A REVIEW OF THE CONTRIBUTION OF THERMAL MASS TO THERMAL COMFORT IN RAMMED EARTH STRUCTURES

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Abstract

Rammed earth is a construction material which has been used to build thermally-comfortable structures in many regions around the world for thousands of years. Despite this heritage, rammed earth is currently considered to be unsuitable for construction by many green-building guidelines due to its low thermal resistance, a property deemed to be necessary if a structure is to reduce its heating and cooling demand. This paper introduces thermal comfort and relates it to thermal resistance and thermal mass. A review of previous work which has investigated thermal comfort in rammed earth structures is then presented. Techniques used to adapt the designs of traditional rammed earth structures to suit their prevalent climate are then briefly discussed and compared to modern construction practices in similar regions to suggest methods by which the thermal comfort and sustainability of modern structures can be improved.

Keywords: Rammed earth, thermal mass, passive solar buildings

1. Introduction

Rammed earth (RE) is an ancient construction technique which has been used consistently since c.2000 BCE, during the Neolithic period (Jaquin *et al.*, 2008). Structures are formed by compacting layers of moist sandy loam subsoil between formwork and were generally built and maintained by their occupants, creating a strong bond between the structure, the local community and its surroundings (Fitch and Branch, 1960; Conti, 2009). An example of the RE construction procedure is shown in Figure 1. Formwork is securely fastened together using ties and is then filled in layers, which are then compacted, forming a "block" when full. The formwork is then removed and moved further down the wall to construct the next block. In this manner, a small amount of formwork can be used to create a large structure. The RE technique was spread through trade, natural migrations and conquest so that now RE structures form part of the heritage of many cultures around the world. RE construction practices have changed very little with time, however it is now common to "stabilise" the parent soil through the addition of small amounts of cement or lime, depending on availability, to improve strength and durability (Venkatarama Reddy and Prasanna Kumar, 2011).

Until recently, RE was regarded as a material whose use and design was based purely on local

