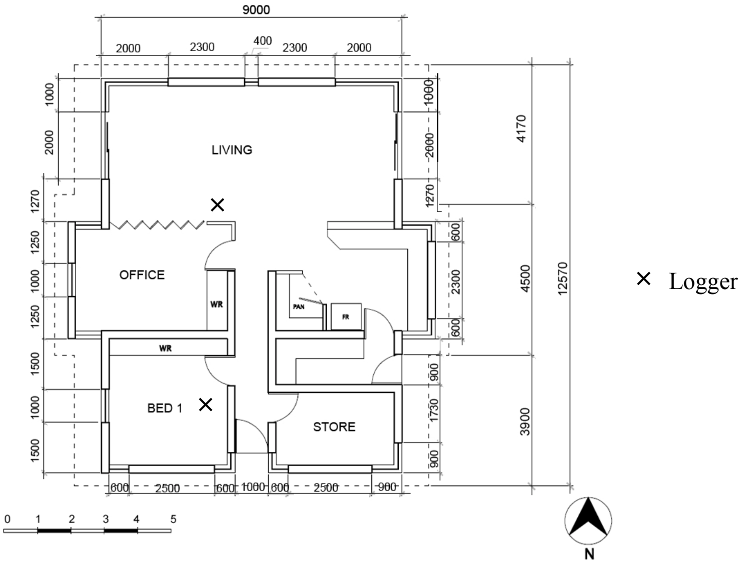

Figure 2 Floor plan of House 2

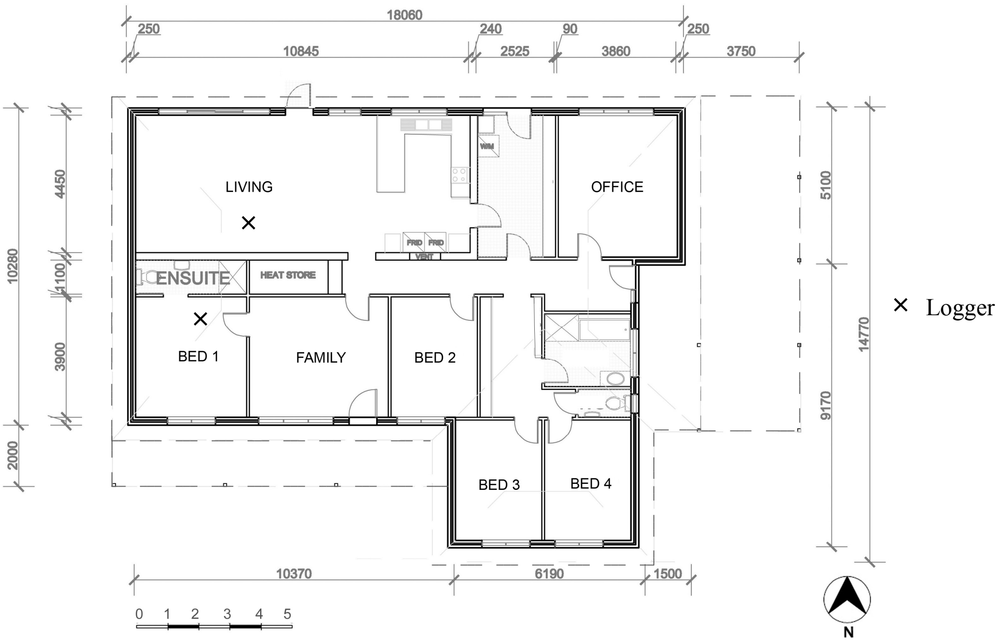

Figure 3 Floor plan of House 3

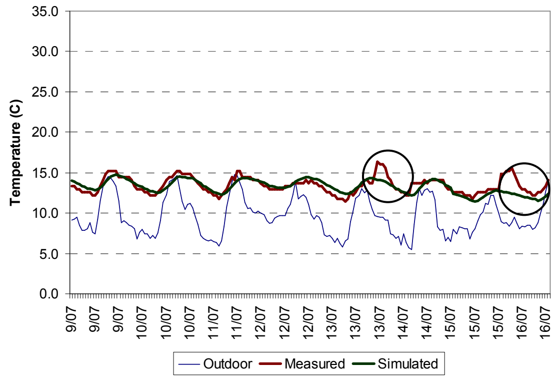

Figure 4 One-week winter comparison of simulated and measured temperatures in the living room of house 1 indicating the use of a space heater in the actual house (in circles)

