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Thermal performance and comfort of naturally ventilated earth house in a dry summer climate

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Abstract: This paper presents a study of the thermal performance and occupant satisfaction of naturally ventilated earth houses during a hot summer period. An earth house community located in Santiago, Chile, was chosen as a case study. Building Use Studies (BUS) survey was used to understand the general satisfaction and thermal comfort of users living in earth buildings. In parallel, two occupied houses constructed with wattle and daub techniques were monitored. Occupants highly rated most aspect of the house, yet thermal related variables are less satisfactory. The monitored results showed that indoor diurnal temperatures in both houses have differences between 15-20°C compared with outdoor temperatures. The indoor temperature of adobe bedroom showed a more drastic deviation when the outdoor temperature was lower than 20°C. This study has verified the thermal comfort potential of earthen constructions, notably contributing to indoor temperatures in summer.

Keywords: Earth house, Thermal performance, Occupant satisfaction, Dry summer climate, BUS survey

1. Introduction

Around 30% of the world's population is still living and working in earth buildings as it has been since the beginning of humankind (Niroumand et al., 2013). Interest in the bioclimatic behaviour of vernacular earthen architecture has grown since the early 1980s (Balaguer et al., 2019). The main focus of study has been on the thermal performance, hence the energy-efficiency that earth buildings could provide (Zhang et al., 2016). According to the Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH), rammed earth stores more heat than concrete with lower density (Soebarto, 2009). This high thermal mass allows a time lag changes between indoor and outdoor temperature, which is the most outstanding feature of an earth building.

However, there is misleading information about the thermal performance of earth buildings material (Soebarto, 2009). As shown in Paul and Taylor (2007) study, rammed earth buildings did not guarantee better thermal performance than conventional buildings, either in summer or winter. Delsante's research (2006) argued that rammed earth walls contribute to acceptable thermal comfort for the building's occupants in summer, but it would have low to average performance in winter.

The purpose of this study is to explore the thermal performance and comfort of earth buildings located in a climate with dry summer. Under the accelerated trend of global warming, it is necessary to analyse the performance of earth construction methods as alternative means of achieving a healthy and sustainable built environment.

