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The thermal performance of earth buildings

El comportamiento térmico de los edificios de tierra

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SUMMARY

This paper examines the theoretical basis for the thermal performance of earth walls and links it to some test results on buildings constructed by the author, and to their predicted performance using a sophisticated computer modelling program. The analysis shows that for all earth walls the steady state thermal resistance is low but that for walls greater than about 450 mm thick the cyclic thermal resistance is high and increases exponentially. Whilst the steady state resistance of all thickness walls is low and results in higher than normal average temperatures in summer and lower than normal in winter the ability of thick earth walls to even out the swings in temperature is thought to be responsible for the materials reputation. The paper notes that good passive design principles (such as providing internal thermal mass and large areas of glazing for winter performance) will greatly improve the performance of earth buildings with thin walls, but it is the author's opinion that external earth walls should be at least 450 mm thick to gain the full benefit of thermal mass.

RESUMEN

Este artículo examina la base teórica del comportamiento térmico de las paredes de tierra y la relaciona con varios resultados de test realizados sobre edificios construidos por el autor, y con su comportamiento previsto utilizando un sofisticado programa de modelado por ordenador. El análisis muestra que la resistencia térmica constante es baja para todas las paredes de tierra, pero que para muros con un grosor mayor que 450 mm la resistencia térmica cíclica es alta y se incrementa exponencialmente. Mientras que la resistencia térmica constante de las paredes de cualquier grosor es baja y se traduce en temperaturas más altas que la media en verano y más bajas que la media en invierno, la capacidad de las paredes gruesas de tierra para amortiguar las variaciones de temperatura es la responsable de la reputación de los materiales. El artículo señala que los principios de un buen diseño pasivo (tales como proporcionar inercia térmica y grandes áreas acristaladas para el comportamiento en invierno) mejorarán enormemente el comportamiento de las construcciones de tierra con paredes delgadas, pero en opinión del autor las paredes exteriores deberían ser de al menos 450 mm para aprovecharse de todos los beneficios de la inercia térmica.

113.106

Keywords: thermal performance, earth walls, thermal resistance, adobe, cob, pise, pressed earth bricks.

Palabras clave: *comportamiento térmico, paredes de tierra, resistencia térmica, adobe, cob, pisar, bloques de tierra.*

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1. INTRODUCTION

Earth walled building has a history dating back thousands of years and remains a common form of construction in many developing communities. There are four major types of earth walls – adobe (mud-brick), pise (rammed earth), pressed earth bricks and cob. Adobe earth buildings abound in India and China, the two largest countries in the world in terms of population, and this form of construction is also popular in countries such as Spain and the USA. Cob and Pise have a long history in Europe whilst pressed earth bricks are a relatively recent form of earth construction.

Commencing in the 1970's there has been a significant revival in interest in these forms of construction in developed communities, particularly after the oil crisis, due to their low embodied energy coupled with reportedly good thermal performance, both of which would result in less energy usage. In recent times the focus on global warming has led to a need to reduce the emission of carbon dioxide from coal powered generators, and this has led to an increased focus on the in-service energy usage of buildings. The response to this has led in most cases to regulations which concentrate on the steady state thermal resistance of walls (the "R" value), or its reciprocal thermal transmittance (the "U" value).

It is well known however that the steady state thermal resistance of earth walls is not good, being roughly equivalent to that of some fired clay bricks. For example a typical adobe earth wall 300 mm thick has a thermal resistance of around 0.5 m^2K/W (U of 2.0 W/m^2K). This is significantly less than for example the thermal resistance (R) of 1.9 m^2K/W (U of 0.53 W/m^2K) required by the Building Code of Australia (1) for a temperate climate such as Sydney, Australia. In double brick, brick veneer or reverse brick veneer construction this deficiency is easily overcome by the inclusion of thermal insulation material in cavities, whilst in other types of construction an external insulating skin may be possible. However the former is not possible for single skin monolithic earth walls, nor in most cases is the latter aesthetically desirable in the case of earth walls as it would detract from the naturalness of the material.

The thermal performance of earth walled buildings is however legendary - "The cob cottage in Devon had the reputation of being cosy in winter and cool in summer" (2) and is at odds with this preoccupation with steady state thermal resistance.

In Australia lobbying by various organisations such as the Earth Building Association of Australia has led to an exception in the Building Code of Australia (BCA) for thermally massive construction such as earth walled buildings. For example in Sydney walls which have a surface density of 220 kg/m^2 (110 mm thick fired clay skin or 135 adobe wall) are assumed by the BCA to have an equivalent R of 1.9 m^2K/W when coupled with masonry internal walls and therefore require no additional insulation. (The wall is considered to be high mass, which slows heat movement into and out of the building (2)). Essentially the argument is that in summer excess heat is stored in the walls during the day and released from them at night, thus reducing the heat load on the building. In the case of winter performance it is assumed that good passive design will allow heat to enter through windows and be stored in the thermal mass of the building to be released to the interior at night.