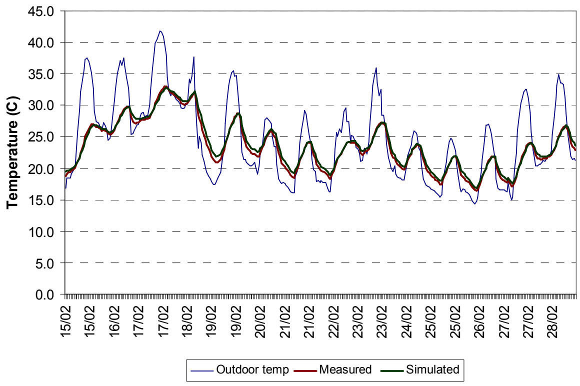

Figure 5 Two weeks summer comparison of simulated and measured temperatures in the living room of house 1

It was found that the most sensitive inputs that affected the accuracy of the results were the natural ventilation rate and window shading. In the first attempt to simulate all houses, natural ventilation was 'turned on' and a ventilation rate calculated from equation [1] was applied, based on the assumption that all windows that could be opened were indeed opened. As a result, the simulated indoor temperatures were slightly higher in summer and lower in winter than monitored data. After several visits back to the houses, it was discovered that most windows were not opened. Correct percentages of openings were then used to recalculate the ventilation rate and after modifying these, the results compared favourably with monitored data.

The other important factor was window shading. This had to be simulated correctly to reflect what actually happened in the house. In the second house, for example, the west facing window in the south bedroom was shaded in summer with blinds, but in winter this window was only occasionally shaded. This was simulated by having 100% 'front shade' in summer and only 50% shaded in winter.

Table 2 summarises the comparisons between simulation and measured data.

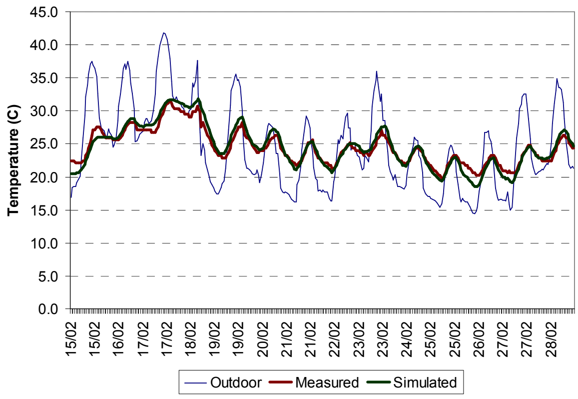

Figure 6 Two weeks summer comparison of simulated and measured temperatures in the living room of house 2

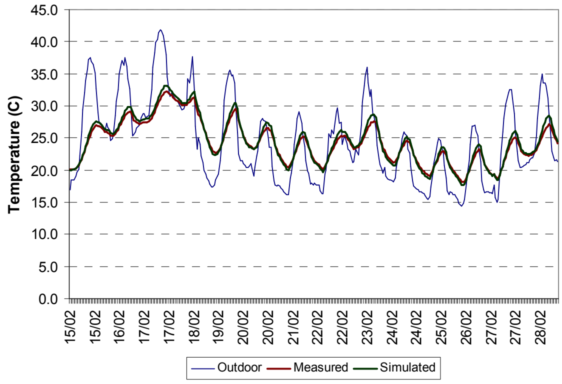

Figure 7 Two weeks summer comparison of simulated and measured temperatures in the living room of house 3

Performance of the houses

Based on the results above, the three simulation models were considered acceptable to be used for further analyses. Both simulation results and monitored data showed that the performance of all three houses was quite similar in summer, as shown in Table 2. The simulated maximum temperature in the living room of the first, second and third house was 32.8˚C, 31.5˚C and 33.2˚C respectively. The simulated average temperature was 21.8˚C, 22.5˚C and 22.8˚C respectively. For the south bedroom the simulated maximum temperature of south bedroom of the first, second and third house was 33˚C, 33˚C and 30.5˚C respectively, while the average was 21.5˚C, 21.7˚C and 21.6˚C respectively.