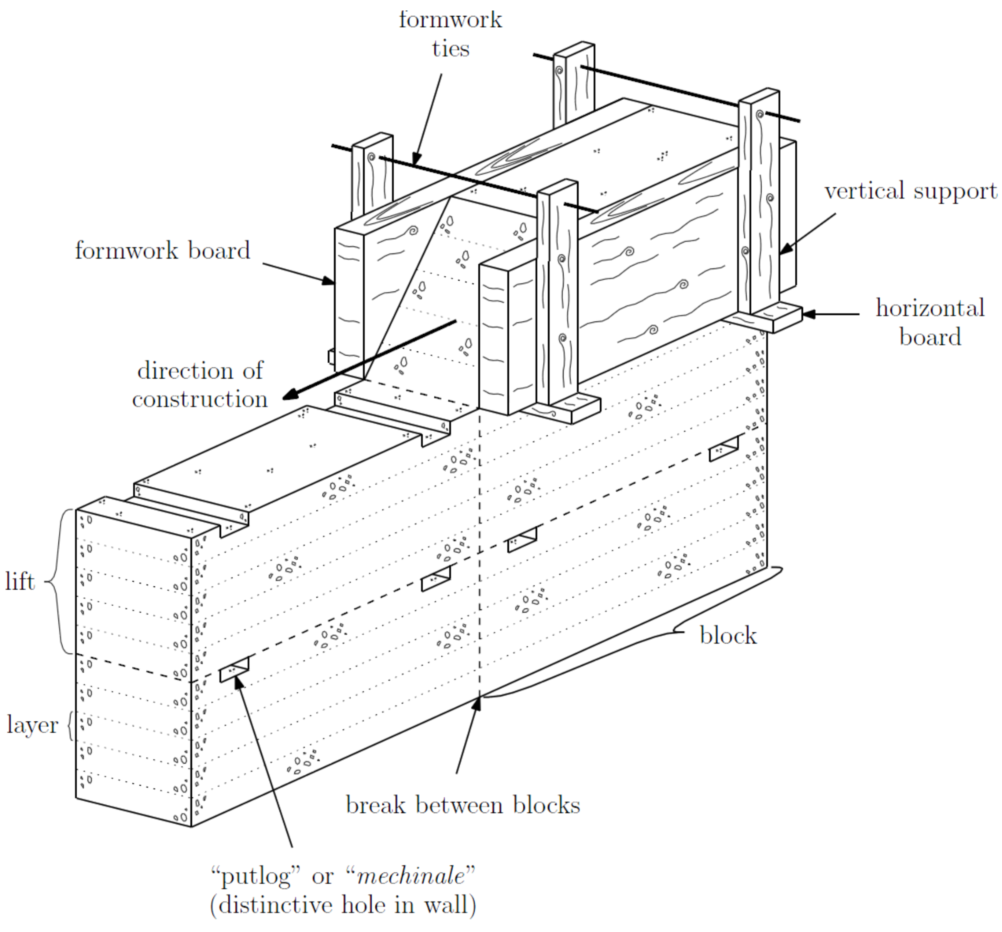


Figure 1: RE wall construction method

experience; however, the increasing cost of energy and RE's inherent sustainability have led to a reinvigoration of research into its behaviour, with it becoming increasingly recognised as a viable sustainable alternative to traditional modern construction materials (Gossen, 1996; Venkatarama Reddy and Prasanna Kumar, 2010). Unfortunately, RE is not currently considered suitable for construction in many countries due to its low thermal resistance (for example as required by AS/NZS 4859.1:2002). Furthremore, it continues to be dogged by its reputation as a “poor man’s material” when compared to more modern materials, for example fired brick and concrete, and mistrust in its use due to a general lack of information concerning construction techniques (Chilkoti, 2012). Its long and successful heritage, however, suggests that the use of appropriate designs should be sufficient to achieve sustainable, environmentally friendly structures whilst maintaining comfortable internal conditions.

This paper discusses the concept of thermal comfort, its relation to thermal resistance and thermal mass. A review of work conducted investigating the role of thermal mass in providing thermal comfort in RE structures in extreme climates is presented and methods used to adapt the designs of traditional, passive solar RE structures to suit their environment and to maintain thermal comfort are identified. These methods are then compared to features of modern RE structures in similar regions and used to recommend changes to improve their comfort and sustainability.

2. Building for thermal comfort

2.1 Thermal comfort, thermal resistance and thermal mass

“Thermal comfort” refers to an acceptable range of temperatures experienced by occupants inside structures. For example, ASHRAE Standard 55 – *Thermal Environmental Conditions for Human Occupancy* defines an internal air temperature range of 23-26°C as acceptable for summer. Early thermal comfort studies were used to determine boundary temperatures for office environments in the northern-hemisphere, although, more recently, thermal comfort researchers have investigated a wider range of building types and locations (Williamson and Bennetts, 2012). In particular, these later studies show that conditions that can be controlled by the occupants, for example opening and closing of windows, are generally considered to be more comfortable than those that cannot (Breesch and Janssens, 2005). These studies highlight the need for shading and natural ventilation in regions where high humidities are common and stress that conditions during and outside of daylight hours should be considered separately. It is also noted that acclimatisation to surroundings will increase the tolerance of occupants to thermal variations over time (deDear and Brager, 1998).

Current green construction guidelines, for example AS/NZS 4859.1:2002, require that materials have a certain minimum thermal resistance R in order to reduce the amount of energy transferred through the boundary surfaces of a structure and so reduce its energy demand (Allinson and Hall, 2007). As such, preference is given to construction which utilises materials with high R values. Thermal resistance quantifies a material's ability to reduce heat flux under steady state conditions and can be calculated for heat flow in one dimension using

$$q = k\frac{\partial T}{\partial x} \approx k\frac{\Delta T}{\Delta x} = \frac{\Delta T}{R} \qquad [1]$$

where q is the heat flux (heat transfer per unit area), k is the thermal conductivity (heat transfer per unit length for a temperature difference of one degree), T is the temperature, x is the lengthwise direction and $\Delta x/k = R$. Materials can therefore achieve a required R value either by having low thermal conductivities (k) or by increasing the amount of material through which the heat has to travel (i.e. increase Δx); this option is unsuitable for most materials, however, due to the significantly higher costs of providing the extra thickness.

