Rammed earth

Citation for published version:
Ciancio, D & Beckett, C 2013, Rammed earth: An overview of a sustainable construction material. in *Proceedings of the 3rd Sustainable Construction Materials and Technologies Conference.* Sustainable construction materials and technologies, pp. 1-9, 3rd International Conference on Sustainable Construction Materials and Technologies, SCMT 2013, Kyoto, Japan, 18/08/13.

Rammed earth: an overview of a sustainable construction material

Daniela Ciancio[1], Christopher Beckett[1,*]

[1]*University of Western Australia, 6009 Australia*
[*]*School of Civil and Resource Engineering M051, University of Western Australia, 35 Stirling Highway, Crawley 6009 Western Australia*
daniela.ciancio@uwa.edu.au
chris.beckett@uwa.edu.au

ABSTRACT

Rammed earth is an ancient construction technique that consists of unsaturated loose soil compacted inside a formwork. Through the analysis of a recent project that sees the application of this material in remote communities of Western Australia, this paper discusses the social, financial and environmental sustainability of rammed earth. It shows that its embodied energy is low when compared to other materials like steel or concrete. This work also argues the need of heating, ventilation and air conditioning (HVAC) units in rammed earth buildings to reduce the dependence on the energy required by these units, energy that is not always available in remote areas or in under-developed countries. In hot arid climatic zones, by simply applying some traditional design features it might be possible to create a comfortable living space without any artificial air conditioning devices.
Keywords. Rammed earth; embodied energy; thermal performance.

1. INTRODUCTION

Recently, the University of Western Australia has established a partnership with the Department of Housing of the Government of Western Australia with the goal of improving the housing program in remote Aboriginal communities of Western Australia (WA) (Ciancio and Boulter, 2012). This research project, partially funded by the State Government of WA and partially by the Australian Research Council, is motivated by the recognition of the potential benefits of using rammed earth as a sustainable construction material, especially in remote areas.

In general, the cost of a house is mainly determined by: 1) the cost of the construction materials and 2) the cost of the labour force working on the construction site. In a remote community, it is often the case that neither construction materials nor skilled labour are readily available on site. For this reason, two more expenses must be added to the list: 3) the transportation of the materials from the closest supply centres to the remote community and 4) the accommodation of the skilled labour force brought on site. In light of this analysis, it is reasonable to state that the overall construction cost of a house in a remote area is always higher than the cost of the same house built in a metropolitan zone. For this and other reasons, in many remote communities of Australia (majority of them occupied by Aboriginal people), families cannot afford the expenses of building their own home.

But construction cost is not the only issue with housing in remote zones. The most preferred construction technique in Australian remote areas is the *steel framed* house. In the hot climate areas of the centre and north of Australia (where the majority of the Aboriginal communities concentrate), generally the comfort of this type of house depends on an air-conditioning system installed inside. If it breaks, the comfort of the dwellers relies on the availability of an air-conditioning technician willing to make a potentially long journey to reach the house and fix the problem. In the likely event that the air-conditioning unit is not fixed, conditions inside the house become hostile and eventually it is abandoned. This leads to further deterioration before the house can be repaired and occupied again. In 2006, 30% of the total permanent dwellings (mainly steel framed houses) in Aborigianl communities required major repair or replacement. In that same year, according to the Australian Bureau of Statistics, AUS$37.4 million was spent in the repair and maintenance of Aboriginal housing (Australian Bureau of Statistics, 2006). The Sydney Morning Herald reported in 2009 that in another occasion the Australian government spent AUS$80 million to inspect or fix 2,900 houses in the Northern Territory alone (Farrelly, 2009).

This paper discusses the motivations behind the choice of rammed earth as a sustainable construction technique in remote and/or under-developed areas of the world. The social and financial sustainability of this material is discussed in detail in the Section 2. The environmental sustainability is presented in Section 3. The thermal performance of a rammed earth house in different climatic areas is presented in Section 4, highlighting the importance of the thermal mass of the material. Some concluding remarks are finally offered in Section 5.