Whilst this mass allowance may solve the problem for earth construction in some cases it does not help in colder climates such as the UK, where Cob is prevalent and a R of 2.86 m^2K/W is required, or certain areas of Australia (Climate Zones 6, 7 and 8) where required values of R vary from 2.2 m^2K/W to 3.3 m^2K/W. The argument in these cases appears to be that the steady state R value is important for winter heat retention.

In order to demonstrate the thermal performance of earth walled buildings this paper will briefly present the theory of heat flow through earth walls based on the admittance method and relate this to the measured summer and winter performance of experimental adobe and insulated brick veneer buildings, and on their modelling by the CIBSE Admittance procedure (3) and the AccuRate thermal modelling program developed by the CSIRO (4).

The main aim of the paper will be to determine whether the anecdotal good performance of traditional earth walled buildings is supported by theory, and in particular how external wall thickness effects thermal performance.

2. DESIGN OF TEST BUILDINGS

The objective of testing was to test the performance of two buildings with different walling systems. The buildings were 4 metres square in plan with pitched metal roofs. The buildings are identical except for the walls. The walls in the mud brick (adobe) building were bitumen stabilised and 250 mm thick. The brick veneer building had 90 mm timber stud walls lined internally with 10 mm thick plasterboard (with R1.5 m^2K/W insulation in the studwork), a 40 mm cavity and an external 110 mm thick fired clay external brick skin, giving a total thickness of 250 mm.

The buildings were not particularly designed with passive solar principles in mind, although the northern glazed single door did have sufficient overhang to shield the glazing from summer sun. Although there was some air leakage through the doors these were kept shut during the testing to minimise air exchange as a variable and the door glazing was the only glazing to the buildings. The buildings were built on concrete slabs poured on the ground and the roofs had R3 m^2K/W insulation on top of the ceiling. For complete details of the construction refer to Heathcote (5).

There is no question that the earth building (or the brick veneer building for that matter) would have behaved better in summer if it had had better shading, windows were opened at night to release hot air and more thermal mass was added to the interior. Similarly larger areas of north facing glazing would have improved its thermal performance in winter. These are however passive design principles that are common to all forms of construction, not just earth walled construction. The main purpose of this paper is however not to justify passive design principles but to demonstrate how effective earth walls (in particular earth walls of different thicknesses) are in moderating heat flow into and out of buildings.

3. STEADY STATE THERMAL PROPERTIES

The steady state thermal performance of earth walls is governed by the following equation [1]:

$$Q_{cw} = \frac{A \times (T_{solair} - T_{si})}{R} \qquad [1]$$

where:

Q_{cw} = Steady State Conduction Heat Flow through wall (W)

T_{solair} = Outside Surface Sol-Air temperature. This is the outside temperature modified (increased) by the effect of solar radiation on the surfaces. The increase is equal to the impacting solar irradiance times the solar absorptance of the external wall surface times the outside surface resistance, the latter depending on wind speed.

T_{si} = Inside Surface temperature. There are various definitions of inside temperature ranging from the environmental temperature (2/3 radiant + 1/3 air) used in the pre 2006 CIBSE Admittance method (3) to the dry resultant or operative temperature (1/2 radiant + 1/2 Air) used in the 2006 guide. In most cases the difference is relatively small and the term inside air temperature will be used in this paper in order to concentrate on the underlying mechanisms of heat transfer.

R = Steady state thermal resistance of the wall including outside and inside surface resistances (m^2K/W).

A = Surface Area of Wall (m^2)
(Note that R = 1/U , where U is the air-to-air transmittance of the wall. This paper will refer to R values rather than U values due to current Australian regulations focusing on thermal resistance).

The steady state thermal resistance of a wall (R) is the sum of the resistance of the wall material (Rwall) and the outside and inside surface resistances. For the purpose of this paper the outside surface resistance will be taken as 0.03 m^2K/W and the inside 0.12 m^2K/W, consistent with the Building Code of Australia (1). The wall resistance is given by [2]:

$$R_{wall} = \frac{\textit{Wall Thickness (m)}}{\textit{Wall Conductivity } (\frac{W}{m.K})} \qquad [2]$$

Test values of conductivity (k) for earth wall construction are difficult to find. Minke (6) reports conductivity values from Volhard for earth walls which depend on density only. Arnold (7) gives a relationship between moisture content and conductivity for masonry materials which agrees reasonably well with these values for a moisture content of 5 %, this being a reasonable assumption for the equilibrium moisture content of loam walls with a humidity of around 75% (6). These values are shown in Table 1.

Table 1

Relationship Between Conductivity and Density

	Conductivity in W/m.K (k)	
Density (kg/m^3)	**(DIN 4108-4)**	**Arnold (5% m.c.)**
1400	0.6	0.56
1600	0.8	0.73
1800	0.95	0.94
2000	1.2	1.21

As can be seen from Table 1 the values from both sources are fairly similar. For the purpose of this paper the following linear best-fit equation of the Arnold data will be used for earth walls with densities in the range 1400 – 2000 kg/m^3.