Using the same simulation models as above the winter performance of the three houses was predicted. The simulation results showed that the first and second house were always cooler in winter than the third house. The simulated average temperature of the living room of the first, second and third house was 12.5˚C, 13.3˚C and 18.4˚C while the minimum was 7.8˚C, 9.8˚C and 13.1˚C respectively. Similarly, the simulated average temperature of the south bedroom in the first, second and third house was

12.7°C, 13.0°C and 14.7°C respectively while the minimum was 9.6°C, 8.7°C and 12.4°C respectively.

Although cannot be directly compared, these winter results were supported by the monitored data that the first two houses were at least 4 degrees cooler in winter than the third house. The monitored average temperature of the living room of the first, second and third house was 12.5°C, 13.5°C and 18.6°C while the minimum was 7.3°C, 10.2°C and 15.2°C respectively. The monitored average winter temperature in the south bedroom of the first, second and third house was 12.9°C, 12.9°C and 16.3°C, while the minimum was 10.6°C, 10.2°C and 14.5°C. Please note that these monitored temperatures included some occasional periods when portable space heaters were used.

Altering the wall materials

The calibrated models were further used to predict the indoor temperature of each house if the wall materials were changed during the monitoring period. In the first and second houses, external walls were changed to insulated rammed earth walls similar to the wall construction of the third house. In the third house, the external walls became rammed earth only with a thickness of 220 mm, similar to the first house. This further investigation was conducted to ensure that the results obtained above were not bias due to differences in the house size and occupancy.

For the first and second houses, the result showed that, if the external wall material were changed from only rammed earth to insulated rammed earth, the changes in the summer temperature would be barely noticeable. By insulating the external walls, the house would be slightly warmer with a maximum increase of 1°C. In winter, however, using insulated rammed earth walls would result in a warmer house, with an increase of up to 4.9 degrees. In a similar fashion, it was predicted that if the external walls of the third house were changed to 220 mm rammed earth walls, the winter temperatures would be lowered by up to 4.7°C (Figure 8), while the maximum increase in summer would be 2.5°C (Figure 9).

These differences of 4.7 to 4.9 degrees between insulating and not insulating the rammed earth walls were similar to the differences between the monitored temperatures of the actual rammed earth houses (first and second house) and those of the insulated rammed earth house (third house).

Predicting discomfort conditions

The overall performance of the houses by using only rammed earth walls and insulated rammed earth, in terms of discomfort conditions, was then predicted. This refers to the indoor condition when it is too cold hence supplementary heating may be required. Lesser requirement for supplementary heating indicates a better performance. Notice that the impact on the need for cooling was not investigated as cooling was not an issue in these houses.

The discomfort condition was predicted based on the cumulative discomfort degree hours. In this study the lower limit of the comfort condition was determined from an equation for calculating the optimum comfort temperature in a non conditioned building developed by Humphrey and Nicol (1998):

$$Tc = 13.5 + 0.54 \times To \quad \text{[2]}$$

where: Tc = optimum comfort temperature, and

To = mean outdoor temperature.

In winter the mean outdoor temperature was 8.9°C, resulting in an optimum comfort temperature of 18.3°C. Note that this calculated temperature does not necessarily represent the occupants' actual comfort temperature. The monitoring results show that the occupants of the third house turned on the portable heater in the living room, though only occasionally, when the indoor temperature was below 18°C, whereas most of the time no heater was used even when the occupants were sleeping though the temperature went down to 15°C. In the first and second houses, the heater was only turned on, though occasionally, when the indoor temperature was below 15°C. Due to these differences the optimum comfort temperature based on the equation above was used in this analysis.

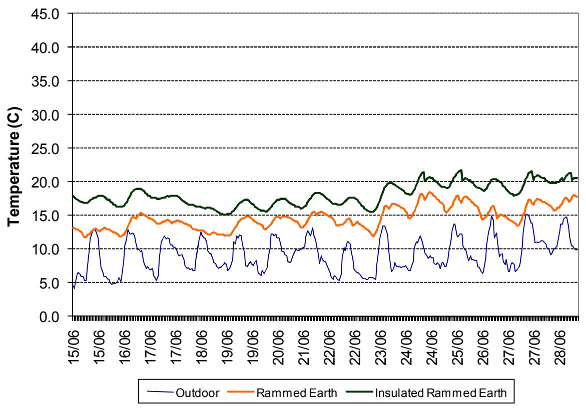

Figure 8 Two weeks of predicted temperatures in winter if house 3 used only rammed earth walls

