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Evaluating rammed earth walls: a case study

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Abstract

The following research has been undertaken as a response to the recent controversy regarding the suitability of rammed earth wall construction as an effective building envelope in regard to its thermal performance. The *R*-value for rammed earth walls is low hence they might be expected to conduct heat into a building during summer. However the large mass of these walls and the associated thermal lag in heat transfer from outside to inside may result in the walls performing satisfactorily in a building which is only occupied during working hours. Internal rammed earth walls may act as moderators of large diurnal temperature swings helping to produce an even comfortable temperature within a building. Empirical (in situ) measurements of temperature and heat flux were taken on the walls of an existing rammed earth office building in New South Wales, Australia during the summer. An analysis was performed which established a methodology to measure the heat flow associated with the walls, floor, ceiling, windows and infiltration for one office during occupied hours and the net energy transferred between the office and these elements was established. During this time the earth walls performed well. External walls were found to transmit comparatively little heat to the office and the internal walls absorbed heat during this time. Diffuse sky radiation transmitted by the window and infiltration are both likely to be important factors in the summer heat load.

1. Introduction

Rammed earth walls have a low *R*-value (CSIRO, 2000). Therefore it might be expected that they will perform poorly as a building envelope since they will conduct heat into the building during the summer. However supporters of earth building suggest that the large mass of the walls mitigate this effect and that they perform well (Kruithof, 2000).

A two storey university office building having 300 mm thick internal and external rammed earth walls was used for this study. A number of transducers were installed in three of the offices which allowed heat flux to be measured in the walls, ceilings and floors. The results from one office on the ground floor are presented here. Due to the high cost of heat flux meters (HFM) only two were used. The first part of this paper presents a methodology that allows heat flux to be established through the use of accurate thermistors without using HFMs. Calculating the heat flow in other building elements such as the windows is also discussed.

In the second part of the paper the performance of the earth walls is examined by establishing the total *energy* supplied or removed from the office by the walls during the occupied time (9 a.m. to 5 p.m.) and comparing this with the energy exchanged with other room elements or with the energy gained through infiltration.

2. Background

The offices are located in the Riverina district in NSW Australia which characteristically has cool wet winters with hot dry summers. The mean temperature for February at the time of the study (2001) was 24.4 °C

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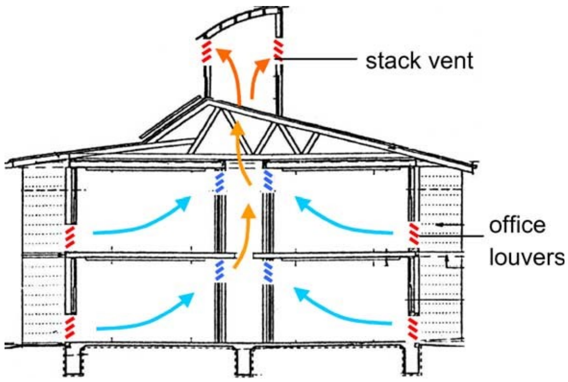

Fig. 1. A section of the building showing its natural ventilation features.

with an average high daily temperature of 31.4 °C, and an average low daily temperature of 17.6 °C. The lowest minimum recorded was 11.4 °C. The summer days often have clear skies with total global daily radiation of 30 MJ/m^2 on a horizontal surface. Outdoor measurements were taken from a portable weather station installed nearby.

The office building does not have a typical HVAC plant. Conditioning is achieved by hydronically heated and cooled floor and ceiling slabs, although at the time of this study no hydronic cooling was used. In the summer the large thermal mass is intended to moderate the large daily ambient temperature swings. Night time ventilation is designed to keep the building cool. The ventilation system consists of computer controlled vents in the offices and in the ventilation stacks (Fig. 1). Each office has a ceiling fan and a sliding sash window. The building provided for an ideal case study of a rammed earth, passively cooled, commercial scale building.