In order to use a steady-state analysis to determine a structure's thermal performance, it must be assumed that the structure is operating using active heating, ventilation and air conditioning (HVAC) systems (Williamson and Bennetts, 2012). In the absence of HVAC, total heat transfer must instead be determined using the time-dependent heat equation, which for flow in one dimension can be written as

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}\right) \qquad [2]$$

where t is time, ρ is the material density and C_p is the specific heat capacity, i.e. the energy required to heat up one kilogram of a given material by one degree. $k/\rho C_p$ is the "thermal diffusivity" and is a measure of the ease with which heat can be transferred through a material (i.e. the lower the thermal diffusivity, the more insulating the material). Eqn 2 can be reduced back to Eqn 1 through the

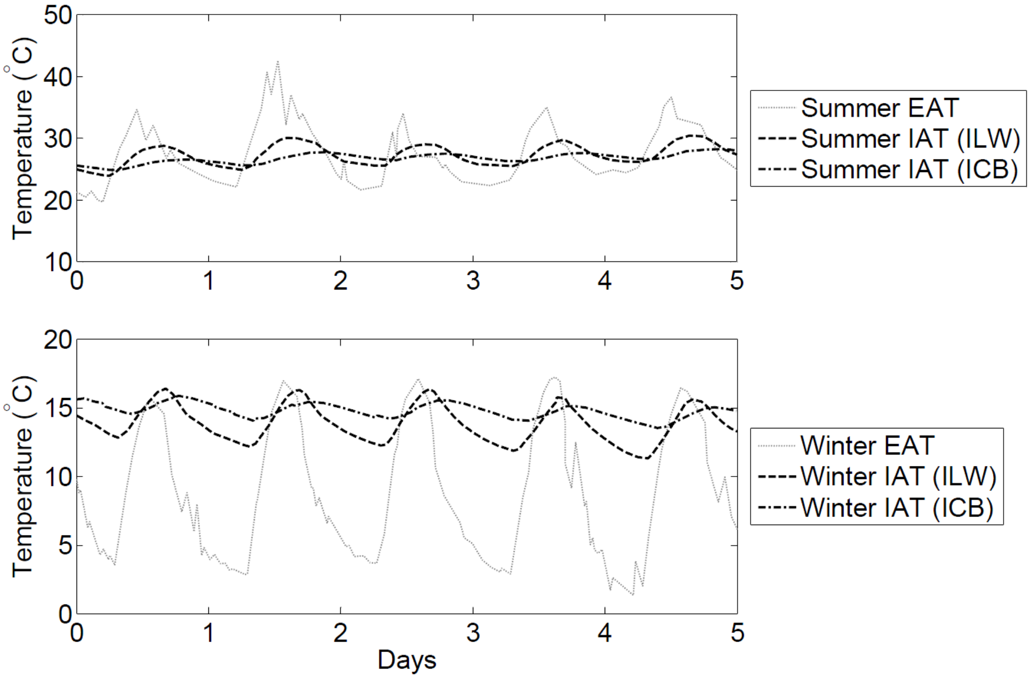


Figure 2: External (E) and internal (I) air temperatures (AT) in ILW (high thermal resistance but low thermal mass) and ICB (low thermal resistance, high thermal mass) structures during typical summer and winter conditions (reproduced from Page *et al.* (2011)).

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)

application of steady state conditions $(\partial T/\partial t = \partial^2 T/\partial x^2 = 0)$. When calculated for the total volume of material present, ρC_p becomes mC_p, where m is the mass of the material and which is more commonly referred to as “thermal mass”, which is a measure of how much heat energy can be stored by the material. High thermal masses, as for example present in RE structures, therefore result in reduced thermal diffusivity and, as a consequence, a time-delay between changes in the external and internal temperatures, referred to as the “thermal lag” (Houben and Guillaud, 1994; Kośny and Kossecka, 2002; Artmann *et al.*, 2008). Specifying a low value of k, does, therefore, reduce thermal diffusivity but ignores the ability of a material to absorb and retain heat energy and, more importantly, its ability to radiate that heat energy if the surrounding air temperature (either internal or external) drops, which has the effect of reducing internal air temperature fluctuations (Allinson and Hall, 2007; Faure and Le Roux, 2012).

Page *et al.* (2011) recently investigated the relative contributions of differing combinations of thermal resistance and thermal mass to thermal comfort. They found 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, with temperatures continually within comfortable levels, 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. Larsen *et al.* (2012) and Orosa and Oliveira (2012) similarly found that the heating and cooling energy demand of monitored massive structures was lower than that 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).