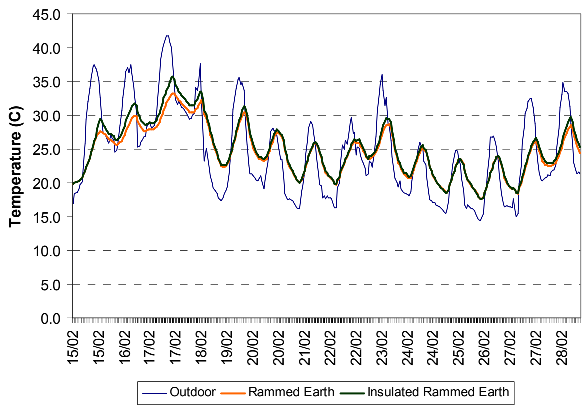

Figure 9 Two weeks of predicted temperatures in summer if house 3 used only rammed earth walls

With the original wall construction, the predicted cumulative discomfort degree hours for the whole year of the first house were 8262 degree hours, whereas if the walls were changed to insulated rammed earth the discomfort degree hours would be reduced to 5883, reflecting a 29% reduction. In the second house, the discomfort degree hours were 8038, and if the rammed earth walls were insulated the discomfort degree hours would be reduced to 5972, or 26% reduction. By changing the walls of the third house from insulated rammed earth to the same wall construction as in the first house, which is non-insulated 220 mm rammed earth, the discomfort degree hours would increase from 6554 to 7775, or 19% increase.

These results show that, opposite to common belief, in the long run, using only rammed earth walls could result in requiring more supplementary heating hence potentially higher energy use than if the house was constructed of insulated masonry walls.

CONCLUSION AND CLOSING REMARKS

This study has confirmed results from other studies on the performance of similar ‘sustainable’ wall material (i.e. mud bricks). Using simulation it was predicted that if a house was constructed of rammed earth walls only, the summer indoor temperatures would be comparable to those in an insulated rammed earth wall house of a similar design (or in reverse masonry veneer houses). In winter, however, the rammed earth house tends to be around 5 degrees cooler than the insulated rammed earth house. This prediction was supported by several monitored data in occupied houses, which indicated similar results.

The study also found that using only rammed earth walls would result in 19 to 29% more discomfort degree hours annually than if the walls were of insulated rammed earth walls. This indicates that more heating would be required in a house that only uses rammed earth walls.

It is interesting to note, however, that in reality the total annual energy use per person of the first two houses, although slightly higher than that of the third house, was around 50% of the average energy use per person in the region. This was reported in Soebarto (2008). Based on the utility records, the first house total annual energy use (electricity and gas) was 4180 kWh per person per year, whereas the second one was 4268 kWh per person per year. In comparison, the average energy use per person per year in a house with electricity and gas in South Australia was 8133 kWh per person per year. So, despite the fact that the house was indeed cold in winter as shown in the recorded minimum and average indoor temperature of around 8°C and 12.5°C respectively, and the simulations showed similar results, the design of the houses and materials used for the external walls did not automatically result in high heating energy as the predictions show. In other words, the general claim that using rammed earth would result in lower heating bills may indeed be based on some facts in actual houses, but this does not necessarily mean that this low energy use is a direct impact of the wall materials used. It is likely that the occupants of rammed earth houses have a different perception and attitude toward their ‘thermal comfort’ as indicated by occassional not continuous use of space heating in winter. This topic however is beyond the scope of this paper, but it is worth investigating in future studies.

ACKNOWLEDGEMENTS

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REFERENCES

AIRAH 2000. Technical Handbook (Millenium edition). The Australian Institute of Refrigeration, Air Conditioning and Heating.

ASHRAE, 1997a. ASHRAE Handbook Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA. Chapter 24.7.

ASHRAE, 1997b. ASHRAE Handbook Fundamentals. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA. Chapter 25.12.

Austin Green Building Program, 2009. Sustainable Building Sourcebook. Chapter: Materials. http://www.austinenergy.com/Energy%20Efficiency/Programs/Green%20Building/Sourcebook/earthConstruction.htm. Accessed 5 May 2009.

Bureau of Meteorology, 2008. Available from: http://www.bom.gov.au. Accessed 4 January 2008.