Conductivity = 0.0011xDensity-1.00(W/m.K) [3]

Table 2 shows indicative values for conductivity for the four common earth wall materials based on representative assumed densities and equation [3]. Note that the conductivity of completely dry materials would be about 60% of these values according to Arnold (7).

Table 2
Indicative Values of Density and Conductivity for Earth Wall Constructions

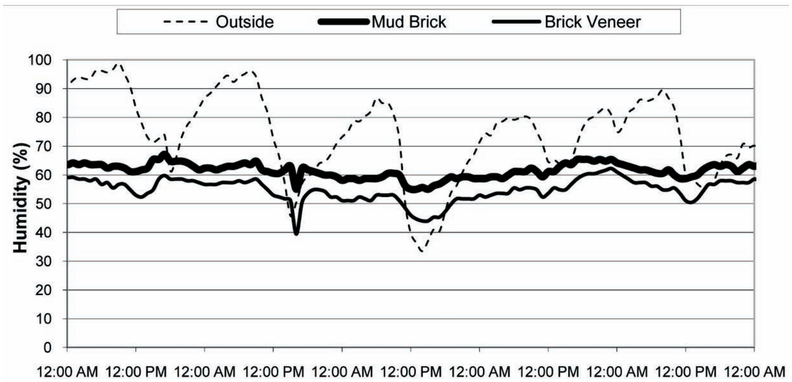
Material	Assumed Density kg/m^3	Conductivity (k) W/m.K
Cob	1450	0.60
Adobe	1650	0.82
Manual Pressed Earth Bricks	1750	0.93
Rammed Earth or Machine Pressed Earth Bricks	2000	1.20

As an indication of the relative values of thermal resistance of earth walls a 250 mm thick adobe wall with a conductivity of 0.82 W/m.K has a thermal resistance of 0.46 m^2K/W whilst a 250 mm thick brick veneer wall has a similar resistance of around 0.52 m^2K/W.

With R1.5 insulation in the cavity the thermal resistance of the latter rises to 2.02 m^2K/W (U of 0.33 W/m^2K). A Cob wall (having the best conductivity of earth walls) would need to be 1.12 metres thick to achieve this value! It is thus clear that in the steady state situation earth walls do not have good thermal resistance.

4. HUMIDITY

It has been argued by some that the ability of earth walls to soak up excess humidity may be one of the reasons why they perform well thermally. Figure 1 shows humidity readings taken in August 2006 for the two test buildings monitored by the author when the external relatively humidity varied from 30% to 100%. In this case the readings in both the brick veneer building and the mud brick building varied from 50% to 65% with the brick veneer building consistently about 5% below that of the mud brick building.



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1. Humidity readings August 2006

Figure 1 would seem to suggest that the pattern of moisture content in the mud brick building is not significantly different from that in the brick veneer building.

5. CYCLIC PERFORMANCE OF WALLS

The advantage of external earth walls has always been attributed to their resistance to a cyclic heat input, the so called thermal mass effect. The argument is that the high thermal mass of these walls delays the passage of heat through the walls in summer and in doing so the magnitude of the internal temperature fluctuations is diminished. The delay in peak of the thermal wave is referred to as "thermal lag" and the reduction in magnitude of the peak temperature is reflected in the "decrement factor". By definition the alternating or cyclic transmittance is equal to the steady state transmittance (U) multiplied by the decrement factor (f). The author is of the view that the concept of air to air resistance (R) is easier to comprehend than transmittance (U) and therefore the term cyclic resistance (Rcyclic) will be used in this paper where Rcyclic = 1/(f×U).

The non-steady state thermal performance of walls is governed by the following diffusion equation [4]:

$$k \times \frac{\partial^2 T}{\partial^2 x^2} = c \times \frac{\partial T}{\partial t} \qquad [4]$$

where:

k = Thermal Conductivity (W/m.K)

c = Thermal Capacity ($kJ/m^3.K$) = Density (kg/m^3) × Specific Heat Capacity (kJ/kg.K) (According to Minke (6) the specific heat capacity of earth walls may be taken as 1 kJ/kg.K.)

T= Temperature (°K)

x = Distance through Wall (m)

t = time

This equation is difficult to solve directly for all but the simplest cases and for more complicated situations computers have to be used. It can be seen from equation 4 however that for the steady state situation ($\frac{\partial T}{\partial t} = 0$) the heat flow depends on conductivity only whilst in the cyclic heat input situation both conductivity and thermal capacity are important heat flow variables.

The Admittance method developed by the CIBSE (3) can be used to visualise the thermal behaviour of earth walls in response to cyclic thermal inputs. It separates cyclic heat flows into a steady state component due to the average outside temperature and a fluctuating component due to an assumed periodic variation in outside temperature.

