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*Article*

# Thermal Performance of Traditional and New Concept Houses in the Ancient Village of San Pedro De Atacama and Surroundings

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**Abstract:** Earth, wood and others traditional materials are still used in house constructions in many regions of the world, especially in the Andes. San Pedro de Atacama, for example, is a small town where earth blocks (adobes) and rammed earth (tapial) are important ways to construct, an art passed on through generations. Energy properties of earth are very interesting: thermal conductivity is low; heat storage capacity is high; color is variable and can be used to absorb or to reject solar radiation. However, nowadays the government social dwelling service is proposing a different type of construction, which does not maintain any relation with the tradition. This paper presents simulation studies and monitoring of four different San Pedro houses, constructed by using different techniques and materials. Results can be used to discuss the thermal performance needed in desert climate and the reliability of social dwelling service houses, under construction at this time in the town.

**Keywords:** energy efficiency; internal comfort; adobe; rammed earth; earth architecture; traditional houses; Atacama desert

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## 1. Introduction

Humanity is facing in recent years the sustainability challenge. Driving future scenarios towards a more inclusive and equitable world without compromise, the ecosystem appears the first objective of the human being [1,2]. This challenge includes a change of vision in many disciplines, with special attention to the built environment related issues [3]. For the next half century, most of humanity will live in cities [4,5], and also ancient villages will face transformation and growth. San Pedro de Atacama, the focus of this study, is growing without any control, transforming itself from an agriculture dedicated village to a touristic town that is receiving thousands of people every week [6]. Moreover, local populations are demanding dwellings and urban infrastructure from the government and local authorities. Authorities are responding to housing demand by constructing small modular houses, typically using commercial materials like cement, blocks and zinc, and have even discussed using materials like asbestos, forbidden in most countries of the world because of its dangerous effects on health. On the other hand, San Pedro de Atacama has an ancient tradition in earth constructions. Earth constructions are very typical of Andean towns, as a visitor can notice on the road from Peru to Argentina, through Chile and Bolivia. These construction methods are ancient traditions that relate to observation and understanding of the desert climate and local materials' characteristics. Nowadays, it is possible to calculate the proprieties of earth blocks or rammed earth walls, and discover once again the ancient experimental knowledge. Literature (for example references [7–9]) offers many examples of tests conducted on this kind of materials, but the outcomes of real construction are often different to that predicted using test results. This paper studies real homes, selected by material characterization: one is done by adobes (earth blocks), one by tapial technique (rammed earth walls), one is self-construction principally on wood, and the last one is done by concrete blocks covered by asbestos cement on the roof.

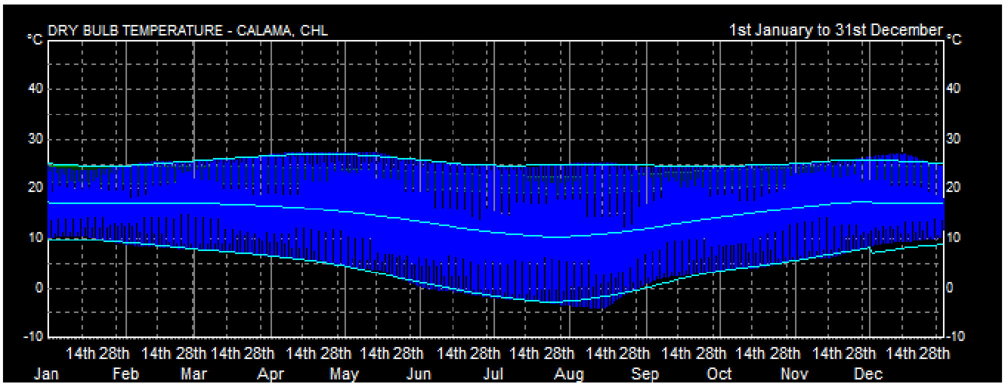
## 2. Methodology

### *2.1. Location and Environment*

Research considers four real cases located in San Pedro de Atacama (22°57′S, 68°15′O, 2389, Figure 1). Monitoring is conducted in the bedroom of each dwelling; simulations consider the entire house distribution. Climate is typical desert, with hot dry days and cold nights all year. Solar radiation levels are very high, with a maximum of more than 1000 W/m$^2$ on the horizontal plane between 12 and 14 hours. Psychometric diagram suggests the use of thermal inertia to protect internal spaces from temperature oscillation and sun radiation. Day-night cycle suggests also using roofs and walls colors and thickness to regulate solar thermal absorption and energy conservation. Figure 2 shows temperature, relative humidity, solar radiation and cloud cover. The ancient village is organized inside the green oasis that appears in the valley. New construction has been taking the soil around the oasis, extending the village limits, especially to the north. Densification of people living in the town signified hard densification in construction, new material use, different technical solutions to seismic problems, visual impact on the ancient village structure, and poor quality in thermal design. Figure 3 shows the location of the four houses studied in this paper, with respect to the center of San Pedro. Cases 1 (adobe) and 3 (concrete block) are located very close to the oasis, whilst cases 2 (rammed earth) and 4 (wood) are located in new urbanization zones, where the town structure is becoming more disperse.