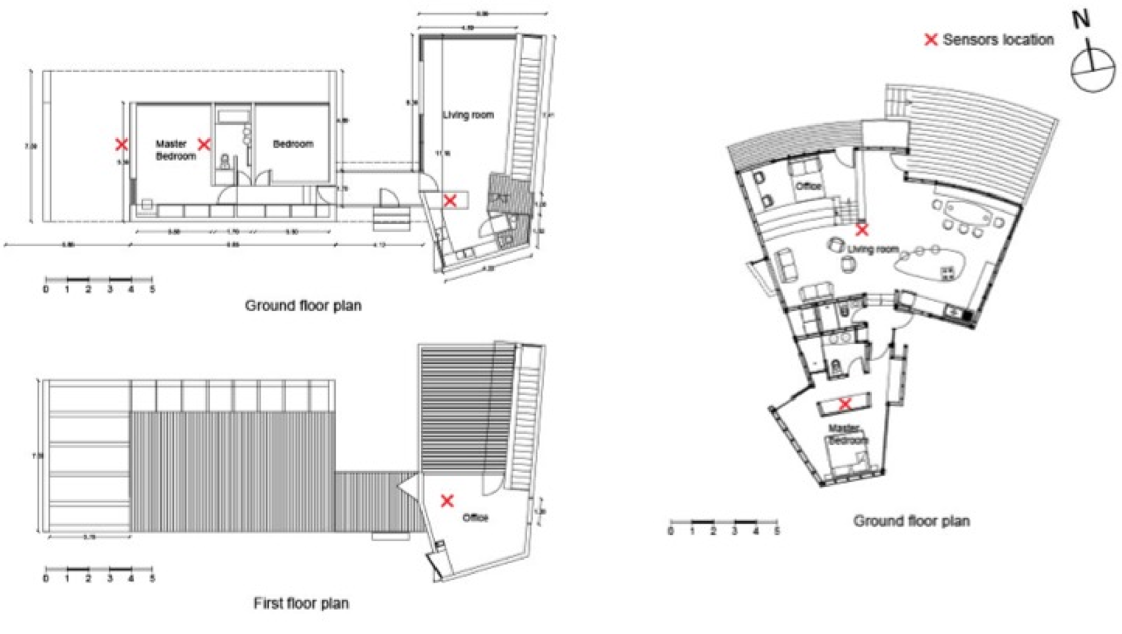
2. Methodology

The research methodology adopted in this study comprised two main data-gathering processes: Building Use Studies (BUS) survey and Monitoring of earth constructions.

The community called '*Comunidad Ecológica*'de Peñalolen was chosen for this study, as it has been established for 36 years in the suburb of Santiago, Chile, where around 500 families live in a distinctive architectural style and employing earth techniques. They share an eco-friendly lifestyle. Two occupied earth houses were also selected as case studies for the monitoring exercise.

2.1. BUS Survey: For primary qualitative and quantitative data, the BUS methodology was distributed and gathered from residents of earth houses. The questionnaire features a seven-point scale and comments about various aspects of the house. It includes individual sections for the residence overall, comfort, noise, lighting, health, personal control, design, etc. Among the multiple categories in the survey, the sections on temperature in summer and winter, and comfort overall were treated as crucial information in determining occupants' satisfaction with thermal conditions. This evaluation provided prioritised topics on the thermal performance of earth houses by occupants. A total of 40 individuals responded to the survey.

2.2. Monitoring: During the period from 13th December 2018 to 7th July 2019, Tiny Tag data loggers were installed in two case study houses. Internal and external temperature(°C) and relative humidity (%) were collected every hour. Data loggers were installed in bedrooms, living room and home office spaces. Location of data loggers is indicated in Figure 1. The assessment of the monitoring data was mainly based on representative summer and winter periods. The hottest two weeks of the summer and the coldest two weeks of the winter were chosen. Hence, to identify the thermal performance of earth houses under the most extreme thermal conditions.



Case study 1 Case study 2

Figure 1. Floor plans of Case study 1 and 2

a) *Case studies:* Both houses were constructed using '*wattle and daub*' techniques. The first house (case study 1) has a volume (bedrooms) constructed with wattle and daub and an insulated wooden cladding volume (living room-dinning room and office). It is a two-storey building which has an office space only on the upper floor of the wooden volume. The external walls of the bedrooms' volume are 200mm thick with no insulation and a roof with polystyrene panels as insulation. The external wooden walls are 200mm thick structures with 10mm of polyurethane insulation (internal insulation). The second house (case study 2) is a one-storey building plus a partially underground parking garage, on a sloping site. Unlike the first house, it is predominantly constructed using wattle and daub technique. It has 150mm thick external wall and a ventilated roof constructed with earth and straw as insulation.

b) *Thermal comfort criteria:* Since the two case study houses are free-running buildings, an adaptive comfort criteria complying with ASHRAE standard 55-2017 was considered in the thermal comfort assessment of each house. The percentage of thermally comfortable hours was determined by the thermal comfort criteria shown in Table 1.

Table 1. Thermal comfort band

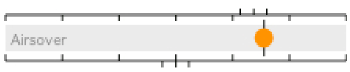
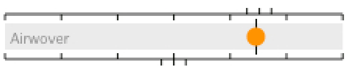
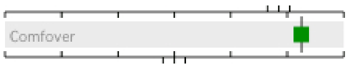
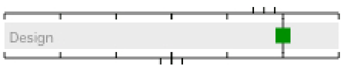
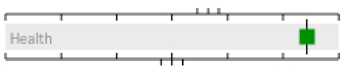
Acceptability		**Limit**	**Comfort temperature ranges (°C)**	**Note**
Summer	80% (±3.5°C)	Upper	29.3	-Prevailing mean outdoor temperature: 25.9°C (Jan, measured data) -Operative comfort temperature: 24°C (Bedroom, CIBSE Guide A Table 1.5)
		Lower	22.3	
Winter	80% (±3.5°C)	Upper	24.4	-Prevailing mean outdoor temperature: 10°C (Jun, measured data) -Operative comfort temperature: 18°C (Bedroom, CIBSE Guide A Table 1.5)