In the steady state condition heat flow through the walls is the same as given above, with the average sol-air temperature used as the driving outside temperature.

For the fluctuating component of heat flow through the walls the cyclic resistance is used rather that the steady state resistance. In this case the driving temperature is taken as the fluctuating component of the wall sol-air temperature taken at a period (equal to the thermal lag of the wall) prior to the time being considered. This is to take into account the delay in passage of the heat wave through the wall [5].

$$Q_{cw} = \frac{A \times (T_{solag} - T_{si})}{R_{cyclic}} \qquad [5]$$

where:

Q_{cw} = Fluctuating Conduction Heat Flow through the wall (W)

T_{solag} = Outside Sol-Air temperature at time t_{lag} hours prior to time under consideration (°K)

t_{lag} = Time lag of temperature wave due to thickness of material

T_{si} = Inside Surface temperature (°K)

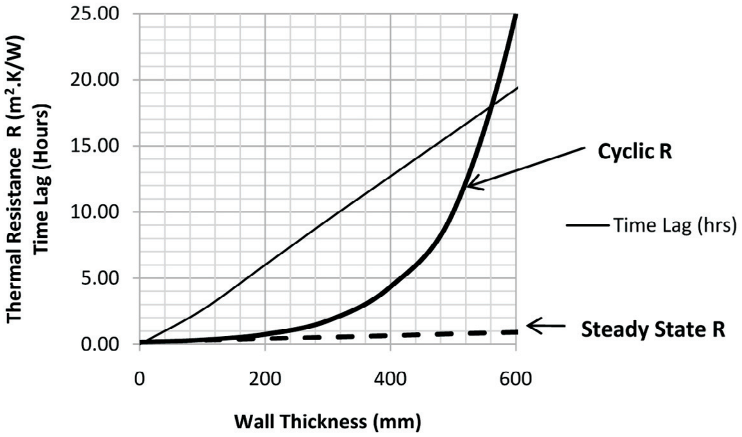
R_{cyclic} = Cyclic Thermal Resistance of the wall (m^2K/W)

A = Surface Area of Wall (m^2)

(Note that R_{cyclic} is equal to R steady state divided by the decrement factor)

The cyclic thermal resistance of an earth wall and its associated time lag can be determined using the matrix method outlined in Davies (8). They depend on the density of the wall material, its specific heat capacity, its conductivity and the wall thickness. Figure 2 is a plot of these values for a wall using this method assuming a density of 1650 kg/m³, a specific heat capacity of 1000 J/kg.K and a conductivity of 0.8 W/m.K. Also included in Figure 2 is a plot of the steady state wall resistance.

Whilst the steady state thermal resistance is linear in relation to wall thickness the cyclic thermal resistance increases exponentially with wall thickness. At above a thickness of 450 mm the cyclic resistance increases rapidly and this, coupled with a time lag greater than 12 hours means that for wall thicknesses greater than 450 mm the heat flow through walls is negligible.



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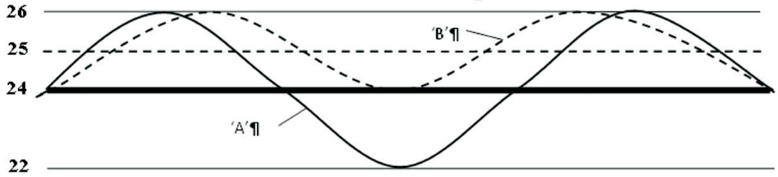
2. Thermal resistance and time lag vs wall thickness

3. Relationship between range and mean temperature

5. THERMAL COMFORT

Traditionally thermal comfort levels have been related to the clothing one wears and the activity being engaged in. Using Fangers formula (9) the neutral temperature for a person seated at rest would be roughly 23 °C in winter (wearing a jacket) and 26 °C in summer (short sleeves). This in fact is not much different than the values predicted using the adaptive method outlined by deDear and Brager (10) for Sydney Australia (Mean Jan temp 25.8 °C, June 16.9 °C).

One of the advantages of thermal mass is that it reduces the swing in temperatures and this reduced swing may lead to a perceived feeling of greater comfort even if the average temperature is higher. Figure 3 shows how a mean temperature of 25 °C in summer with a swing of +/–1 °C gives the same maximum temperature as a mean temperature of 24 °C with a swing of +/–2 °C .



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The fact therefore that people are not having to adjust to significantly varying temperatures in an earth building may more than compensate for a slightly higher average temperature. It has been suggested by Trappel (personal communication) that this may have something to do with the relationship between blood thickness and average body temperature.

Another factor that has not been researched much for earth construction is the psychological expectation of the occupants. Put simply some people are pre –conditioned to expect that earth buildings are thermally more comfortable because the thermal mass effect seems logical and because historically people have reported such houses as being nice to live in. The concept of cognitive dissonance would also suggest that earth building aficionados possibly block out the prospect that earth buildings may in fact have poor thermal performance in some situations and thus tolerate higher or lower than normal temperatures.