2. FINANCIAL AND SOCIAL SUSTAINABILITY OF RAMMED EARTH

Rammed earth is a building technique where moist earth comprising varying proportions of clay, sand and gravel is compacted into rigid formwork in successive layers until the desired height is reached (Middleton and Schneider 1987, Walker and Standards Australia 2002, Easton 2007). There are many thousands of historic rammed earth structures around the world, some of them dating from 1500 BC (some famous historical examples are still visible in the Great Wall of China or in the Alhambra in Spain) strong evidence that rammed earth can be a durable construction material. Traditionally stabilised with lime or bitumen, nowadays rammed earth is stabilised with cement whose content is usually between 3 and 10% of the soil mass. In Australia and USA, cement stabilisation has become an accepted routine practice.

Sustainable, cost effective and durable houses made of rammed earth may provide a solution to the problem of expensive housing in remote areas mentioned in the previous Section. Soil can be sourced on-site at zero or almost zero cost. The transportation cost of the construction materials when the main bulk component (earth) is sourced on-site is significantly reduced. Furthermore, rammed earth walls do not require painting or other wall treatments resulting in minimum on-going maintenance cost (Bui *et al.*, 2009).

In 1933, as part of the National Industrial Recovery Act in USA, a total of 7 rammed earth houses were built in Gardendale, Alabama. Architect and engineer Thomas Hibben successfully taught unskilled labourers to build a rammed earth house. Fourteen men needed 5 weeks to build the walls for the first house, but only 5 days to build the last of the 7. The original houses are still occupied today (Easton, 2007). In a similar way, in June 1997, the Arrillhjere house project in the west of Alice Springs, Australia, was successfully completed. Aboriginal unskilled labourers were employed to build the rammed earth foundation and the mud brick walls of the Arrillhjere house (Hueneke, 2004). Aboriginal people gained knowledge of appropriate technologies and building techniques through participation and hands-on involvement, taking those experiences and utilising them back in their own communities. The bulk of rammed earth construction is very straightforward (as shown in Figure 1). It is necessary to have only one experienced rammed earth contractor on site during construction when sufficient (even semi-skilled) labour is available. As a result, not only can local jobs be created, but the overall cost of the construction may be reduced by eliminating the need for expensive accommodation for labour brought in from outside.