2.2 Thermal comfort in earthen structures

Recent advances in the understanding of the behaviour of earthen materials mean that their thermal and physical properties can now be related. Adam and Jones (1995) investigated the effect of cement and lime stabilisation on the thermal conductivity of compressed earth blocks, establishing that thermal conductivity increases with increasing material dry density and that the effect was greater for cement stabilisation than for lime, due to the former's higher density. Hall and Allinson (2009; 2010) showed that lower densities result in reduced volumetric heat capacity, due to higher material porosities, and that the thermal resistance and heat capacity of RE are strongly dependent on the presence of liquid water within the material. This liquid water also allows RE walls to regulate internal relative humidity, another key factor in achieving comfortable internal conditions (Breesch and Janssens, 2005; Allinson and Hall, 2010).

Despite their reputation for comfortable living, relatively little work has been conducted investigating the thermal performance of earthen structures. Fitch and Branch (1960) presented results for the conditions within an adobe (mud brick, a similar material to RE) house in Egypt during a typical summer's day, as shown in Figure 3. Despite external air temperature (EAT) and roof surface temperature (ERST) ranges of between 22 and 40°C and 23 and 59°C respectively, internal air temperatures (IATs) only ranged between 24 and 29°C, with an associated thermal lag of roughly 10 hours. Similar results were found by Hardin *et al.* (2003), Taylor and Luther (2004), Mani *et al.*

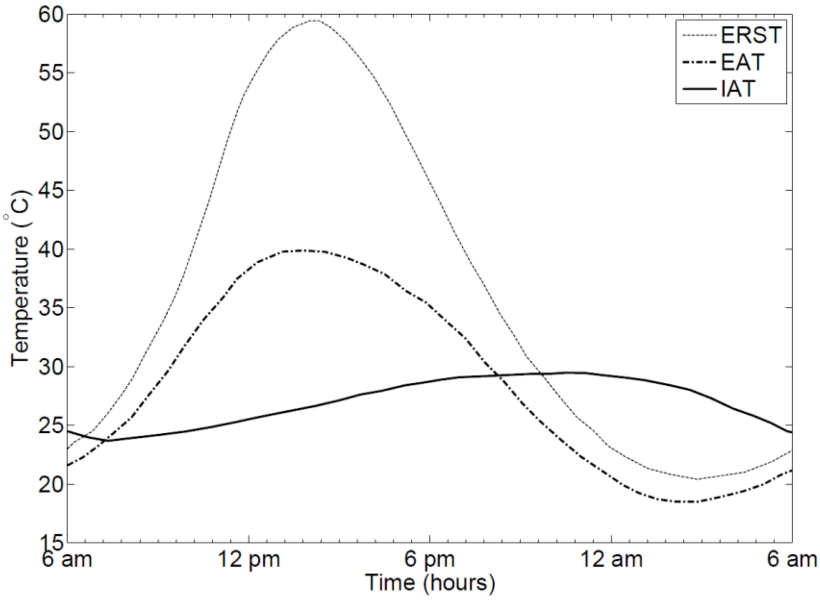


Figure 3: External and internal air temperatures (EAT and IAT respectively) and external roof surface temperature (ERST) for an adobe structure in Egypt (reproduced from Fitch (1960))

(2007) and Soebarto (2009), as summarised in Table 1, who also determined that the contribution of thermal mass to thermal comfort was the greatest for those structures subjected to large diurnal temperature variations, for example as found in hot arid regions, as high temperature gradients between the external and internal air allow for the most heat to be stored and subsequently released (Maniatidis and Walker, 2003). 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 non-earthen structures (both commercial and domestic) and identified that the provision of high thermal mass, in combination with adequate ventilation, was critical in passively maintaining comfortable conditions. The key to effective passive solar design is therefore the intelligent deployment of both thermal mass and appropriate ventilation within a structure.

3. Thermal mass in RE structures

3.1 Traditional structures

By comparing the designs of traditional RE structures (i.e. those designed to operate passively), methods used to adapt their designs to maintain comfort in their respective environments can be identified. Such a comparison is presented in Beckett and Ciancio (under review), the key findings of which are shown in Figure 4 for structures located in different climatic regions as classified by the Köppen-Geiger Climate Classification (KGCC) system (the reader is referred to Peel *et al.* (2007) for more information on the development of the KGCC). Four broad design categories are identified to allow these structures to be compared: wall thickness; roof type; wall protection and wall opening size. The first two design categories are indicative of the use of thermal mass within a stucture, whilst the final two demonstrate the provision of ventilation and shade. Trends in the features of traditional structures are shown as bold, solid lines between adjacent KGCC categories, whist broken bold lines denote trends between non-adjacent categories. Trends in generalised expected temperatures and rainfall for each category are also shown.