6. WHOLE OF BUILDING PERFORMANCE

In reality the contribution of conduction heat gain/loss through the walls (Q_{cw}) is only part of the story. There are conduction heat gains/losses through the glazing (Q_{cg}), the roof (Q_{cr}) and the floor (Q_{cf}), solar heat gains through the glazing (Q_{sg}) as well as ventilation gains/losses (Q_v) to consider .

6.1. Summer Performance

In summer one might expect the outside temperature to be higher than the inside and that the driving sol-air temperature through the walls and roof higher still. The admittance method can be used to get an understanding of the heat flows involved and their contribution to internal temperature.

In the average steady state situation there is solar gain through the glazing and conduction heat inflow through the walls and roof. Heat flows out through the floor (assuming a slab on ground) and through the glazing fabric as well as through ventilation exchange [6].

Table 3

Analytical Average Heat Flows and Temperatures

	Brick Veneer (+R1.5 Insulation)	Mud Brick
	Heat Flows (Watts) – In Positive	
Door Solar Gain (Qsg)	57	57
Walls (Qcw)	33	91
Roof (Insulated) (Qcr)	8	2
Ventilation (Qv)	-18	-28
Floor (Qcf)	-53	-81
Door Fabric (Qcg)	-27	-41
Predicted Average Inside Temperatures	25.7 ºC	26.9 ºC
Measured Average Inside Temperatures	25.4 ºC	26.6 ºC

Thus $Q_{sg} + Q_{cw} + Q_{cr} = Q_{cf} + Q_{cg} + Q_v$ [6]

Balancing these heat flows using equation [1] enables us to determine an average value for internal temperature. Note that the driving external temperature for the right hand side variables is the mean outside temperature, for the walls and roof the mean outside sol-air temperature (outside temperature plus an increase due to solar radiation impinging on the surface) and the solar gain through the glass is due to the average value of incident solar radiation.

Table 3 shows the results of such an analysis for the test buildings on the 9th January 2007 where the outside average temperature was 23.6 ºC. The buildings were identical except for the wall material. For further details of the tests and an expanded discussion of the results refer to Heathcote (5)

Table 3 illustrates that the admittance method provides a good indicator of mean inside temperature in summer and in these situations the steady state thermal resistance is the determining variable. In this instance the steady state thermal resistance of the brick veneer walls was 2.04 m^2K/W and for the mud brick walls 0.47 m^2K/W. This difference is reflected in the significant difference in average heat flow through the walls but the higher resultant internal temperature in the mud brick building causes more heat to flow out through the door.

Fluctuations in temperature about the average are determined by fluctuations in driving temperatures about the average, bearing in mind any time lag associated with a particular form of construction. Using the CIBSE guide

Swing in Inside temperature =
Swing in Internal Heat Gain / ∑ A x Y

where:

A= Internal surface areas (m^2)

Y = Surface Admittance ($W/m^2.K$)

The surface admittance *"is the rate of flow of heat between the internal surfaces of the structure and the environmental temperature in the space, for each degree of deviation of that temperature about its mean value "*(3). Note that for earth walls the surface admittance is determined roughly by the inner 100 mm of wall and therefore does not vary significantly with wall thickness. It is however significantly higher than other forms of construction such as insulated brick veneer and therefore should theoretically have a moderating effect on temperature swing.
The swing in heat gain is calculated as follows (Terms defined in Table 4).

Swing in Internal Heat Gain [8]:

$$Q = Q_{sg} + Q_{cw} + Q_{cr} + Q_v + Q_{cf} + Q_{cg} \quad [8]$$

Equation [5] is used to calculate the swing in heat flow through the walls Q_{cw} , i.e. using the cyclic thermal resistance of the wall with lagged sol-air temperature.
The swing in ventilation heat flow (Q_v) is defined as follows [9]:

$$Q_v = C_v \times (T_{out} - T_{in}) \quad [9]$$

Table 4 shows the results of such an analysis for the same simple buildings analysed by the author. In this instance the cyclic thermal resistance of the brick veneer walls was 2.65 m²K/W and for the mud brick walls only 1.15 m²K/W. This accounts for the much higher heat flow through the mud brick walls.

Table 4 shows that the predicted swing temperature for the mud brick building was less than that for the brick veneer building because even though the swing heat gain through the mud brick walls is high, the admittance (ΣAY) of the mud brick building is almost twice that of the brick veneer building.

Figure 4 shows the sensitivity of the above analysis to the value of solar irradiance assumed. In the case of the mud brick building with a lag time of 8 hours the lagged solar irradiance on the eastern wall is very sensitive to both the lag time and the assumed time of maximum internal temperature (assumed to be 5pm). The fact that average solar irradiances were used in the analysis instead of actual values (not measured because of cost) also introduces some degree of inaccuracy in comparing actual to predicted swings.