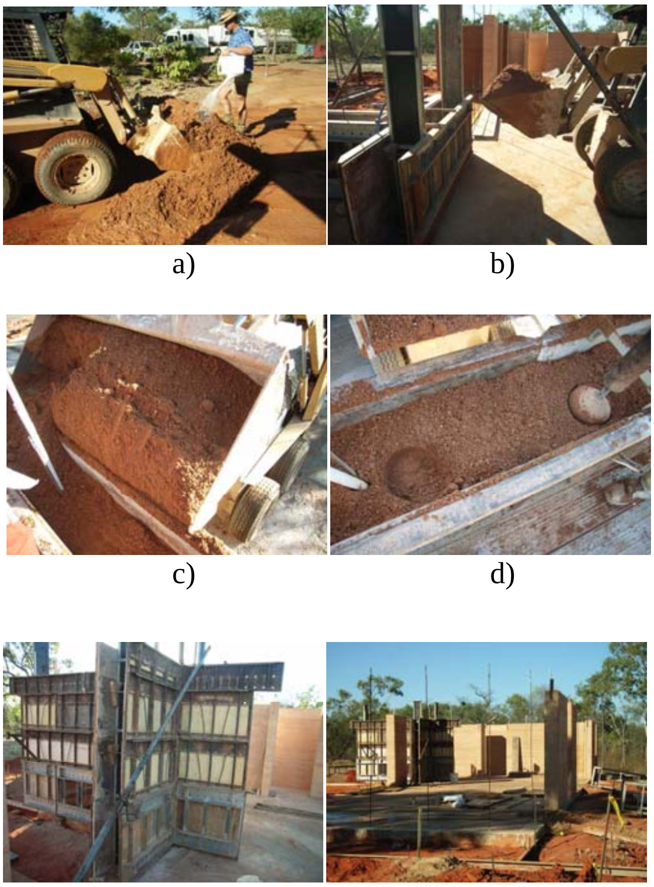
3. ENVIRONMENTAL SUSTAINABILITY OF RAMMED EARTH

The economic and social benefits of rammed earth are not the only attractive features of this material. It has been recognised in different applications around the world that earthen techniques in general and rammed earth in particular have environmental and sustainable benefits. In a study conducted in France (Morel et al., 2001), the use of locally sourced materials in rammed earth construction demonstrated a significant reduction in the environmental impact when compared to a case in which the construction material is sourced far away and transported to the building site. The energy consumed in transportation can be reduced by 85% when comparing a rammed earth to a typical concrete house. In another project in India (Venkatarama Reddy and Jagadish, 2003), the use of soil and cement to create unfired masonry blocks resulted in a 62% reduction in embodied energy (which is the energy used to produce a material or a product) when compared with a reinforced concrete framed structure and a 45% reduction when compared with burnt clay brick masonry and reinforced concrete solid slab construction.

Table 1. Comparison between the total production energy per unit length of wall made of cement-stabilised rammed earth and steel framed

	rammed earth	steel
height [m]	2.4	2.4
length [m]	1	1
thickness [m]	0.3	0.005
volume rammed earth	0.72	-
density rammed earth [kg/m3]	2000	-
mass rammed earth [kg]	1440	-
mass of cement (10% mass rammed earth) [kg]	144	-
density cement [kg/m3]	1500	-
volume cement and steel [m3]	0.096	0.012
specific production energy e_p [GJ/m3] (Harris 1999)	10.296	370.8
total production energy $E_p = e_p \times Volume$ [GJ]	0.988416	4.4496

It is beyond the scope of this paper to give a proper definition of the word ‘sustainability’. In this work, ‘environmental sustainability’ is used as a term to indicate the environmental impact of the building materials analysed in this case study. The amount of embodied energy, or ‘emergy’, of a material is often used to give an indication of this type of impact (Boyle, 2005). Table 1 compares the production energy – the energy required to produce the materials from which a building is constructed (Harris, 1999) – of a 1 m long and 2.4 m high wall made of 10% cement-stabilised rammed earth and of steel framed panels. In the case of rammed earth, the thickness of the wall has been taken as 300 mm. In the case of the steel framed panels, an equivalent thickness of 5 mm has been calculated averaging the material used in a steel frame of 300 mm/m horizontal and 800/2.4 m vertical spacing, with a corrugated steel laminate on top of it. Assuming that the production energy of earth is negligible with respect to that of steel and cement (no mining or burning is required), the production energy for cement-stabilised rammed earth has been taken as equal to the energy of the cement used in the stabilisation. The numbers in Table 1 show that 10% cement-stabilised rammed earth has significantly lower production energy than steel.



a) b)

c) d)

e) f)

Figure 1. Rammed earth construction procedure: (a) water is added to soil; (b) and (c) moist soil is put into the first layer of formwork; (d) moist soil is compacted; (e) following layers are built up in the formwork to achieve the desired height of the wall; (f) after 1 day the formwork is removed and the wall is allowed to cure

4. THERMAL PERFORMANCE

Current energy saving criteria require that materials of high thermal resistance (that is, a material's ability to reduce heat flux) are used for construction, purportedly to reduce the amount of heat transferred through the boundary surfaces of a structure and so reduce its energy demand (Allinson and Hall, 2007). Thermal resistance can be increased either by reducing a material's thermal conductivity or by increasing the distance through which the heat is passing; this latter option is unsuitable for most applications, however, due to the extra cost of providing the additional thickness. Rammed earth construction suffers as a consequence of this requirement, as the material has a very low thermal resistance (between 0.35 and 0.7 m^2K/W, depending on wall thickness) as compared to more modern construction materials, for example insulated lightweight panels (1.51 m^2K/W) (Maniatidis and Walker, 2003; Page *et al.*, 2011). However, rammed earth buildings around the world are renowned for their ability to provide comfortable living conditions for a range of climate types without the need for active HVAC control. This success therefore suggests that thermal resistance is not the material property responsible for ensuring comfortable living (Allinson and Hall, 2007; Faure and Le Roux, 2012).