The four days chosen for this analysis were from Friday the 23rd to Monday the 26th of February. There were clear skies for most of this period but the 25th was overcast during the day. The lowest temperature reached was 14.6 °C at 6 a.m. on the 26th.

3. Instrumentation and office description

The monitored room is on the south east corner of the building. The installed instrumentation and its use are given in Table 1. The transducers were connected to Campbell Scientific data loggers and data recorded every 15 min. The wall mounted thermistors and HFMs were embedded 5 mm in the wall surfaces (exterior and interior) and mortared over. The HFMs were mounted to ASTM standards (ASTM, 1995). All heat fluxes into the office were taken as positive.

The locations of the HFMs and the thermistors are shown in a plan of the office (Fig. 2). The office is 2.7 m high. At location 1 a chain of thermistors was established from floor to ceiling at heights of 0.0, 0.1, 0.6, 1.1, 2.5 and 2.7 m. A thermistor was placed just on the inside of the vent underneath the window (location 2).

4. Heat flow methodology

Heat was transferred from the walls to the office space by convection and radiation. The power (q_{c+r}) exchanged with the room may be expressed as the product of a surface coefficient (h_{c+r}) and the temperature difference between wall and the air (Eq. (1)). (All powers and heat fluxes in this section have units W/m^2.)

$$q_{c+r} = h_{c+r}(T_{surface} - T_{air}) \tag{1}$$

where $T_{surface}$ is the temperature of the internal wall surface; T_{air} is the temperature of the air in the room.

The coefficient combines the effects of both radiative heat transfer and convection and so might be expected to be a function of the temperature difference. However this formula gave a good visual match between the flux

Table 1
Instrumentation chart indicating measured parameters and their requirements

Parameter	Data use and purpose	Instrument/sensor
Air temperature stratification	Uniformity of room temperature. Thermal comfort. Heat transfer between surfaces	Radiation shielded thermistors placed at 0.1, 0.5, 1.0 and 2.5 m from floor
Thermal comfort	To establish periods of thermal comfort. Combines air temperatures and fan use information	• Globe thermometer • Humidity • Air velocity (fan use, estimation)
Wall temperatures	Heat flux calculation and conductivity analysis in wall. Surface to room air heat transfer	Embedded thermistors: external, middle and internal wall
Wall heat flux	Heat flux calculation within wall. Conductivity analysis verification	Embedded heat flux meters: external and internal to wall surfaces
Window use	Occupant periods of use	Magnetic reed switch, on/off
Fan use	Occupant periods of use, air velocity, thermal comfort	Magnetic reed switch, pulse counted, calibrated to air velocity at head height

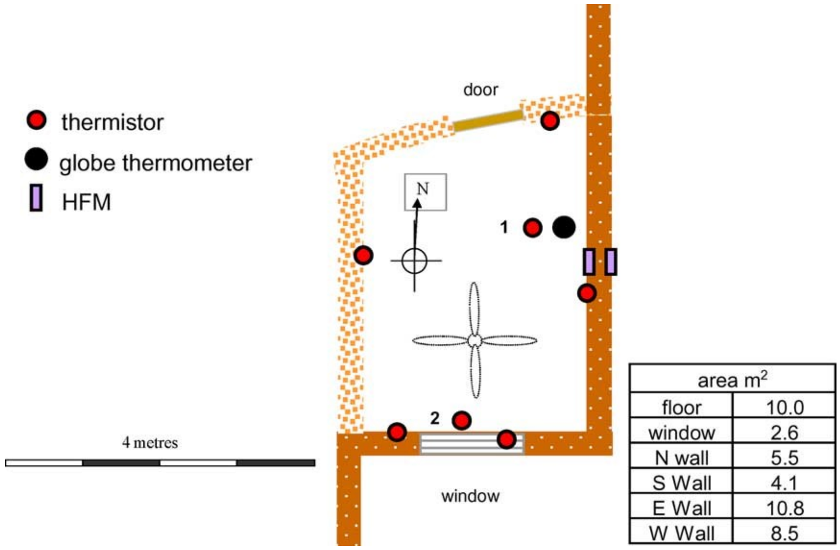

Fig. 2. Office plan showing sensor locations and room element areas.

measured with the HFM and a calculated flux when an empirical value of 6.5 W/m^2 K was used for the surface coefficient (Fig. 3). It was found that a better match was obtained if the globe temperature was used rather than the air temperature as the former is the average of the mean radiant temperature and the air temperature. Having established a value for h_{c+r}, heat fluxes can be determined for walls which have only the surface temperature measured such as for the south wall (Fig. 3).

