Journal of Building Engineering 15 (2018) 243–251

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Measured and simulated thermal behaviour in rammed earth houses in a hot-arid climate. Part A: Structural behaviour

C.T.S. Beckett[a], R. Cardell-Oliver[b,*], D. Ciancio[a], C. Huebner[c]

[a] *School of Civil, Environmental and Mining Engineering, The University of Western Australia, Australia*
[b] *School of Computer Science & Software Engineering, The University of Western Australia, Australia*
[c] *Institute for Industrial Data Processing and Communication, University of Applied Sciences, Mannheim, Germany*

ARTICLE INFO

Keywords:
Rammed earth
Insulated rammed earth
Thermal stability
Thermal lag
Environmental monitoring
Rural housing

ABSTRACT

Heating and cooling of residential buildings consumes around ten percent of the world's energy. One approach for reducing these costs is to exploit the high thermal mass of sustainable building materials, for example rammed earth (RE), for intelligent solar passive design. However, there is a lack of scientific evidence about the thermal performance of RE houses in real-world settings.

This research investigated to what extent thermal performance in unconditioned RE structures in rural Australia can be captured by current accreditation software. Two custom-designed houses were built in the hot-arid city of Kalgoorlie-Boulder, Western Australia: one comprising traditional solid cement-stabilised rammed earth walls (RE) and the other walls with an insulating polystyrene core (iRE). Otherwise the houses were identical in orientation and design. The houses were instrumented to monitor indoor temperature and humidity conditions prior to and during occupancy. Results were compared to those simulated using cutting-edge assessment software *BERS Pro* (v4.3) as an example of that used for energy efficiency accreditation in Australia. This first paper in this series discusses the houses' construction and instrumentation and results obtained during the unoccupied period, i.e. those purely demonstrative of the structure's thermal performance. A second paper in the series presents data gathered during occupancy, to contrast occupant thermal comfort with that predicted numerically.

Measured data showed that both houses performed nominally-identically: the houses did not receive any relative benefit from including iRE. Simulated data was also similar per house. However, measured performance did not match that simulated: simulated rooms had poorer thermal stability and lag and, consequently, exaggerated internal temperature variations. Collected data has been made publicly available for future analyses.

1. Introduction

Almost ten percent of the world's annual energy consumption is used for heating and cooling residential buildings [19,3]. Reducing this energy demand, even by a small amount, would yield significant environmental and economic savings [23]. Adopting passive thermal designs is one way to achieve this. A key component of this approach is the intelligent use of thermal mass; the passive ability to absorb and retain heat energy [24,15].

Rammed earth (RE) elements have high thermal mass but low thermal resistance. RE elements consequently perform poorly under current heating and cooling energy efficiency calculations [22]. In response, RE practitioners around the world developed insulated cavity RE walls (iRE), comprising a central insulation panel flanked by external RE leaves. Hall and Allinson [14] and Dong et al. [13] demonstrated that this innovation successfully addressed poor predicted thermal properties whilst retaining the same aesthetic appeal as traditional RE walls. However, iRE construction is slower, and so more costly, owing to the need to compact material either side of the central panel. Furthermore, it is well understood that wall thermal resistance is not the sole predictor of a building's thermal behaviour; rather, the performance of the building as a complete system must be taken into account [20,8]. Therefore, substituting iRE for RE may or may not provide adequate performance improvement for its cost depending on the building's design, location and use.

This series examines the ability of current energy accreditation software *BERS Pro*, (v4.3), typical of that used in Australia, to simulate the thermal performance of an unconditioned RE and iRE house built in Kalgoorlie-Boulder, Western Australia. Both houses were designed to optimise passive solar behaviour and both exceeded the minimum

---

* Corresponding author.
E-mail address: rachel.cardell-oliver@uwa.edu.au (R. Cardell-Oliver).

https://doi.org/10.1016/j.jobe.2017.11.013
Received 14 April 2017; Received in revised form 13 October 2017; Accepted 17 November 2017

energy efficiencies required for construction under the Australian Nationwide House Energy Rating Scheme (NatHERS). This paper, being the first in the series, describes the house construction and instrumentation processes and examines the thermal performance of the structures with no occupants. Measured and simulated performance were contrasted using thermal stability and thermal lag. Measured performance was superior to that predicted by the simulations for both houses, particularly in rooms with lightweight external walls or north-facing floor-to-ceiling windows.

2. House design

Kalgoorlie-Boulder in Western Australia was selected because its arid climate (Köppen Classification Bwh) is well suited to passive indoor thermal and humidity regulation using high thermal mass walls [1]. Temperatures in Kalgoorlie-Boulder can exceed 45 °C in Summer and drop to freezing in Winter. As such, houses are almost exclusively fitted with large artificial heating and cooling units that consume a considerable portion of their annual energy and water (through evaporative cooling) budgets [17,6]. A key aim of this project was to investigate to what extent adopting passive solar design principles founded on using RE could reduce dependence on artificial climate control.

Two houses were custom-designed comprising several features to promote beneficial passive solar behaviour: both made extensive use of high thermal mass RE or iRE walls, the living room was placed centrally with a high (3.6 m) ceiling and central vent to encourage air flow and a wide veranda shaded the north-facing living room windows. Neither house was equipped with means of artificial heating or cooling, however both houses featured ceiling fans in the living rooms and bedrooms and a central vent in the living rooms connected to a Venturi fan at the roof's apex.