Under unsteady conditions, heat flow through a surface is dependent on the material's "thermal diffusivity", a quantity which can be calculated by dividing its thermal conductivity by its thermal mass, calculated via mC_p where m is the material's mass and C_p is its specific heat capacity. A low thermal diffusivity represents a material's ability to slow down the rate of heat transfer due to heat absorption and storage, so that high thermal masses are desirable (Balcomb and Neeper, 1983).

The issue of whether thermal resistance or thermal mass contributes the most towards establishing thermal comfort was recently investigated by Page et al. (2011). They found

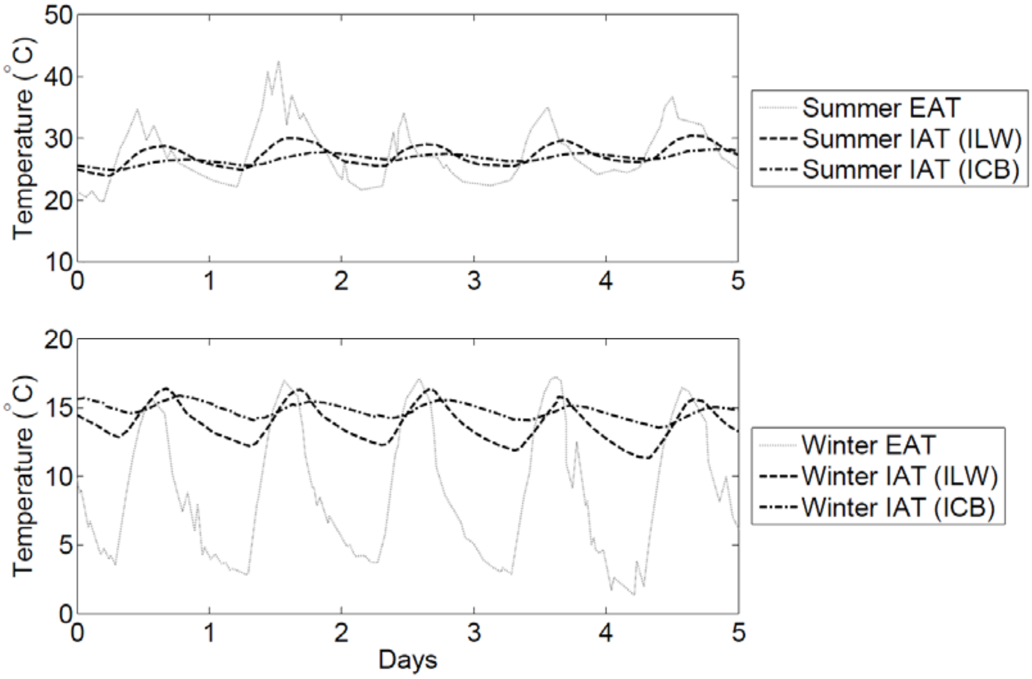


Figure 2: External (E) and internal (I) air temperatures (AT) in ILW (high thermal resistance but low thermal mass) and ICB (low thermal resistance, high thermal mass) structures during typical summer and winter conditions (reproduced from Page et al. (2011)).