3. Result analysis

3.1 BUS survey

Earth houses in the community were given high scores in most aspects. Occupants were quite satisfied with the comfort provided by their earth dwelling. Table 2 shows the results of the ten outlined overall variables from the BUS survey. Six out of ten were relatively better: comfort, design, perceived health, lighting, noise and temperature in summer overall. However, thermal-related variables – air in summer, air in winter, and temperature in winter overall – were less satisfactory to occupants compared to other variables. It is also shown that there is a slightly better performance of the air and temperature variables in summer than in winter.

Table 2. BUS Survey results – Summary

Study Variables	**Slider (7-Scale)**	**Mean**	**Percentile**
Air in summer overall	Unsatisfactory:1  7: Satisfactory	5.55	57 (A)
Air in winter overall	Unsatisfactory:1  7: Satisfactory	5.46	41 (A)
Comfort overall	Unsatisfactory:1  7: Satisfactory	6.25	69 (A)
Design	Unsatisfactory:1  7: Satisfactory	6	64 (A)
Health (perceived)	Less healthy:1  7: More healthy	6.43	97 (A)

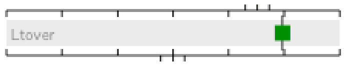
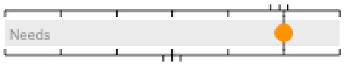
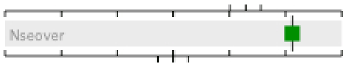
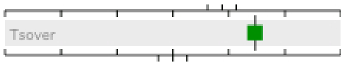
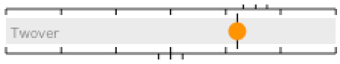
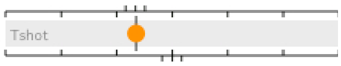
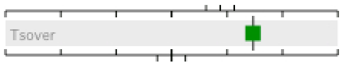
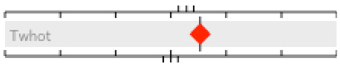
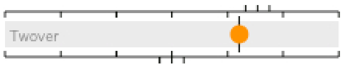
Lighting: overall	Unsatisfactory:1		7: Satisfactory	5.97	71 (A)
Needs	Unsatisfactory:1		7: Satisfactory	6	62 (A)
Noise: overall	Unsatisfactory:1		7: Satisfactory	6.12	74 (A)
Temperature in summer: overall	Uncomfortable:1		7: Comfortable	5.47	74 (A)
Temperature in winter: overall	Uncomfortable:1		7: Satisfactory	5.21	31 (A)

Table 3 shows the thermal assessment regarding temperatures in summer and winter. Earth houses tended to be a bit hot, but overall thermally comfortable in summer. In winter, they were slightly cold, which did not make occupants highly satisfied with their thermal environment. The findings indicated that indoor temperatures of the dwellings in summer seemed more comfortable than in winter.

Table 3. BUS survey – Temperature in summer / winter

Study Variables		**Slider (7-Scale)**		**Mean**	**Percentile**
Temperature in summer: hot/cold	Too hot:1		7: Too cold	3.35	41 (B)
Temperature in summer: overall	Uncomfortable:1		7: Comfortable	5.47	74 (A)
Temperature in winter: hot/ cold	Too hot:1		7: Too cold	4.53	79 (B)
Temperature in winter: overall	Uncomfortable:1		7: Comfortable	5.21	31 (A)

3.2 Monitoring

In the hottest month of January, external temperatures ranged between 16.2°C and 41.5°C. Both December and February were also similarly represented as hot-dry summer with a peak around 40°C. The outdoor mean temperature of the summer period was around 25°C, with lower relative humidity about 40%. During autumn, the average temperatures gradually fell to approximately 12°C before winter, whereas the relative humidity went up until 90%.