**Figure 1.** San Pedro de Atacama location in the north of Chile.

**Figure 2.** Temperature **(a)**, relative humidity **(b)**, direct solar radiation **(c)** and cloudiness **(d)**.

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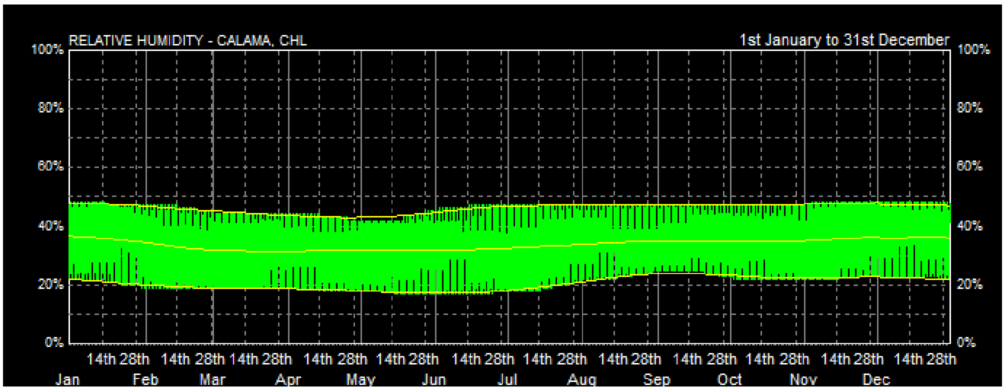


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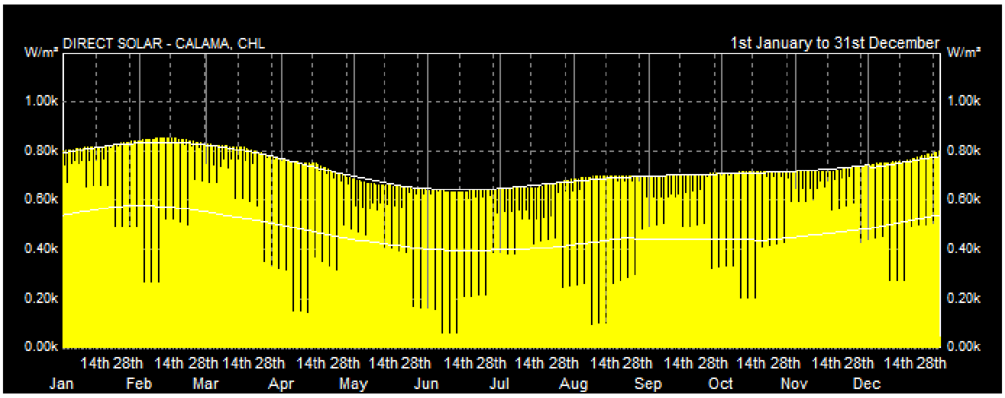


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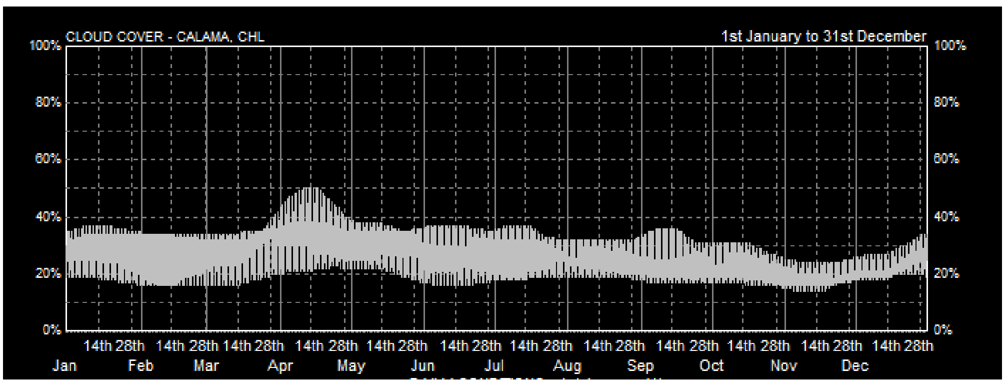
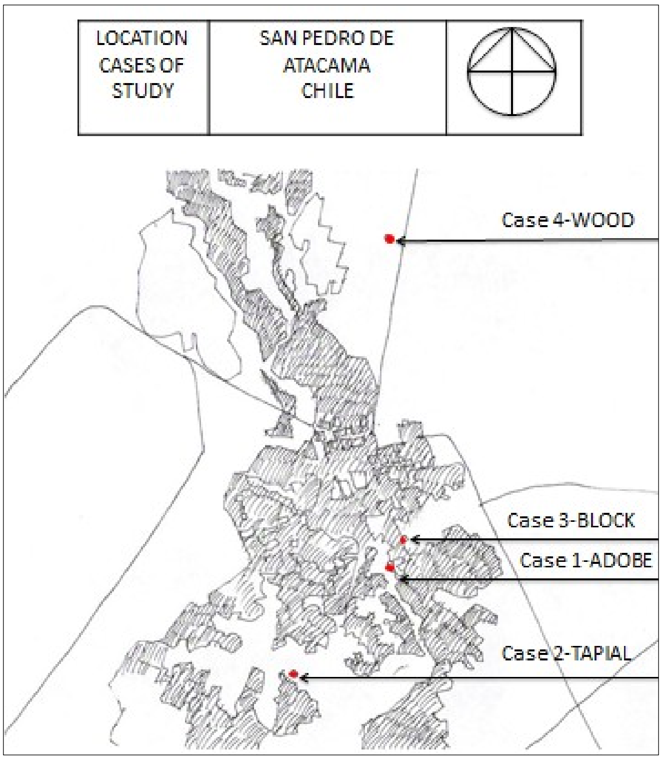



**(d)**

**Figure 3.** Location of the four cases studied.




## *2.2. Study Cases*

Analyzed houses try to meet thermal and structural requirements in different ways. The first house is a typical adobe house, designed by architect Magdalena Gutierrez and constructed using the ancient tradition of earth construction. It is a family dwelling composed of a bedroom and a small laboratory. Kitchen and living zones are external, under a traditional wood structure to guarantee shadows. Walls are adobe walls 30 cm thick and the roof is a rammed earth roof of 15 cm. Windows are single glazed and the door is a wood door. Figure 4 shows the house's internal aspect, the architecture plan and the general orientation with respect to environmental surroundings.

The second house is a tapial house, a massive construction of curved walls designed by architect Magdalena Gutierrez, also using the ancient tradition of earth structures. Tapial walls are 50 cm thick and the earth roof is 15 cm. Windows are single glazed, doors are made of wood. Figure 5 shows the external aspect, environment and orientation.

The third case is a self-construction house, aligned to the street. It is made of concrete block and covered curved cement. Blocks are 20 cm thick. Figure 6 shows the external aspect of the project. The concrete block house has a small window that is single glazed.