CSIRO 2000. Media Release. Available from: http://www.csiro.au/files/mediaRelease/mr2000/RammedEarth.htm. Accessed 17 July 2007.

Degelman, L.O. 2007. Ener-Win Energy Simulation Software for Buildings. Available from: http://www.enerwin.com. Accessed 5 May 2009.

Degelman, L.O., and Soebarto, V.I. 1995. Software Description for ENER-WIN: A Visual Interface Model for Hourly Energy Simulation in Buildings, Proc. of Building Simulation ’95, Fourth International Conference, International Building Performance Simulation Association, Madison, WI, Aug. 14-16, pp.692-696.

Degelman, L.O. 1970. Monte Carlo simulation of solar radiation and dry-bulb temperatures for air-conditioning purposes. Proc. of Kentucky Workshop on Computer Applications to Environmental Design. Lexington, KY, 213-223.

Degelman, L.O. 1991. A statistically-based hourly weather data generator for driving energy simulation and equipment design software for buildings. Proc. of Building Simulation '91, International Building Performance Simulation Association (IBPSA), Nice, Sophia-Antipolis, France, 20-22 August.

Delsante, A. 2006. A Comparison of AccuRate Predictions with Measured Data From a Mud Brick House. Proc. of the IBPSA Australasia 2006 Conference. Adelaide, Australia, pp 96-103.

Delsante, A. 2005. Is the New Generation of Building Energy Software up to the Task? – A Review of AccuRate. ABCB Conference 'Building Australia's Future 2005', Surfers Paradise, September 2005.

Humphreys, MA. and Nicol, J.F. 1998 Understanding the adaptive approach of thermal comfort, ASHRAE Transaction (1998) 991–1004.

Lawson, B. 1996. Building Materials Energy and The Environment, RAIA Publisher, Canberra.

MABEL 2005. Performance Assessment of a Mud Brick House in Victoria. Report, Mobile Architecture & Built Environment Laboratory, Deakin University.

Rammed Earth Construction. 2009. Available from: http://www.rammedearthconstructions.com.au/index.php?mp_id=5. Accessed 5 May 2009.

Soebarto, V.I. and L.O. Degelman. 1998. Energy Analysis Software as a Design Tool in Architectural Design Studio Projects. Proc. of the 32nd Annual Conference of the Australian and New Zealand Architectural Science Association (ANZAScA), Wellington, NZ, 15-17 July, pp.259-266.

Soebarto, V. 2008. Indoor performance, energy use and rating of three naturally-ventilated houses. Proc. of International Symposium on the Interaction between Human and Building Environment, Yonsei University, Korea, 2-3 July.

Table 1 Thermal properties of wall materials of the case study buildings

	U-Value* ($W/m^2.K$)	Solar Absorptivity**	Time Lag* (hrs)	Decrement Factor*
Rammed earth 110 mm	4.26	0.5	2.81	0.714
Rammed earth 220 mm	3.089	0.5	6.16	0.374
Rammed earth 330 mm	2.411	0.5	9.30	0.189
Reverse-masonry veneer (1): Harditex cladding, Air gap, R2 insulation, Rammed earth bricks 110 mm	0.377	0.3	4.3	0.638

* = Calculated based on assumed density, conductivity (k), and specific heat.
Rammed earth: density 1540 kg/m^3; conductivity 1.25 W/m.K; specific heat 1260 J/kg.K.
** = Estimated based on the surface colour.

Table 2 Comparison summary of simulated temperatures and monitored data (in degree Celsius)

SUMMER													
		Living Room						South Bed					
		House 1		House 2		House 3		House 1		House 2		House 3	
	Outside	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea
Maximum	41.8	32.8	33	31.5	31.8	33.2	32.3	33	32	33	31.5	30.5	28.7
Average	21.8	21.8	21.5	22.5	22.6	22.8	22.5	21.5	21.4	21.7	22.3	21.6	22.1
WINTER													
		Living Room						South Bed					
		House 1		House 2		House 3		House 1		House 2		House 3	
	Outside	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea	Sim	Mea
Average	10.3	12.0	12.5	13.3	13.5	18.4	18.6	12.7	12.9	13.0	12.9	14.7	16.3
Minimum	3.7	7.8	7.3	11.5	10.2	13.1	15.2	9.6	10.6	10.3	10.2	10.9	14.5