The monitoring results collected from the hottest two weeks in summer and coldest two weeks of 2019 are presented in Figure 2. Indoor temperatures in both seasons were found to be more stable in case study 1 compared to the extremely high outdoor diurnal temperature. It seemed that the bedroom in case study 1 has a difference almost 15°C from outdoor temperature during summer. In winter, the indoor diurnal temperature in the range of 12–20°C can be seen, which made the bedroom much warmer than outside.

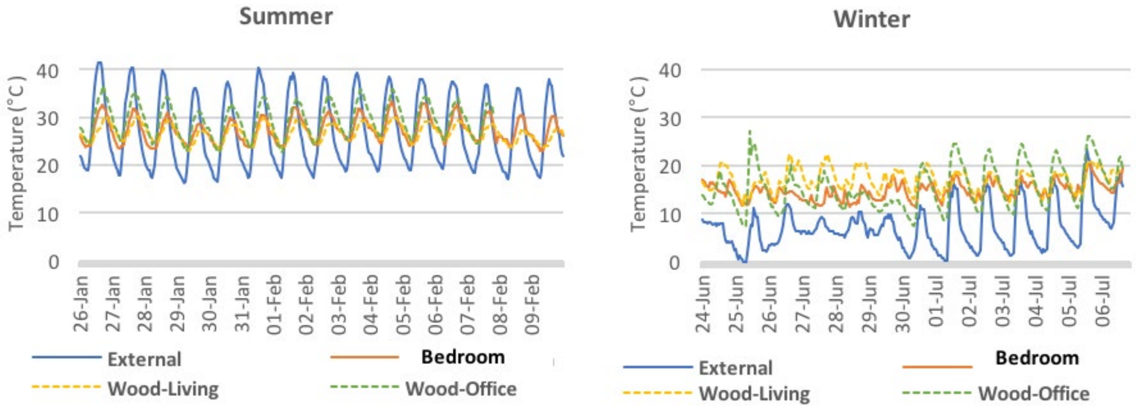


Figure 2. Case study 1 – Indoor and outdoor air temperature in two weeks in summer and winter

Under the same external conditions, case study 2 also showed stable indoor temperatures during both periods. Diurnal indoor temperatures ranged between 27ºC and 32°C during summer, decreasing to 15°C to 20°C from the outdoor temperature. In winter, it showed slightly irregular fluctuations, with above the temperature of 12°C.

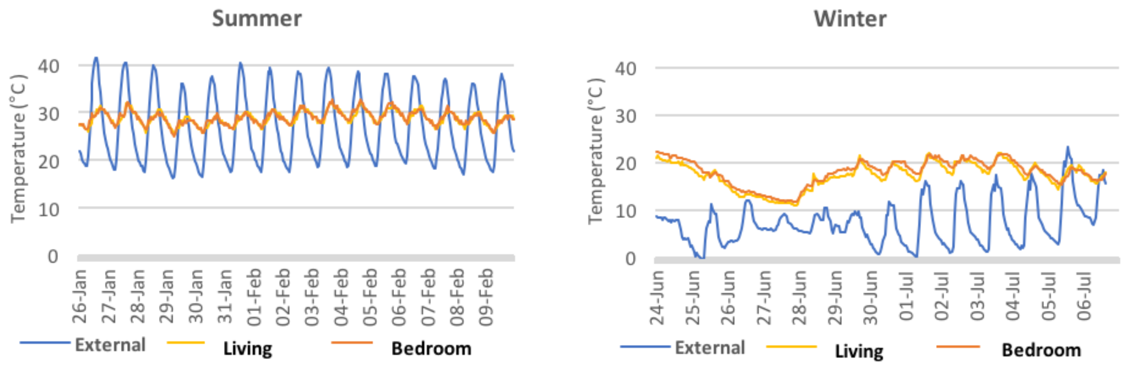


Figure 3. Case study 2 – Indoor and outdoor air temperature in two weeks in summer and winter.