The fourth case is another self-construction example, but made of wood. The house is built of recycled materials and structures, like the packing pellets that are used as insulation for oriented strand board (OSB). The roof is composed by paper insulation and zinc covering. There are no windows and infiltration is hard (about 10 air changes per hour, depending on wind pressure). The only protection provided is from paper. Figure 7 shows this case aspect, orientation, *etc*.

**Figure 4.** Adobe house orientation and structure.

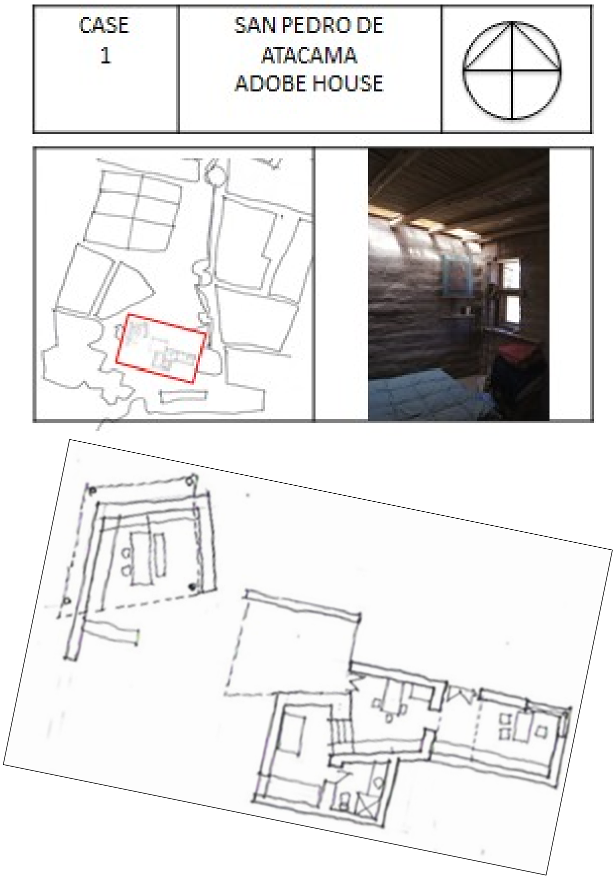



**Figure 5.** Rammed earth house orientation and structure.

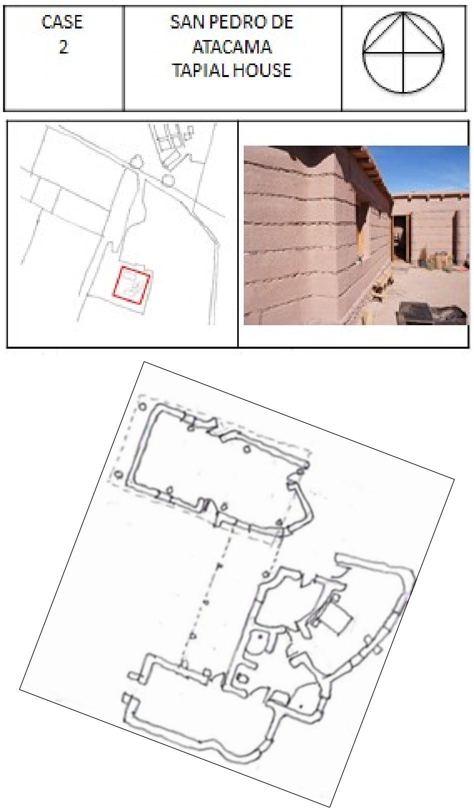


**Figure 6.** Block house orientation and structure.

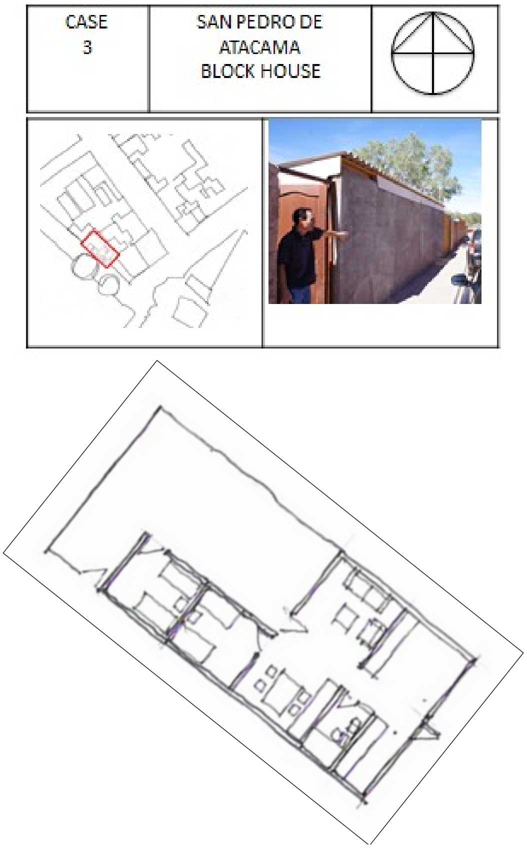
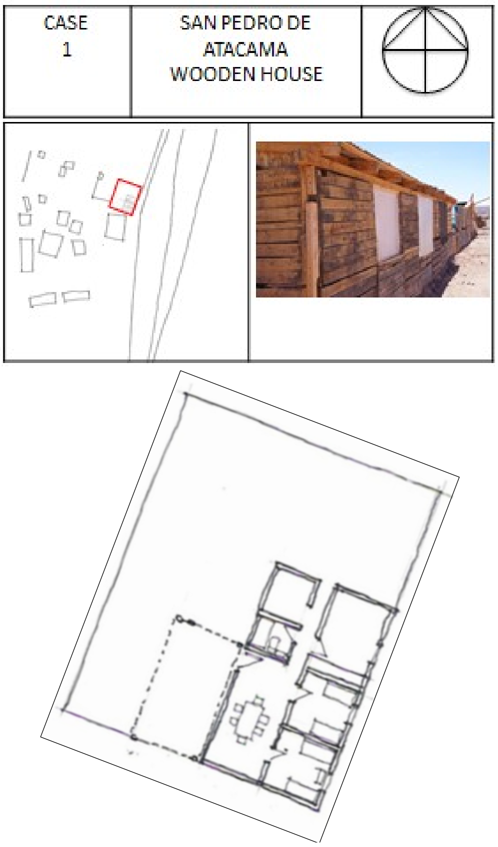