Figure 4 suggests that there is a strong relationship between the designs of traditional RE structures and expected rainfall (and so humidity). Although a strong link between the protection afforded to RE structures and rainfall is to be expected, given the sensitivity of RE materials to water (Jaquin *et al.*, 2009), the link between all of the design feature trends and humidity demonstrates the strong impact of humidity on perceived comfort previously identified by Breesch and Janssens (2005). Figure 4 also shows that traditional RE structures in hot, arid regions (category [B]) rely heavily on high thermal mass construction (thick walls and heavy roofs) to provide thermal comfort, supporting results given in Table 1. The high thermal mass of these structures, combined with the relatively low amount of shade provided to the walls, ensures that considerable external heat can be absorbed and stored during the day. As windows are small they can easily be closed off, again to reduce heat loss during cold periods. Conversely, traditional structures found in highly humid regions (category [A]) rely more heavily on shade and ventilation (large wall openings and extensive shade) to provide comfort, with lower thermal masses resulting in cooler night time temperatures. Structures found in intermediate temperature and humidity regions (categories [C] and [D]) incorporate combinations of these features, although their characteristics suggestibly remain humidity-dominated.

3.2 Modern structures

Modern RE structures are generally perceived to be unsuitable for modern living, despite the technique's long and successful heritage. A major contribution to this reputation is their poor design, both from a structural and passive solar perspective, due to a decline in the familiarity of building with earth.

Although Figure 4 shows little difference between their wall thicknesses, a significant disparity is