To establish heat fluxes from floor and ceiling the air temperatures near and on these surfaces were used. The h_{c+r} surface coefficients used were 9.26 W/m^2 K for upward heat flow, and 6.13 W/m^2 K for downwards heat flow (ASHRAE, 1997).

To examine the effect of the large mass of the rammed earth wall on its heat transfer characteristics it is useful to produce a fictitious heat flux for a wall which

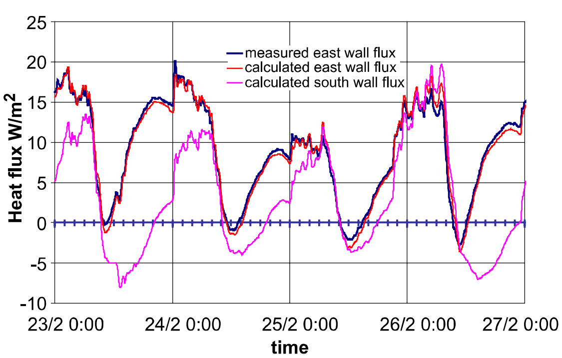

Fig. 3. Measured and calculated heat fluxes in the rammed earth walls.

has no mass, but the same R-value. This may be done using the recorded surface temperatures (Eq. (2)).

$$q_{\text{wall}} = \frac{(T_{\text{outside\_surface}} - T_{\text{inside\_surface}})}{R_{\text{wall}}} \tag{2}$$

where q_{wall} is the fictitious heat flux; $T_{\text{outside\_surface}}$ is the temperature of the external wall surface; $T_{\text{inside\_surface}}$ is the temperature of the internal wall surface; R_{wall} is the thermal resistance of the wall (excluding air films).

The empirically established R-value was 0.27 m^2 K/W based on the rammed earth conductivity of 1.1 W/m K and wall thickness of 300 mm. The conductivity was obtained by using a numerical method described by Balcomb and Hedstrom (1980) and matching simulated and measured heat flux and wall temperatures.

Solar radiation falling on a window can be described by Eq. (3) (Szokolay, 1987).

$$G_{\text{vertical}} = G_{\text{b}} \frac{\cos(\text{INC})}{\sin(\text{ALT})} + 0.5G_{\text{d}} + 0.5\rho(G_{\text{b}} + G_{\text{d}}) \tag{3}$$

where G_{b} is the direct beam radiation; G_{d} is the diffuse radiation; ρ is the ground reflectance taken as 0.2; INC and ALT are sun angles.

The windows are shaded to stop direct solar radiation. The diffuse component of sky radiation which entered the building via the window was estimated from figures taken from the Australian Solar Radiation Data Handbook (Lee et al., 1995) for Mildura which has a similar climate. The total heat flux transmitted by the window (q_{window}) was then calculated from Eq. (4) (ASHRAE, 1997). The SHGC is the solar heat gain coefficient estimated for the effect of a Venetian blind and 3.2 mm glass. U was calculated as 3.0 W/m^2 K for the heat conduction part of the equation.

$$q_{\mathrm{window}} = G_{\mathrm{vertical}}(\mathrm{SHGC}) + U_{\mathrm{window}}(T_{\mathrm{ambient}} - T_{\mathrm{air}}) \quad (4)$$

where T_{ambient} is the ambient outside air temperature; T_{air} is the temperature of the air in the room.