Figure 5 shows some typical results for March 2007, where the recorded swing for the brick veneer building was around 2° C and for the mud brick building 1.75° C. The average temperature in the mud brick building during this period (with E and W walls painted a light colour) was only about 0.5° C higher than in the brick veneer building.

Note that prior to painting the east and west walls of the mud brick building a light colour the average recorded temperature in the mud brick building was significantly higher (up to 3° C) than in the brick veneer building, although the swings were still similar (See Figure 6).

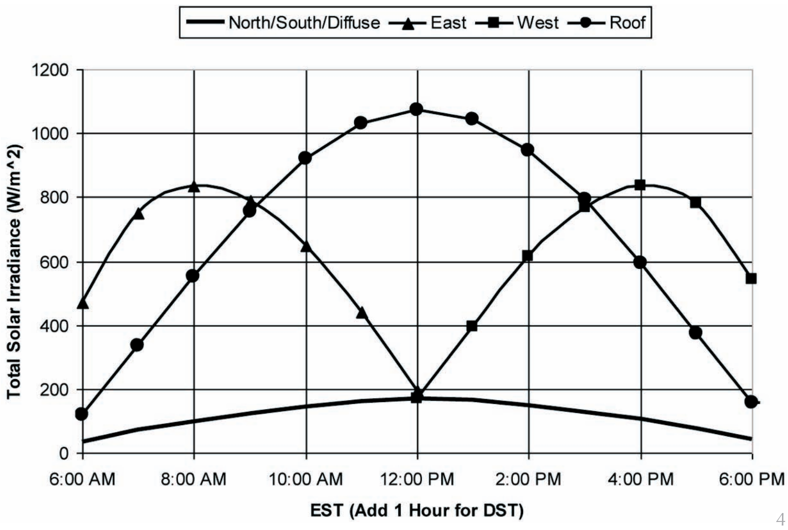
The same two buildings were analysed using the AccuRate thermal modelling program developed by the CSIRO in Australia (4), with both painted and unpainted east and west walls.

Table 4

Analytical Heat Flows and Swing Temperatures

	Brick Veneer	**Mud Brick**
	Heat Flows (Watts) – In Positive	
Walls $\widetilde{Q}_{cw}$	55	204
Door Solar Gain $\widetilde{Q}_{sg}$	23	23
Roof $\widetilde{Q}_{cr}$	47	37
Ventilation $\widetilde{Q}_{v}$	49	24
Floor $\widetilde{Q}_{cf}$	0	0
Door Fabric $\widetilde{Q}_{cg}$	44	53
Total Heat Gain $\widetilde{Q}$	**218**	**307**
ΣAY	175	338
Predicted Swing Temperatures	1.2 ºC	0.9 ºC

4. Temporal variation in average solar irradiance in Sydney (11)



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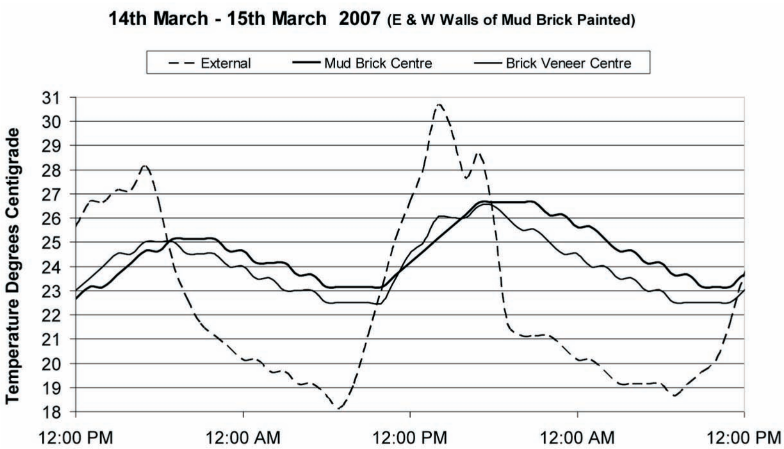
5. Temperature swings in March 2007



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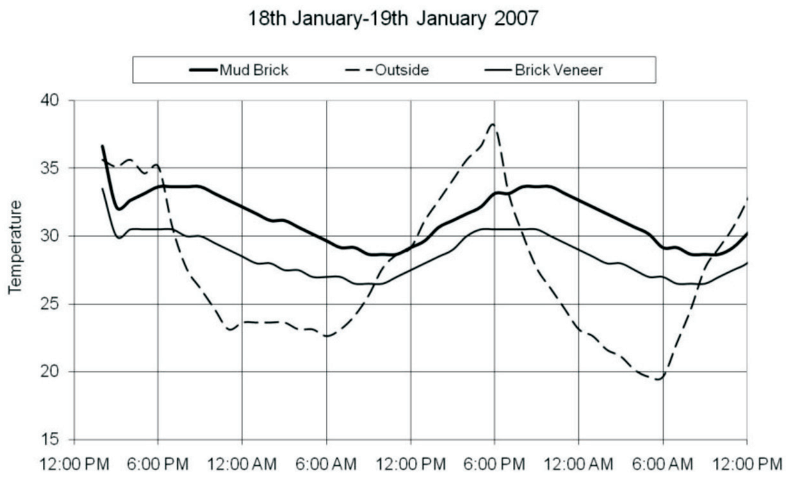