**Figure 7.** Wood house orientation and structure.



### *2.3. Simulations Parameters*

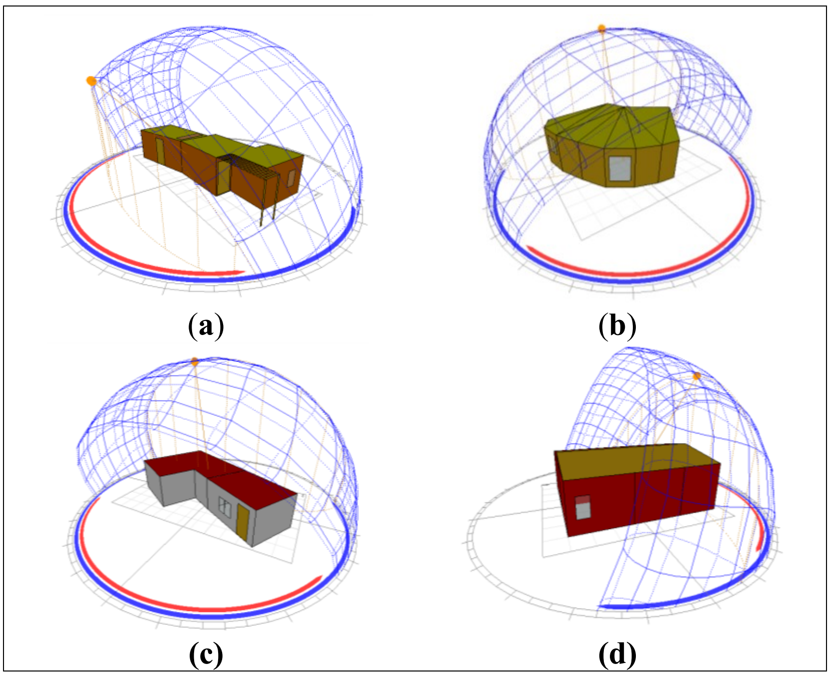
Simulation studies have been conducted using Ecotect tool to perform thermal behavior. Ecotect is a simulation tool developed by Andrew Marsh and the Square One Research Group and recently distributed by Autodesk. It has the limitation of using the admittance method in thermal calculation, but it is suitable for small construction simulations if correct values of thermal decrement and thermal lag are correctly inserted. More information about Ecotect capabilities and limitations can be founded in manuals [10] and in some scientific literature [11]. A description of the materials is provided in Table 1.

**Table 1.** Walls' and roofs' properties.

| Material Type | Thickness (cm) | Transmittance ($W/m^2K$) | Time Lag (h) | Solar Absorption (%) |
|---|---|---|---|---|
| Adobe wall | 30 | 1.7 | 8 | 0.4 |
| Earth roof | 15 | 2.3 | 3 | 0.5 |
| Concrete wall | 20 | 3.5 | 5 | 0.7 |
| Cement roof | 0.2 | 5.0 | 0 | 0.8 |
| Zinc roof | 0.2 | 7.0 | 0 | 0.9 |
| Rammed earth | 50 | 1.3 | 14 | 0.4 |
| Wood | 1.2 | 1.6 | 2 | 0.6 |

Ventilation and infiltration values imputed in the software are 0.4 air changes per hour in the adobe, tapial and block cases, whilst in the wood house ventilation is set to 50 air renovations, caused by uncontrolled openings. Zone occupation is set to two people with light working activity during the entire day. No appliances or lighting are considered under thermal considerations. Figures 8–11 show the houses models constructed in Ecotect with orientation and solar path. Adobe house has only a small window west oriented, whilst tapial house has a big window north oriented and a small one facing west. In regards to the wood and concrete houses, the concrete house has a small window facing north and the wood house has a window east-oriented without any glass.

**Figure 8.** Ecotect models and sun paths (**a**) Adobe, (**b**) Tapial, **(c)** Block, **(d)** Wood house.



## 3. Results and Discussion

### *3.1. Simulation Results*

Simulation considers one year of hourly data, searching for comfort adaptive sensation in terms described by Humphreys and Nicol [12,13] and later used by de Dear and Brager [14,15]; available using the Ecotect calculation with the Formula (1):

$$T_{comfort} = 11.9 + 0.534\ T_{average} \tag{1}$$

The adaptive comfort concept assumes that human behavior responds to thermal stress, especially if people are used to living without any environmental conditioning. The formula is recommended for natural ventilated buildings (free-running), and for this reason it appears appropriate to use it in all the analyzed cases. Humphreys discussed [16] many cases and founded by linear regression a correspondence of 94%. The calculation was also introduced in ASHRAE regulations [17]. In the Ecotect formula, it is used to calculate the degree-hour of discomfort considering a range of $T_{comfort} \pm 1.75$ °C. Ecotect results for annual discomfort are outlined in Table 2 as the degree hour of overheating and undercooling.