The net energy transferred to or from the room for each surface from 9 a.m. to 5 p.m. was calculated by multiplying the flux by the area of the surface in question for each 15 min interval and integrating over the time period.

The infiltration rate for the office was not known. However there may be significant infiltration because it is known from the occupants that the vents do not seal effectively and the building itself is designed to promote air circulation through the stack effect. Eq. (5) was used to calculate energy flowing into the office (ASHRAE, 1997). A flow rate of one air change per hour was assumed.

$$q_{\mathrm{infil}} = AV\rho c_p(T_{\mathrm{ambient}} - T_{\mathrm{air}}) \quad (5)$$

where q_{infil} is the power transmitted to the office through infiltration; A is the air changes per hour; V is the office volume; ρ is the density of air; c_p is the specific heat of air.

To establish the heat entering the building through infiltration equation (5) was integrated over the 9–5 time period.

5. Office air temperatures

The temperature of the air in the office is in part determined by the computer controlled cooling ventilation. The vent into the office and those in the stack are opened when the outside air temperature falls to 2 °C below the average temperature inside the building. Ventilation continues until the internal and external temperatures equalize. The temperature of the air entering the office via the vent was measured with the sensor at location 2 (Fig. 2) and clearly shows the control algorithm in action (Fig. 4).

The air temperatures recorded by the chain of thermistors (location 1, Fig. 2) fell sharply when the vent opened and continued to fall until the incoming air started to warm with the sunrise, at which time they also started to rise (Fig. 5). When the vent closed the internal temperatures increased at a more gradual rate until the vent reopened.

Temperature stratification occurred at all times. The stratification increased during the ventilation period suggesting that the ventilation air flow was insufficient for good air mixing.

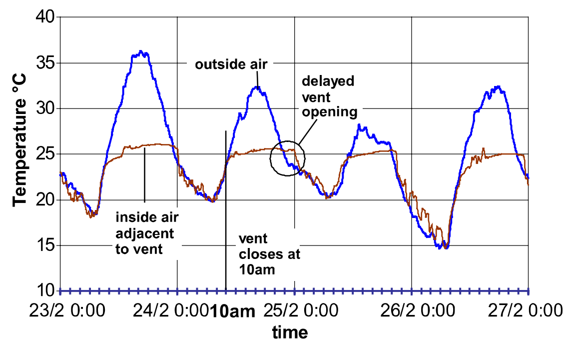

Fig. 4. Ventilation air and outside air temperatures.

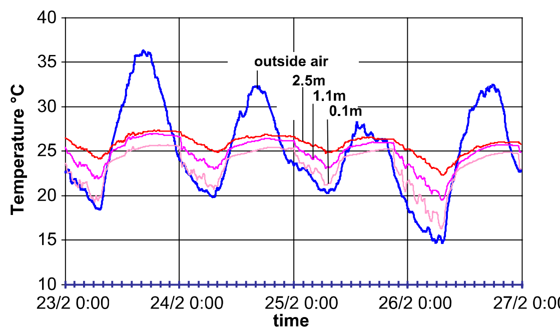

Fig. 5. Office air temperatures at different heights.

6. External walls, the decrement factor and thermal lag

The east facing external wall is entirely exposed to the sun. Fig. 6 shows the measured heat fluxes at the outside and at the inside together with the fictitious flux. A large peak in the external flux is a result of the early morning sun (23rd and 26th).

When the fictitious flux is compared to the measured inner surface flux the latter shows a decrease in amplitude of approximately 25% and a phase shift of about 10

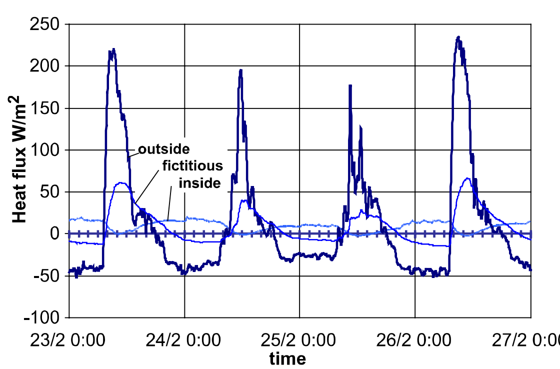

Fig. 6. External and internal measured heat flux for the east wall, and a fictitious (no mass) flux.