4. Discussion

4.1 Thermal comfort satisfaction in summer and winter

The results from the BUS survey provided a good overview of occupants' perceptions about the thermal comfort of earth houses. Residents were in general satisfied with the performance of their houses. However, a few thermal-related variables, such as air quality and temperature were relatively lower than other variables. As presented in Table 3, occupants indicated that the houses were either hot or cold during each season, which made them less than highly satisfied with the thermal environment of the houses. Thermal discomfort issues in summer and winter seemed to be the main concerns for users, as also frequently mentioned in the survey comments. Nevertheless, it was discovered that the thermal comfort satisfaction with an earth house in summer showed better aspects than in winter.

As shown in Figure 4, in both case studies, temperatures fell outside the lower acceptable comfort limits as the mean outdoor temperature gradually decreased. Case study 1 showed a more drastic deviation than case study 2 when the outdoor temperature was lower than 20°C. The presence of straw in the earth mixture of case study 2 could be contributing to the difference in the thermal performance of the two cases. In summary, the monitored results showed that an earth house could provide more satisfactory thermal comfort conditions in summer than in winter.

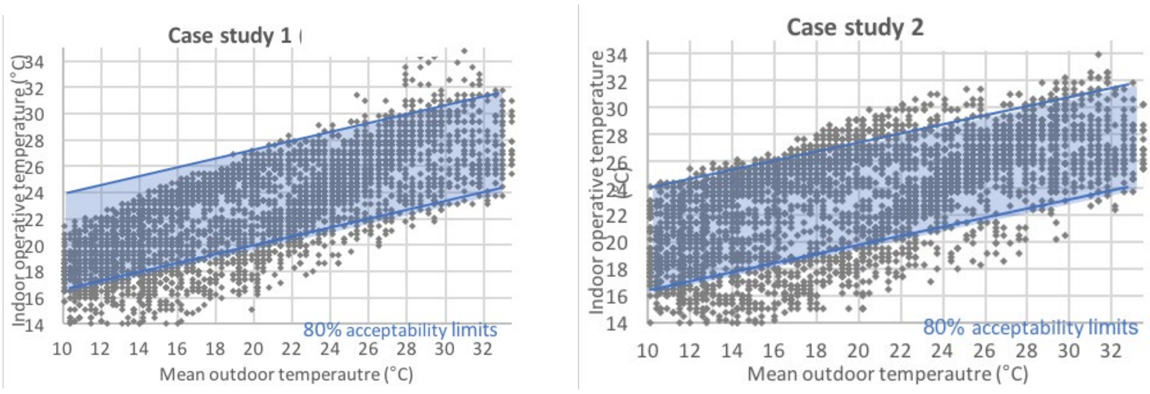


Figure 4. Adaptive comfort zone

4.2 Thermal performance of earth house

A more stable indoor temperature compared to an unpredictable outdoor temperature was verified by measured results. A high thermal mass of earthen materials enabled the storage of heat and delivered time lag heat flux to minimise a high diurnal temperature range (Koch-Nielson 2002). The two case studies featured earth walls 200mm thick, and they exhibited time lag properties of around 1–5 hours, referred to as the thermal storage capacity. It is undeniable that the external earth wall made a considerable contribution to indoor thermal comfort. Both case studies reduced by about 15°C to 20°C the range of external temperature amplitude in summer. It was also found that the thermal behaviour of of both houses where different. The indoor temperature of the case study 2 was in the range of 25–32°C in summer. This conditions were slightly more stable than case study 1, which was in the range of 24–33°C. Different earth techniques resulted in different thermal performances of earth houses. Case study 2 has mixture of earth and straw as insulation in roof, which could be playing an important role on the better environmental conditions.

5. Conclusion

The results obtained thermal behaviour with occupant satisfaction in an earth house, which could potentially be used for alternative construction in a dry summer. As it demonstrated a more thermally comfortable indoor environment in a hot summer than in a cold winter, an earth house also can be a low-cost sustainable home in a hot arid climate such as prevails in sub-Saharan Africa. By improving and modernizing earth construction methods and details, it would provide a healthy, energy-efficient and secure environment to people.

6. References

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