**Table 2.** Adaptive discomfort results.

| House Type | Overheating (degree hour) | Undercooling (degree hour) | Total Discomfort (degree hour) |
|---|---|---|---|
| block | 22538 | 144 | 22682 |
| wood | 10387 | 2703 | 13090 |
| adobe | 4040 | 1460 | 5500 |
| tapial | 6475 | 539 | 7015 |

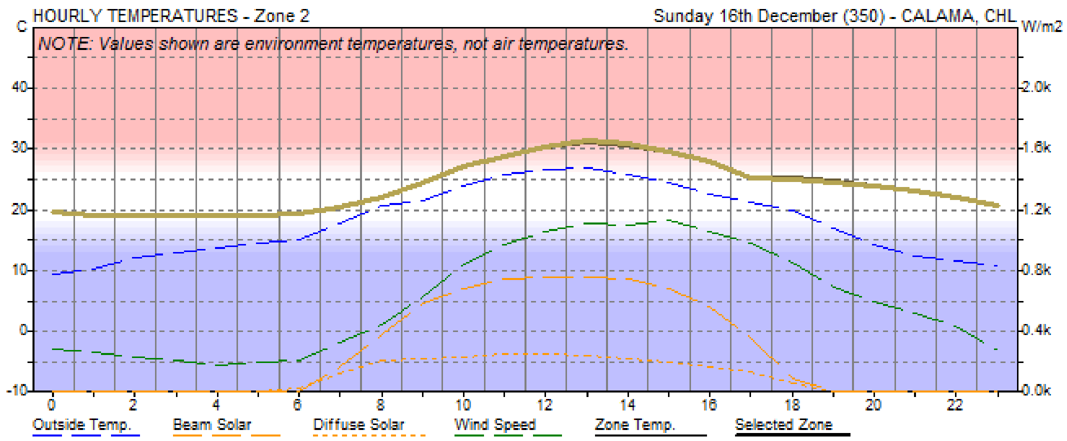
The block-work house seems to have strong problems in terms of overheating during the entire year. Wood house (actually due to infiltration) has overheating and undercooling. Adobe and tapial houses demonstrate a better performance, especially adobe *versus* overheating and tapial *versus* undercooling. Total discomfort degree-hour is reduced by 60%–70%, a better than expected result. Single day analysis can help to understand the inertia effect of each material and to explain previous results. Figure 9 shows the hottest and coldest day (average) and temperature evolution in the block-work house.

Similarly, Figure 10 shows hourly performance of the wood house during the hottest and coldest days. Please note the strong relation between external and zone temperature evolution, due to infiltration.

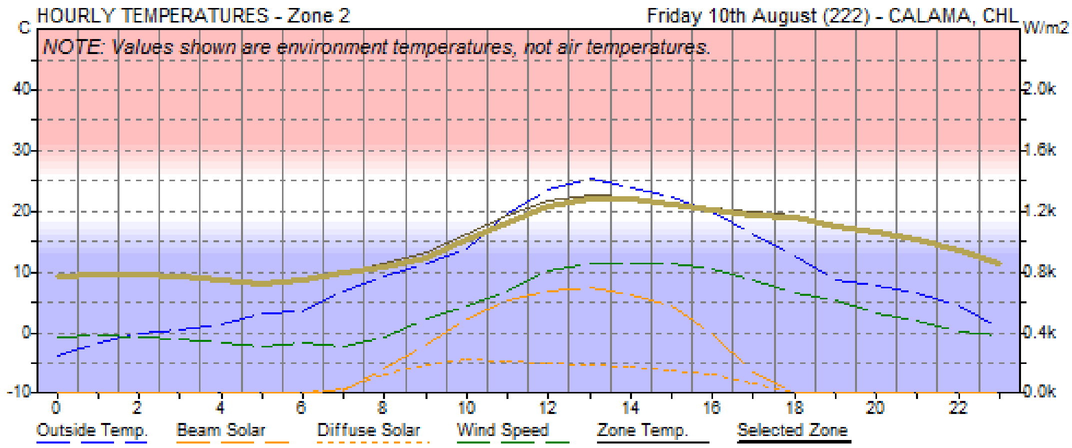
Figure 11 shows the adobe house results. It can be noted the inertia effect of thermal lag: Temperature peak is displaced by about 4–5 h to the right. The time lag that occurred from adobe construction is a very successful result; however, in terms of total discomfort evaluation, the adobe house appears to perform less effectively than the tapial one.

In fact, free-running evaluation has considered the 24 hour evolution, leading to a better result in the case of stronger decrement (which is a typical character of tapial constructions). Considering some habitability or operation concepts, it can be supposed that day performance is rather more important than night performance, and the adobe time lag effect provides the best results. Figure 12 shows the tapial house performance, always for the hottest and coldest days. Tapial structure assures an extreme thermal decrement of about 80%, whilst the adobe wall achieves a result of 55%. However, thermal lag of more than 14 hours makes the solar gain in the first hours of the night unsuitable, as in the adobe case.

**Figure 9.** Simulation results of the block house, hottest and coldest day. **(a)** Block house, hottest day, **(b)** Block house, coldest day.