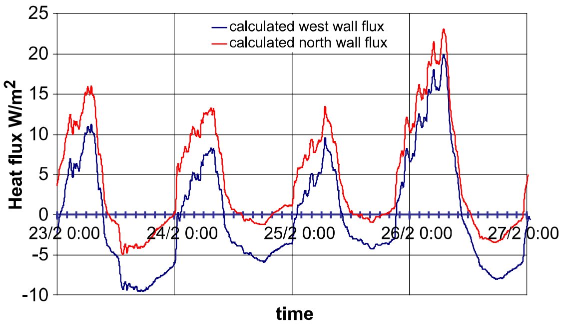

Fig. 7. North and west wall calculated fluxes.

h compared to the fictitious flux (Fig. 6). This is an indication of the benefit of a high mass wall. Nevertheless the wall continuously transferred heat into the office.

The south wall calculated heat flux (Fig. 3) is negative during the middle of the day, and during the afternoon, and becomes positive at night. This wall was having a cooling effect during working hours, and was loosing the absorbed heat to the ventilation air (and by conduction to the outside of the building) at night.

7. Internal walls

The internal north and west walls behaved in a similar fashion to the south wall in that heat was absorbed during day and lost at night (Fig. 7). The west wall performed more effectively. The north wall borders a corridor near an external door and has some exposure to sunlight and hot outside air. The north wall did not remain as cool as the west wall which absorbed more heat during the day.

8. Energy exchange from 9 a.m. to 5 p.m.

Having established heat fluxes for each surface it was possible to find the net energy (heat transfer) to the office

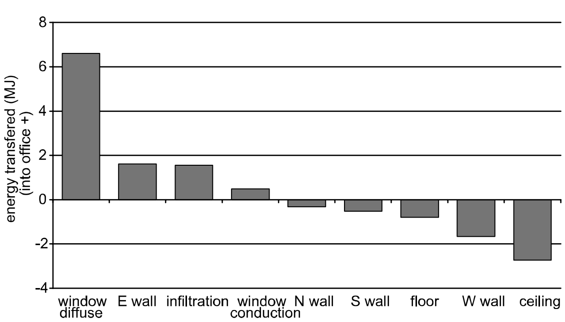

Fig. 8. Net energy transfer from 9 a.m. to 5 p.m. for various elements.

for a working day of 9 a.m. to 5 p.m. (Fig. 8). An assumption had to be made that the flux calculated is an average over its entire surface. This is probably more realistic for the floor and ceiling (horizontal) surfaces than for the walls due to the stratification, however by using temperatures at mid-height variation due to stratification was averaged.

9. Conclusion

The methodology established allowed heat fluxes to be calculated by using accurate thermistors located in the wall at its internal surface and in the airspace within the room. A constant surface transfer coefficient was assumed and this gave good agreement between measured and calculated heat fluxes for the temperature differences and air movements that existed in the office. This procedure does not rely on the characteristics of rammed earth and can be applied to measure heat flux in other construction methods.

The energy transfer calculations for occupied hours indicated that the heat load from the east wall was the same as the infiltration heat load, but was only 25% of the diffuse radiation heat load. The internal west wall absorbed as much heat as the east wall emitted. Data demonstrate that the east wall delays the early morning radiation peak being transmitted to the interior wall surface until the evening. The floor, ceiling and other walls absorb heat during the day helping cool the office.

The thermal performance of rammed earth walls in this climate and at this time of year could possibly be improved with more effective night cooling. However the analysis has shown that the large thermal capacity of earth walls improves their thermal properties above that expected by consideration of *R*-values alone.

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