Table 1: Thermal lag and internal air temperature variations for investigated RE structures (S = "summer", W = "winter")

Source	Location	External daily temperature range (°C)	Wall thickness (mm)	Thermal lag (hours)	Internal diurnal air temperature variation (°C)
Hardin *et al.* (2003)	Sonoran Desert, North America	21-40	450-610	12-16	Maxima and minima unreported, 4.5°C range for all cases
Taylor and Luther (2004)	New South Wales, Australia	18-31	300	3	23-27 (1.1m above floor level)
Mani *et al.* (2007)	Banskuti, West Bengal	21-33	300	5	23.5-25.5
Soebarto (2009)	Willunga, South Australia	6-15 (W, worst case) 17-38 (S)	220	6	12-15 (W, worst case) 21-32 (S, worst case)

that, for identical ventilation and occupation regimes, structures in Newcastle, New South Wales (Australia) with high thermal mass and low thermal resistance (insulated cavity brick, ICB) produced greater thermal lags and reduced diurnal temperature variations than the structures with high thermal resistance but low thermal mass (insulated lightweight material, ILW). Results for typical five-day periods in summer and winter are shown in Figure 2. Temperatures within the ICB structure were continually within occupancy comfort levels, whilst the greater fluctuations found within the ILW structure resulted in uncomfortable conditions during both summer (too hot) and winter (too cold). Figure 2 also shows that a considerable time delay of roughly 6 hours occurred between the peak external and internal temperatures in the ICB structure, whereas a delay of only roughly 2 hours was found to occur in the ILW structure. This time delay is due to the large amount of heat stored and later released by the high-thermal mass walls and is referred to as the "thermal lag", a property which is highly desirable when designing for thermal comfort as it allows stable temperatures to be maintained overnight (Baggs and Mortensen, 2006).

Similar to the work of Page *et al.* (2011), the relative effects of thermal resistance and thermal mass on resulting thermal comfort were also investigated by Larsen et al. (2012) and Orosa and Oliveira (2012), who found that the heating and cooling energy demands of monitored massive structures were lower than those for similar lightweight structures for both winter and summer conditions in North West Argentina and Galicia, Spain respectively. These works therefore clearly support the observation that it is thermal mass, and not thermal resistance, that is the key factor in passively achieving comfortable internal conditions and that, by ignoring materials with low thermal resistance, many current green construction guidelines are, in fact, leading to the creation of largely unsustainable structures (Balcomb, 1992). This is reflected by the recent acknowledgement of thermal mass as an important factor in reducing the energy use of non-domestic structures (BREEAM, 2011).

Several authors have investigated thermal conditions within traditional earthen structures in order to investigate their ability to passively maintain comfortable internal conditions. Fitch and Branch (1960) presented results for the conditions within an adobe house in Egypt during a typical summer's day, as shown in Figure 3. Adobe is a similar material to rammed earth, in that it uses local soil to form structural components and has a low thermal resistance, however it is less dense (as it has a higher clay content and is generally not compacted) so that its thermal mass, per amount of material, is lower than that of rammed earth (Oti *et al.*, 2009). Although results showed that, for the period in question, the external air temperature ranged between 22 and 40°C and the roof surface temperature approached 60°C, internal air temperatures only ranged between 24 and 29°C, due to the protection afforded by the high thermal mass of the adobe walls, with a thermal lag of roughly 10 hours.

Hardin *et al.* (2003), Taylor and Luther (2004), Mani *et al.* (2007) and Soebarto (2009) have all conducted investigations into the indoor performance of rammed earth structures in different regions around the world. A summary of their findings is shown in Table 2. In each case, significantly reduced internal thermal variations were observed with respect to external conditions and, with the exception of Soebarto (2009) in winter, each structure was able to maintain comfortable internal conditions throughout the year. These results are supported by those of Florides et al. (2002), Wagner et al. (2007), Breesch and Janssens (2010) and Miller et al. (2012), who conducted comfort analyses on massive, non-earthen structures (both commercial and domestic) and who again identified that it was the intelligent use of high thermal mass which was responsible for maintaining comfortable conditions and that the