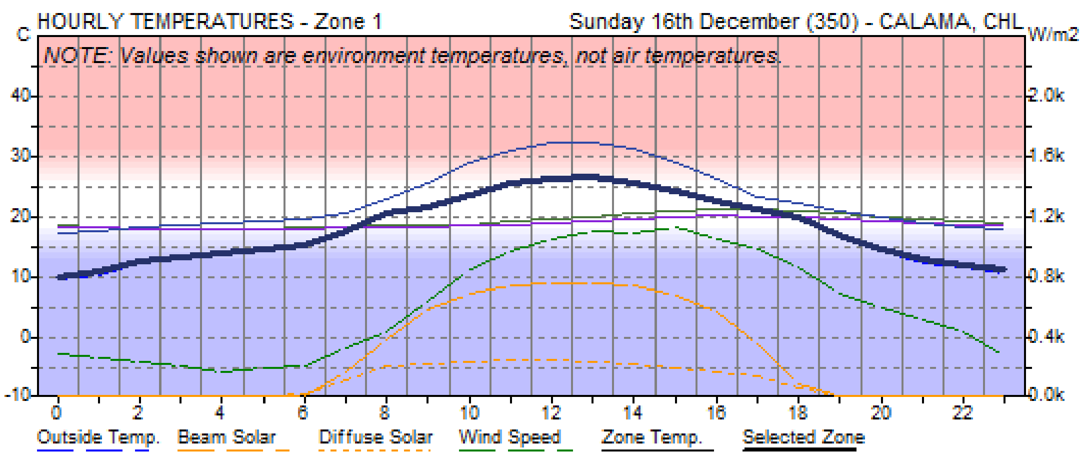



**(a)**



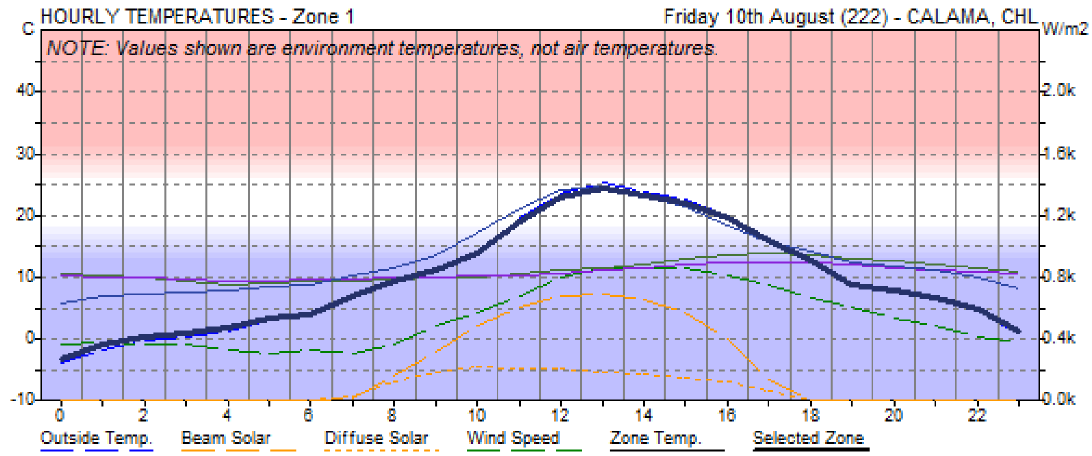

**(b)**

**Figure 10.** Simulation results of the wooden house, hottest and coldest day. **(a)** Wooden house, hottest day, **(b)** Wooden house, coldest day.




**(a)**

**Figure 10.** *Cont.*

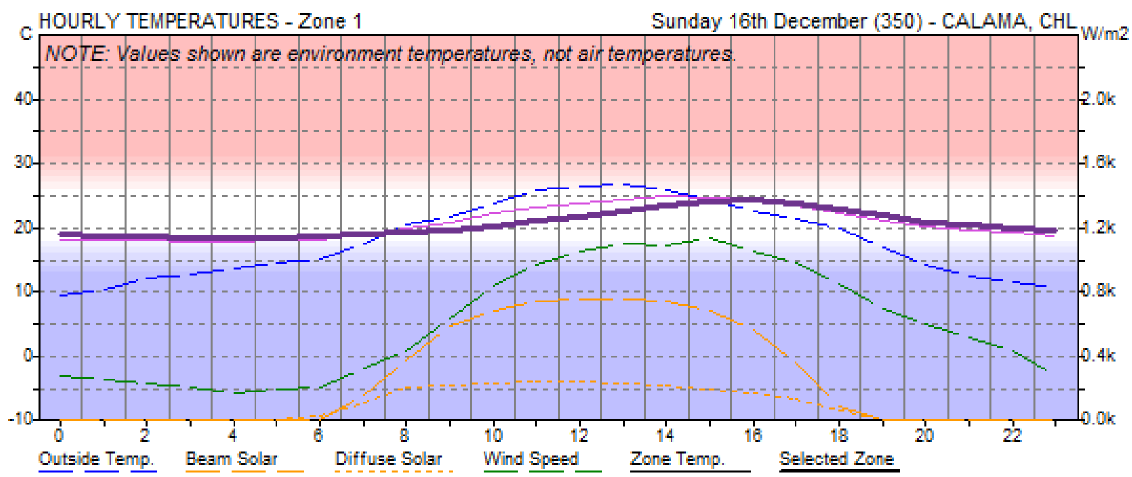



**(b)**

### *3.2. Monitoring Results—Summer Time*

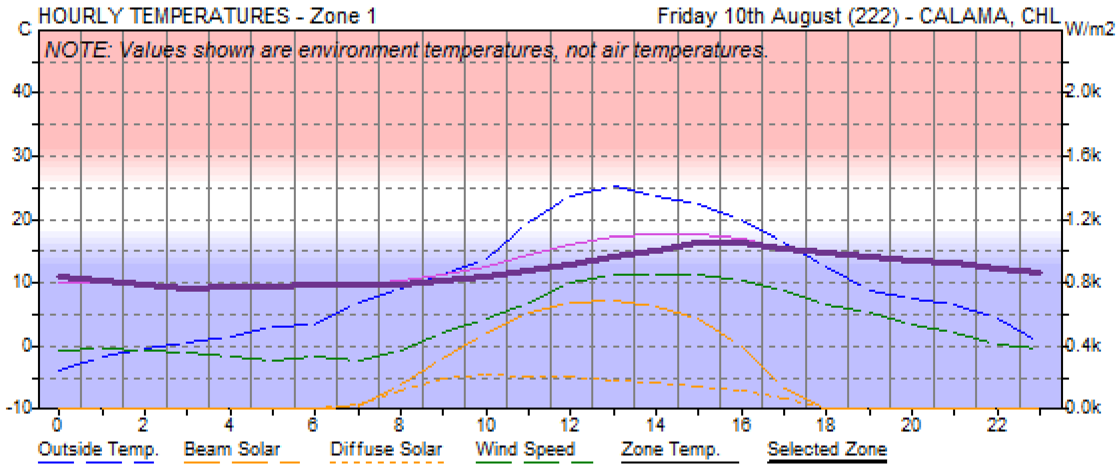
Monitoring instruments used are five TESTO thermo-hygrometers, model 175. Four testers were placed inside the houses and one was used to register external temperature and humidity. To make comparable the results, testers were placed always in the bedroom, in the high part of the wall, if possible quite far away from the windows and doors. Figure 13 shows block-work monitored data. Consistent with the simulation results, the temperature inside the block-work construction is always greater than the external temperature. This fact explains perfectly estimated the degrees-hour discomfort result of Table 2. Figure 13 also shows monitoring results for the wood self-construction home.