Fig. 1 shows the houses' floor plan and orientation. The rightmost house in Fig. 1 comprised 300 mm thick monolithic RE walls throughout. The leftmost comprised a mix of 300 mm thick iRE and monolithic 300 mm RE external walls and 300 mm monolithic RE internal walls. Both houses featured lightweight timber stud/insulated steel panel (“Colorbond” walling system, insulation $R - \text{value} = 1.5\ \text{m}^2\ \text{K/W}$) external walls in the kitchens and bathrooms and both had steel sheet cladding roofs with batt insulation ($R - \text{value} = 3.0\ \text{m}^2\ \text{K/W}$) and timber lining. Externally, the houses appeared identical. For convenience, these houses will be referred to hereafter as the “monolithic” and “insulated” houses respectively.

The RE components were stabilised with roughly 9% by mass of dry soil of Portland cement and compacted to a dry density of approximately 2050 kg/m^3 using a reciprocating pneumatic hammer. Raw soil was obtained from a Coolgardie, roughly 50 km from Kalgoorlie-Boulder, from a pit previously used by the contractor, and combined in 3 parts soil to 1 part river sand to improve particle grading. The iRE walls were formed from a central 50 mm thick extruded polystyrene panel, flanked by two 125 mm RE leaves.

iRE is used in several countries around the world (e.g. Krayenhoff [16]) but is relatively new to Australia. Therefore, concessions were made to structural integrity for iRE panel design. Panels were built with a 300 mm monolithic RE border around their extremities (except at the base) and H-shaped ties, cut from 10 mm reinforcing bar mesh, were placed at 600 mm height intervals connecting the leaves. Insulation was not used in any panels <1000 mm width, for example under windows or in lintels. Resulting insulation configurations for the external walls, corner panels and lintels are shown in Fig. 2.

3. Instrumentation

3.1. Sensor types

The instrumentation layout was designed to accommodate changing regimes prior to and during occupancy. Prior to occupancy, temperature and humidity sensors were placed centrally at head and ceiling level in free air in the living rooms, bedrooms and kitchens to monitor indoor air temperature and humidity. Head-height sensors were then removed on occupancy to avoid damage: approaches used to determine head-level temperatures from ceiling-level data are discussed in the second part of this series. Sensors were also placed within the RE and iRE walls at head height (and additionally at knee and ceiling height in the living rooms) to monitor temperature changes with depth through the walls. A weather station sensing wind speed and direction, precipitation, dry bulb temperature and humidity was positioned between the two houses, as indicated in Fig. 1. A schematic representation of the sensor deployment in this study is shown in Fig. 3. Positions of all sensor groups per house are shown in Fig. 4 and described in Table 1.

Multiple sensor types, obtained from three suppliers, were deployed in each of the monitored environments. *Onset* “HOBO” sensors were placed at room ceiling-level (A1–5), within and on the surfaces of the RE and iRE walls (H1–6) and used for the weather station. “Mannheim” sensors, provided by The University of Applied Sciences Mannheim in

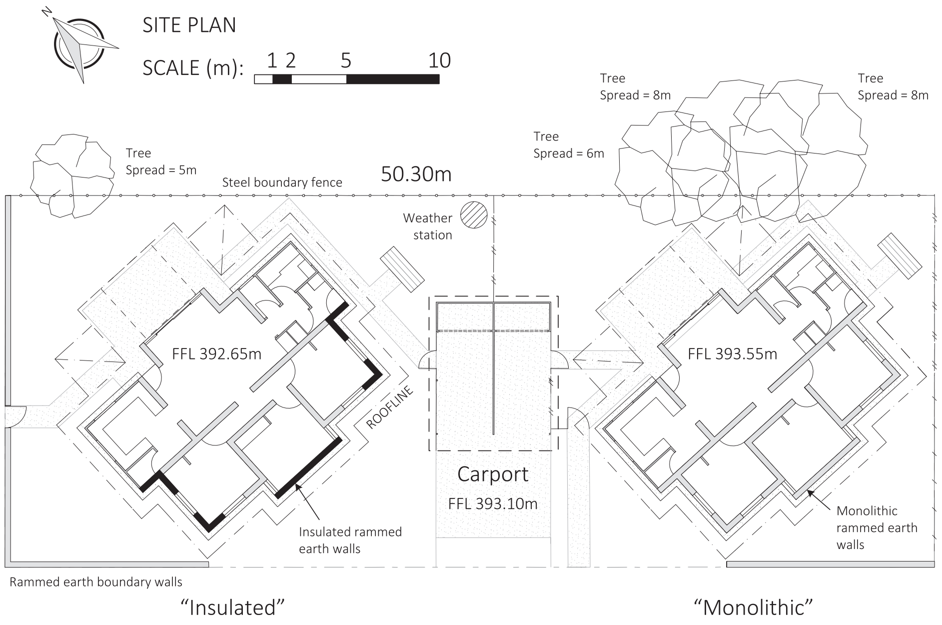

Fig. 1. Site plan for the two houses. RE walls are shown in grey and iRE walls in black. Thin grey walls denote lightweight “Colorbond” walling construction. FFL: Finished Floor Level (above mean sea level).