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6. Temperature swings in January 2007

The program is based on a frequency-domain matrix method and combines this with a heat balance in the building interior within the frequency time domain to produce harmonic responses to the driving environmental parameters. The resultant response of the zones to the periodic input is then converted into a response to transient pulses, thus enabling calculation of the hourly responses of each zone to fluctuating external conditions. The treatment of radiative heat transfer between surfaces involves a combined convective plus modified radiative surface heat transfer coefficient connecting each surface to a central zone temperature point. The resulting internal zone temperatures are therefore not true temperatures but are "environmental" temperatures, similar to the admittance procedure.

The results of the analysis are shown in Table 5 for the month of February. Note that in this case the range given is the difference between daily maximum and daily minimum temperatures which would correspond to twice the swing for a uniform periodic temperature. The range(swing) is similar for the 250 mm thick mud brick and the 250 mm thick brick veneer walled buildings (around 1.75-2.00° C) and is consistent with the measured values shown in Figure 5. The monthly average temperature is however about 2° C higher in the mud brick building but if the east and west walls are assumed to be painted a light colour as was the case after February 2007, the average temperatures drop dramatically and the figures for the 250 mm thick walls are consistent with those in Figure 5.

Table 5

Predicted Temperatures Using AccuRate Program

	Average Monthly Temp (°C) (Painted E&W Walls)	Typical Daily Range	Temperature Lag (hrs)/Approx. Solar Lag Time	Average Monthly Plus Half Range (°C)
B/V Walls with R1.5 insulation	25.2	3.5	4/1pm	27.0
Mud Brick Walls 250 Thick	27.1 (25.5)	4.0	8/9am	29.1 (27.5)
Mud Brick Walls 450 Thick	26.4 (25.1)	0.5	14/3am	26.7 (25.4)
Mud Brick Walls 600 Thick	26.1 (24.9)	1.0	19/10pm	26.6 (25.4)

Table 5 shows that for walls 450 mm thick the lagged time for swing driving temperature is around 3am for the 450 wall, whereas for the 250 mm thick wall it is around 9am, when the solar irradiance is almost at its maximum.

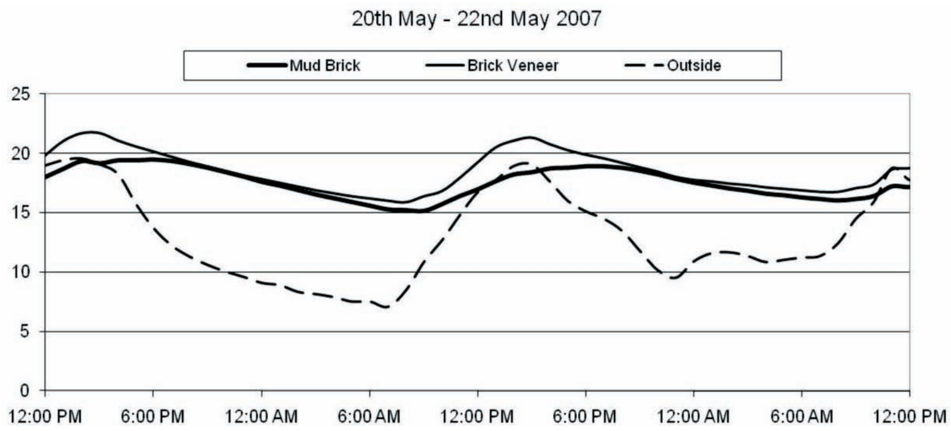
What is also interesting is that the range is least for a mud brick wall thicknesses of 450 mm, increasing slightly for a wall thickness of 600 mm. This is possibly due to the differing times for lagged driving temperature.

Mean outside temperature for the month was 23.3 °C with an average adaptive comfort temperature of 25° C (0.31×23.3 + 17.6) according to ASHRAE standard 55 (9). Importantly the unpainted mud brick option produces the same maximum temperature (defined as average monthly plus half the range) as the insulated brick veneer building (the latter having an R of 2.04 m^2K/W) at a thickness of 450 mm.

7. WINTER PERFORMANCE

In winter when the outside temperature is relatively low there is very little heat gain through the walls and roof and the main driver of inside temperature is solar gain through the glazing. One might expect that in the absence of heating the inside temperature would be above the outside temperature but still significantly below normally accepted comfort levels. This is illustrated in Figure 7 for the test buildings with the average temperature in the insulated brick veneer building (18.5 °C) being about 1 degree higher than in the mud brick building. The outside average temperature was around 13 °C.