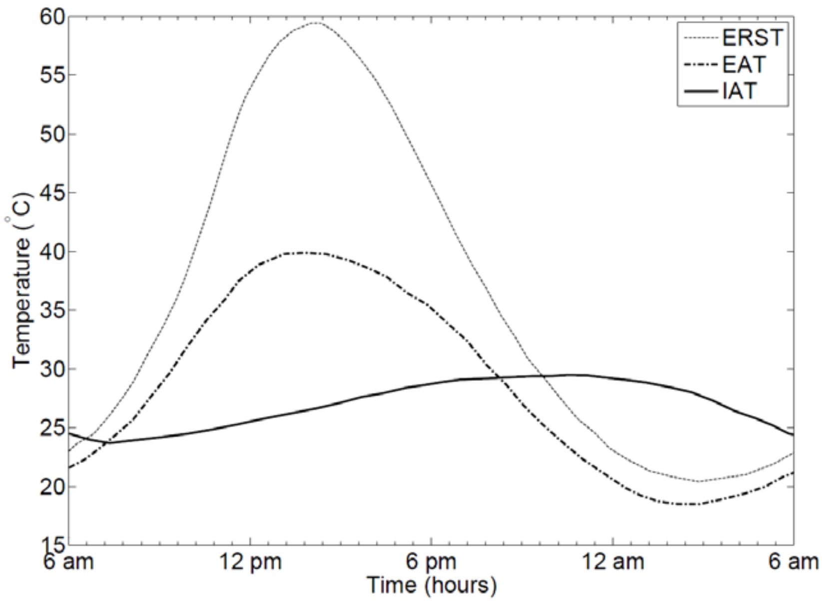


Figure 3: External and internal air temperatures (EAT and IAT respectively) and external roof surface temperature (ERST) for a traditional adobe structure in Egypt (reproduced from Fitch (1960))

ability of thermal mass to passively regulate internal temperatures is maximised when subjected to large diurnal temperature variations, for example as found in hot, arid regions. This is a critical finding for supporting the use of rammed earth in WA, as it is in such areas that the demands for Aboriginal housing are at their greatest and that the current construction solutions, which are heavily dependent on HVAC, are failing.

5. CONCLUSIONS

This paper presented an overview of the sustainable features of rammed earth. The use of this construction material in remote regions or under-developed countries is suggested as a viable alternative to other more common building techniques like concrete and steel. The analysis presented in the paper refers to a real project that aims to create a more sustainable housing program in remote Aboriginal communities of Western Australia. Nevertheless, it is reasonable to state that the motivations to promote the use of rammed earth are also valid in any part of the world affected by remoteness, scarceness of energy resources and poverty.

ACKNOWLEDGES

The authors would like to thank the Department of Housing of the Government of Western Australia and the Australian Research Council for providing the necessary funding for this work.

REFERENCES

Allinson, D. & Hall, M. (2007). “Investigating the optimisation of stabilised rammed earth materials for passive air conditioning in buildings”, *International Symposium on Earthen Structures*, 109-112.

Australian Bureau of Statistics (2006). “Housing and Infrastructure in Aboriginal and Torres Strait Islander Communities”, http://www.abs.gov.au/AUSSTATS/abs@.nsf/Lookup/4710.0Main+Features22006.

Baggs, D. and Mortensen, N. (2006). “Thermal mass in building design”, *Royal Australian Institute of Architects for the Australian Council of Building Design Professions Ltd.*

Balcomb, J. D. and Neeper, D. A. (1983). “Diurnal heat storage in direct-gain passive-solar buildings”, *Proceedings of the 21st AIChE-ASME National Heat Transfer Conference*.

Breesch, H. and Janssens, A. (2005). “Uncertainty and sensitivity analysis to evaluate natural night ventilation design in an office building”, *AIVC 26th Conference*, 3-8.