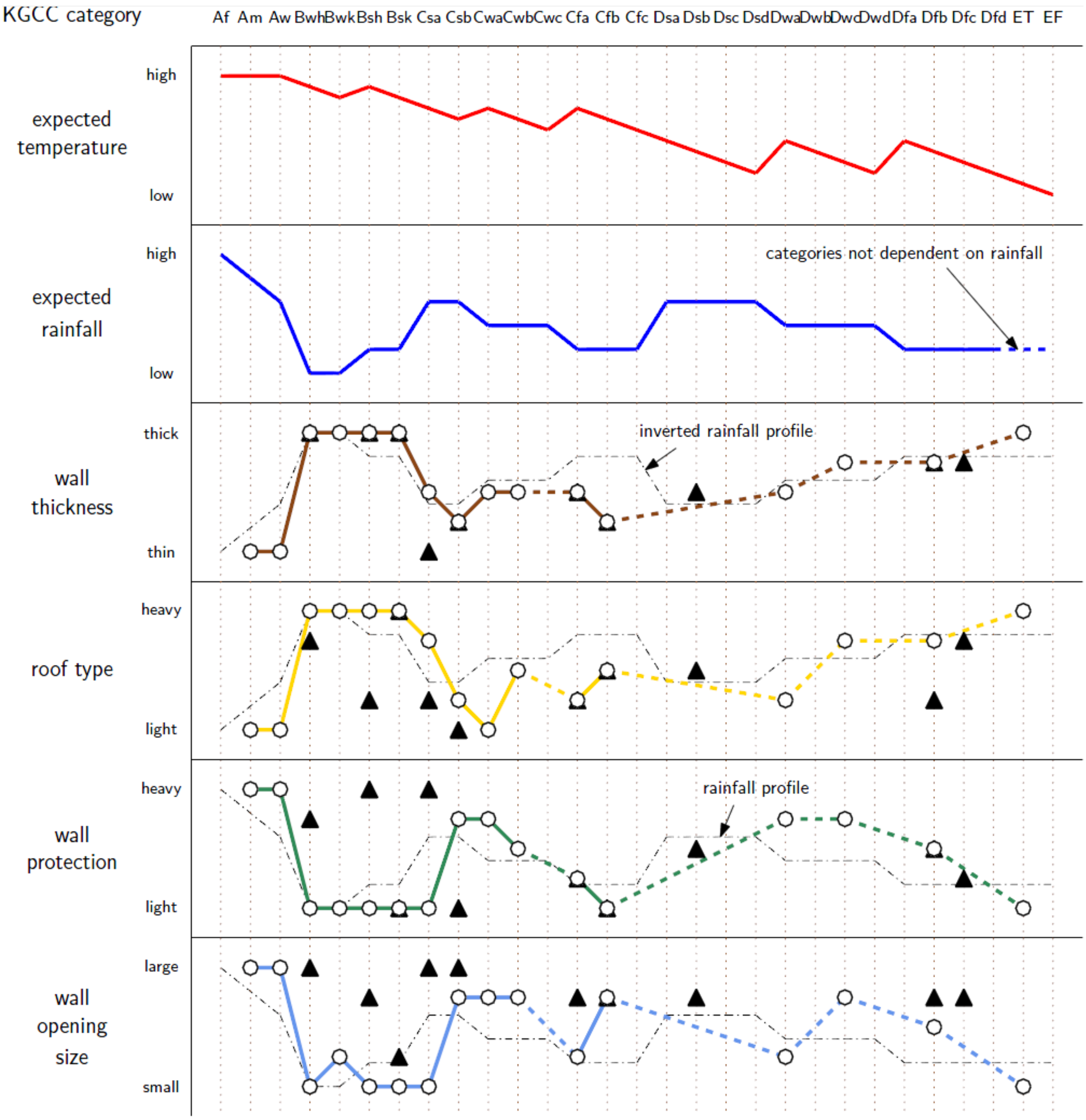


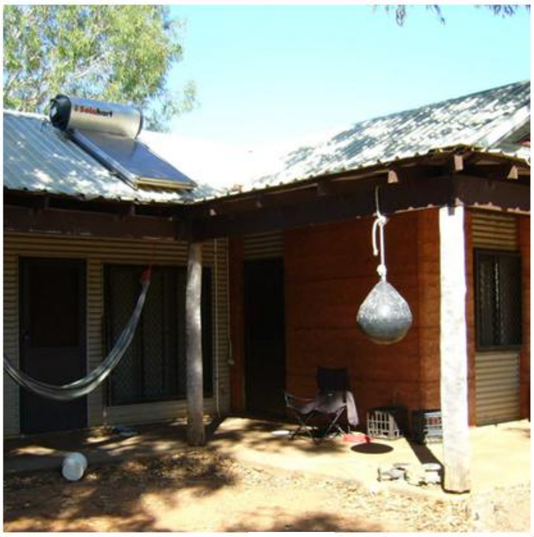
Figure 4: Design features of traditional (white circles) and modern (20^{th} century or later, black triangles) RE structures.

seen between the other identified features of traditional and modern RE structures, particularly for climate category [B], in that modern RE structures in these regions typically comprise far less thermal mass than their traditional counterparts and instead depend on shade and ventilation to provide comfort. This is unexpected, as previous authors have demonstrated that it is under these hot, arid conditions that RE's inherent thermal mass is most able to regulate internal temperatures and so provide comfortable conditions.

Examples of two modern RE structures found in northern Western Australia (KGCC category [B]) are shown in Figure 5, illustrating the lightweight, shaded roofs and large wall openings typical of modern arid-region RE construction. An HVAC unit is also clearly visible in Figure 5(a), whose use is necessary to counter overly-hot and cold daily temperatures. Although the use of HVAC is now commonplace, reliance upon such systems is clearly unsustainable, especially considering rising energy prices which have already rendered such units unrealistic in many poorer areas around the world (Liu *et al.*, 2010). Results shown in Figure 4 for successful passive solar structures therefore suggest that the root of these structures' poor thermal performance, in the absence of HVAC, is due to their low thermal mass compared to traditional structures in similar regions. Therefore, the inclusion of greater thermal mass should improve their sustainability and reduce their reliance on expensive, high energy demand HVAC systems.

4. Conclusions

This paper has presented the concept of thermal comfort and how it can be related to thermal



(a)

(b)

Figure 5: Examples of modern RE construction in arid regions: a) Beagle Bay, Western Australia; b) Derby, Western Australia

resistance and thermal mass. Examples of work investigating thermal in a range of building types have been discussed and it has been argued that thermal mass, and not thermal resistance, is a key contributing factor to achieving comfortable internal conditions, particularly in regions subjected to high diurnal temperature variations. This observation has been supported by investigating the designs of traditional RE structures in many regions around the world. A disparity between the designs of modern and traditional RE structures in arid regions was identified, showing that their reliance on thermal mass is significantly lower than in their traditional counterparts, with comfort instead depending on active HVAC units during peak times. It was therefore suggested that a change in the designs of these structures to incorporate greater thermal mass would reduce their reliance on energy-intensive HVAC systems and so significantly improve their sustainability.

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