When heat is added to bring the inside temperature up to a comfortable temperature, say 20 degrees Centigrade, the loss of heat through the walls to the outside is controlled by the steady state thermal resistance of the walls and the energy required to keep the interior at a constant temperature is thus related to the steady state thermal resistan-



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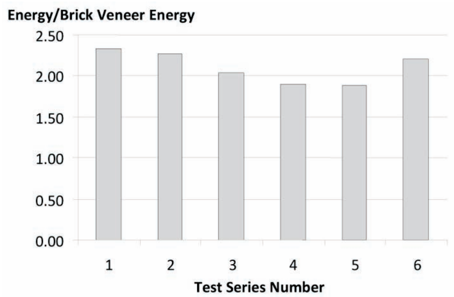
7. Winter temperatures May 2007

8. Energy required to keep mud brick building at comfortable temperature relative to brick veneer building

9. Heating energy/annum vs wall thickness

ce of the building envelope. In the case of the buildings in question (Figure 8) the total steady state thermal resistance of the mud brick building was half that of the brick veneer building and the energy required to keep it at a constant temperature was around twice that of the brick veneer building.

The two buildings were run in "Rating" mode using the AccuRate program to see the effect increasing the size of north facing glazing would make. Figure 9 shows the heating energy outputted by the program to keep the buildings within the winter comfort conditions (approx 23 °C) for the actual conditions (glazed door with glass area of 1.6 m^2), and for glazing three times that area. This shows that the heating energy required is inversely proportional to wall thickness and that increasing the glazing area threefold reduces the heating energy demand by approximately 50%.



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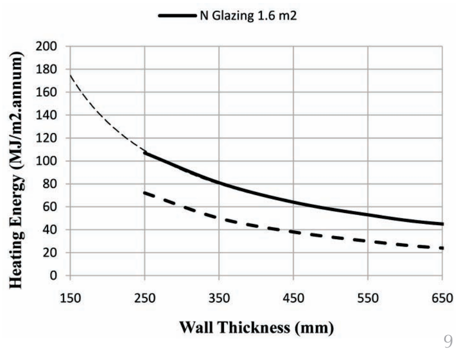

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8. CONCLUSIONS

As a result of my examination of theory relating to heat transfer, my experimental work and my modelling of the experimental buildings, I have come to the following conclusions.

1. Earth walls have poor steady state thermal resistance, and although this increases linearly with thickness even walls 600 mm thick still have relatively low steady state thermal resistance. This means that in summer average temperatures will generally be higher and in winter more heating would be required to bring **average** temperatures up to comfortable levels than would be the case with insulated construction, **everything else being equal**. Both these effects can be alleviated with good passive design (eg shading, light coloured walls etc) and good building operation (eg venting, shutting curtains etc).

2. In summer earth walls do in fact moderate the passage of heat as predicted by theory but this moderation is only significant for fairly thick walls. The cyclic thermal resistance of earth walls increases exponentially with thickness and for walls greater than 450 mm thick this has the effect of almost totally levelling out external temperature swings. This levelling out of temperature swings can in the author's opinion lead to a tolerance for slightly higher average temperatures, thus reducing the effect of low steady state thermal resistance. The provision of internal mass to buildings can also reduce temperature swings and eliminate the need for thick walls in this instance.

3. In the absence of introducing large areas of north facing glazing and internal thermal mass better winter thermal performance

would require additional insulation or walls greater than 450 mm thick. One other option to improve the thermal performance of thinner walls that is worth considering is to place a layer of polystyrene in the centre of the wall. A 250 mm thick wall with a layer of 50 mm of polystyrene in the middle has a steady state thermal resistance equivalent to a brick veneer wall with R 1.5 insulation in the cavity. It also has a very high cyclic thermal resistance.

4. Having light coloured walls significantly reduces sol-air temperatures in summer, and in the experimental buildings constructed by the author this was sufficient to mitigate the low steady state thermal resistance of the walls, such that the performance of the unconditioned mud brick building with painted external walls in summer was only marginally worse than the brick veneer building with R1.5 insulation. In the author's opinion however light coloured walls detract from the naturalness of earth walls

5. The thermal performance of earth walls cannot be isolated from the rest of the buildings construction, and in particular to talk of thermal lag as if it applies to the whole building is misleading. The thermal properties of the roof and floor are very important as is the existence/non-existence of internal thermal mass, which may not necessarily be of earth.

6. Modern earth buildings in developed countries typically have thinner walls than is historically the case with traditional earth buildings. Like buildings of any material the thermal deficiencies of thinner walls can be compensated for by good design and building operation but in general external walls less than about 450 mm thick fail to harness the thermal mass benefits of earth.

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