Bui, Q., Morel, J., Venkatarama Reddy, B. and Ghayad, W. (2009). “Durability of rammed earth walls exposed for 20 years to natural weathering”, *Building and Environment*, 44: 912-919.

Ciancio, D. and Boulter, M. (2012), “Stabilised rammed earth: a case study in Western Australia”, *Proceedings of the ICE – Engineering sustainability*, 165(2): 141-154.

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

Farrelly, E. (2009). “A shamed nation turns a blind eye”, *the Sydney Morning Herald,* http://www.smh.com.au/opinion/society-and-culture/a-shamed-nation-turns-a-blind-eye-20091116-ignn.html>(Nov. 16, 2009).

Faure, X. & Le Roux, N. (2012). “Time dependent flows in displacement ventilation considering the volume envelope heat transfers”, *Building and Environment*, 50; 221-230.

Fitch, J. M. and Branch, D. P. (1960). *Primitive architecture and climate*, Scientific American, 203; 134-145.

Florides, G., Tassou, S., Kalogirou, S. and Wrobel, L. (2002). “Measures used to lower building energy consumption and their cost effectiveness”, *Applied Energy*, 73; 299-328.

Hardin, M. C., Merry, S. and Fritz, W. 2003. “Towards an affordable rammed earth dewelling”, *Proceedings, 2003 PLEA (Passive and Low Energy Architecture) Conference*, Bustamante, W. & Collados, E. (Eds.).

Harris, D.J. (1999). “A quantitative approach to the assessment of the environmental impact of building materials”, *Building and Environment* 34(6): 751–758.

Hueneke, H. and Wright, A. (2004), “Olive’s Place: Reflections on a Housing Project, Seven years On”, *Centre for appropriate technology*, http://www.icat.org.au/media/Research/housing/Olives-place-reflections.pdf.

Larsen, F. S., Filippín, C. and González, S. (2012). “Study of the energy consumption of a massive free-running building in the Argentinean northwest through monitoring and thermal simulation”, *Energy and Buildings*, 47; 341-352.

Mani, M., Dayal, A. and Chattopadhyay, R. N. (2007). “An assessment into the sustainability of earthen structures and modern transitions”, *International Symposium on Earthen Structures*, 154-166.

Maniatidis, V. & Walker, P. (2003). *A Review of Rammed Earth Construction*.

Middleton, G.F., and Schneider, L.M. (1987). *Bulletin 5: Earth-Wall Construction, 4th edn*, CSIRO, Sydney.

Miller, W. and Buys, L. (2010). “Post-occupancy analysis of a sub-tropical Zero Energy Home (ZEH)”, *Proceedings of the 48th AuSES Annual Conference*.

Morel, J., Mesnah, 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: 1119-1126.

Orosa, J. A. and Oliveira, A. C. (2012). “A field study on building inertia and its effects on indoor thermal environment”, *Renewable Energy*, 37; 89-96.

Oti, J., Kinuthia, J. and Bai, J. (2009). “Unfired clay bricks: from laboratory to industrial production”, *Proceedings of the ICE - Engineering Sustainability*, 162(4): 229-237.

Page, A., Moghtaderi, B., Alterman, D. and Hands, S. 2011. “A study of the thermal performance of Australian housing”, The University of Newcastle Australia, Priority Research Centre for Energy, The University of Newcastle.

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

Taylor, P. and Luther, M. B. (2004). “Evaluating rammed earth walls: A case study”, *Solar Energy*, 76; 79-84.

Venkatarama Reddy, B. and Jagadish, K.S. (2003), “Embodied energy of common and alternative building materials and technologies”, *Energy and Buildings*, 35: 129-137.

Walker, P. and Standards Australia (2002). *HB 195: The Australian Earth Building Handbook*, Standards Australia International Ltd, Sydney.

Wagner, A., Kleber, M. and Parker, C. (2007). “Monitoring Results of a Naturally Ventilated and Passively Cooled Office Building in Frankfurt, Germany”, *International Journal of Ventilation*, 6; 3-20.