**Figure 11.** Simulation results of the adobe house, hottest and coldest day. **(a)** Adobe house, hottest day, **(b)** Adobe house, coldest day.



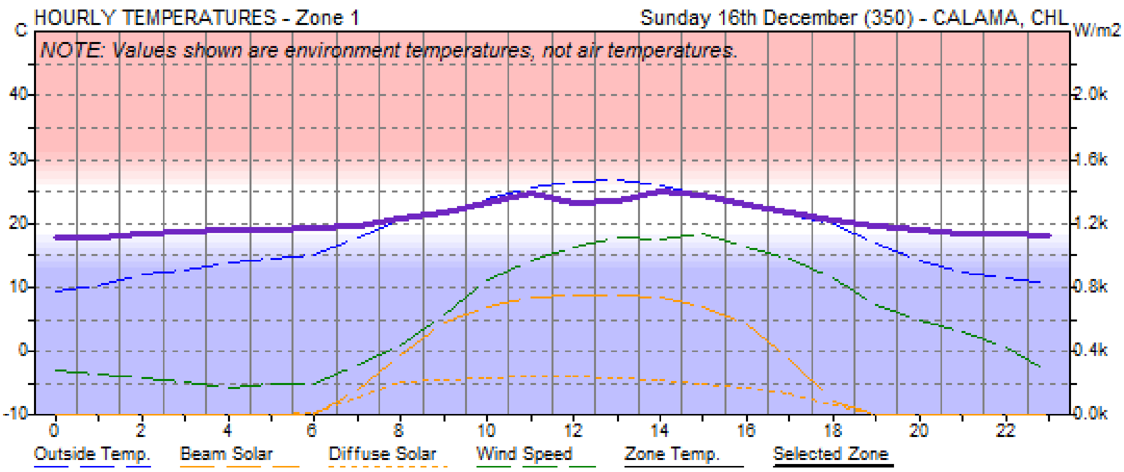

**(a)**

**Figure 11.** *Cont.*




**(b)**

**Figure 12.** Simulation results of the tapial house, hottest and coldest day. **(a)** Tapial house, hottest day, **(b)** Tapial house, coldest day.

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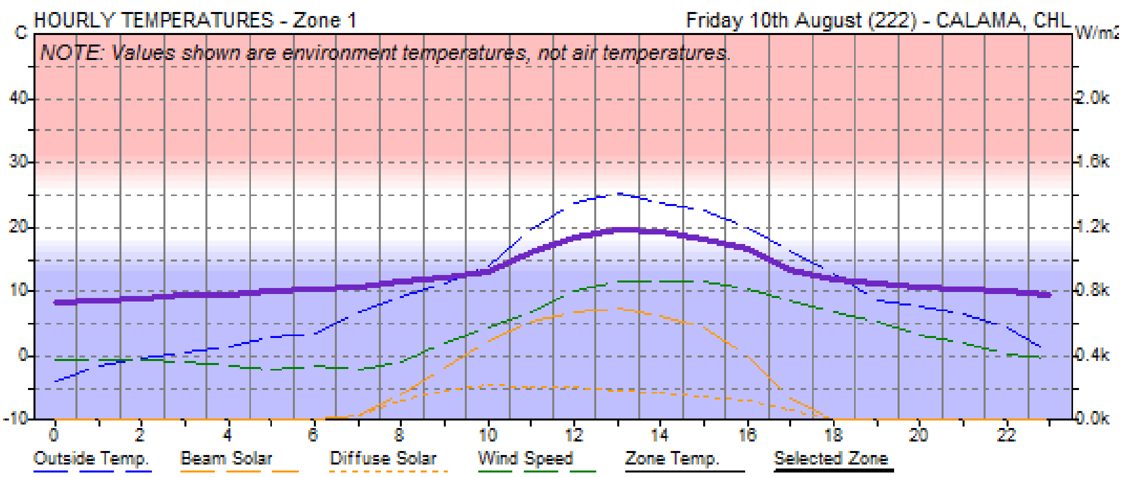
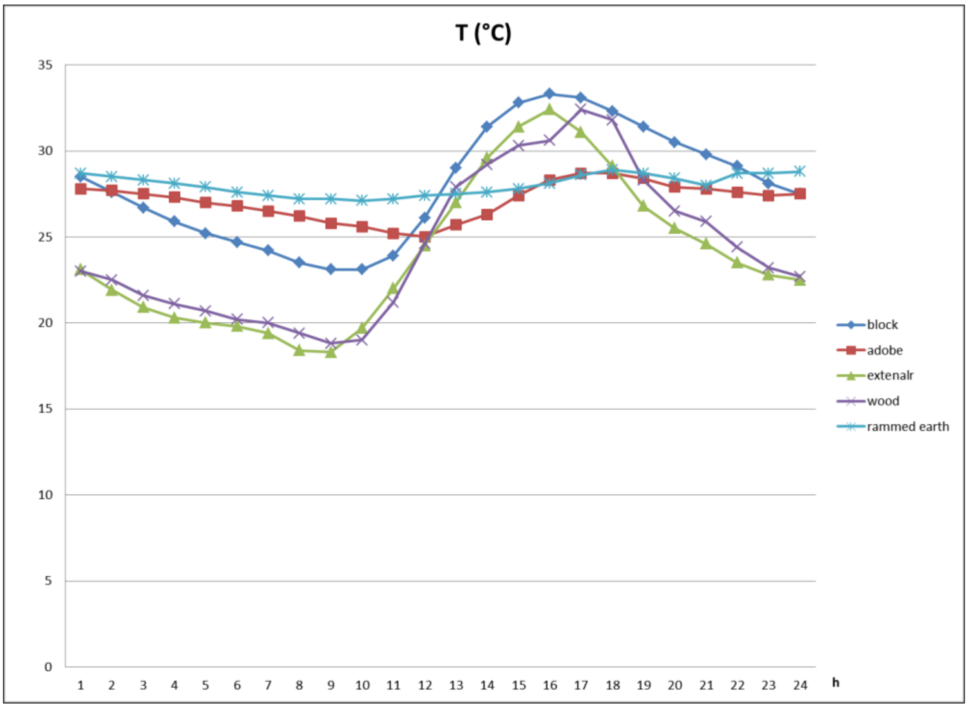



**(b)**

**Figure 13.** Monitoring result for February 5 (summer time), 2012.



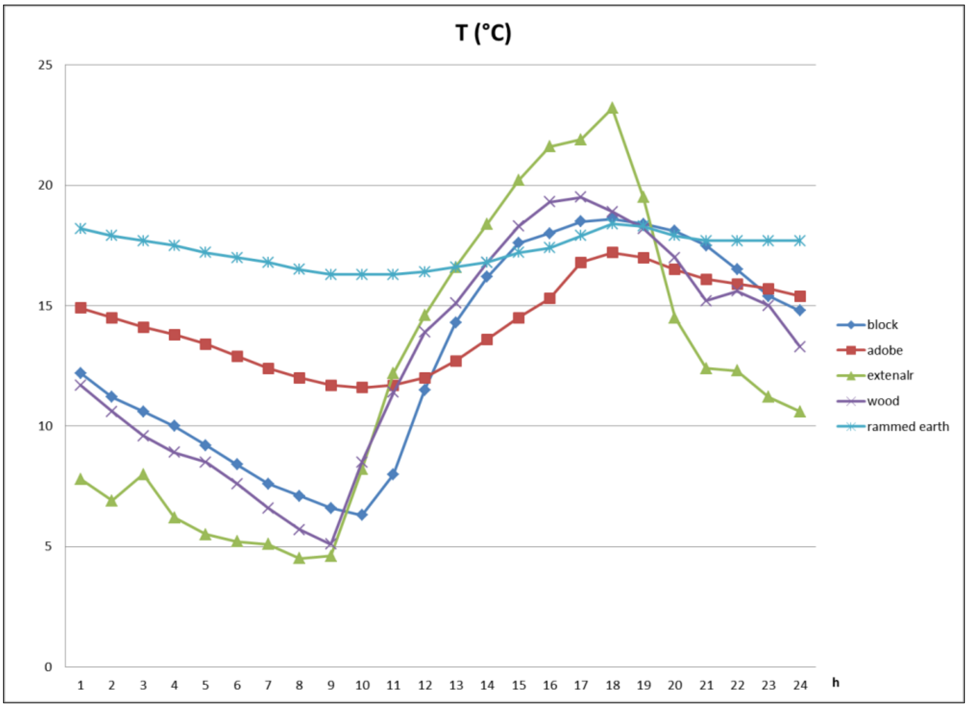

Like in the preceding case, monitoring fully confirms the simulation results, showing an evolution curve very close to external temperature variation. Infiltration gains seem to be the most sensitive variable in this house. Adobe house monitoring shows the effect of thermal decrement (more than 50%) and a real thermal lag that is lower than predicted (3–4 h), but which also effective to optimize energy performance (day/night cycle). Once again, the simulation result is quite close to monitored temperature evolution. Adobe properties are also described quite well in figure 13, and suggest that this house would probably respond better to San Pedro de Atacama climate. Tapial structure assures high thermal decrement (more than 80%, with only 1.5 degree oscillation), but night-day cycle is not related with thermal lag, resulting in a non-effective radiation capitation and reutilization during night time.

### *3.3. Monitoring Results—Winter Time*

Winter situation is shown in Figure 14 for the four cases analyzed. Block and wooden houses have high dependence on the environment, due to solar gains and ventilation, respectively.

Adobe and tapial constructions, on the other hand, show very resilient behavior and internal temperature oscillation is only between 12 and 18 degrees Celsius (15 and 18 in the case of tapial—rammed earth wall). Seasonal robustness is the most important factor in many climates, and in the Andes, it is also quite important to select a construction material. Rammed earth seems to respond better to solicitation of the desert, guaranteeing comfortable conditions in both summer and winter, during the night and day.

**Figure 14.** Monitoring result for June 27 (winter time), 2012.




Results show that traditional houses are 50% more effective than self-construction or new block homes consigned by the Dwelling Service of Chile (SERVIU) in terms of comfort, energy saving, internal temperature oscillation reduction (thermal inertia) and time lag (radiation absorption during the day and devolution of heat during the night). Our conclusion is that the properties of construction materials in use are quite close to predicted: traditional materials have an excellent on site thermal performance and can be put forward as a standard component of construction, upon resolving the possible problems of dynamical response to earthquakes, characteristic of the Andean zones. In fact, the Ministry of construction in Chile is not recommending earth adobes or tapial structures in public constructions, due to structural performance, their performance supposed to be poorer than concrete blocks or bricks [18]. However, some studies (see references [19–24]) indicate that structural problems can be resolved in earth walls using different techniques and maintaining better energy performance. Simulation shows very clearly that block-work (covered by cement) leads to significant problems in summer and overheating during winter. Monitoring confirms totally the simulation suppositions and offers a clear quantification of the internal condition in the four houses. Adobe and tapial have very resilient behavior dealing with day-night and seasonal external variations, and it appears very logical that the traditional techniques should consider earth as the principal element of construction. Energy performance is one of the most important factors to be taken into account at the moment of buying or constructing a home, but nowadays it is not assigned the same importance as other parameters. Furthermore, the traditional Andean villages are changing very fast, due to self-construction and to economic speculation. In respect to the government social dwellings that are currently under construction, it seems very probable that they will achieve a poorer performance than the analyzed ones. The project uses zinc on the roof and block-work as structural walls. It is not difficult to imagine hot days during the entire year and very cold nights due to the high sensitivity of the roof to earth-sky radiation interchanges. Really, it seems that the preferred houses, which can be used in other climates, are not the solution in San Pedro town and its desert surrounding. Finally, building energy simulation and certification has to be reconsidered, in the opinion of some authors (e.g., Palme *et al.* [25–27]), taking into account robustness and energy sensitivity, which will increase the importance of rammed earth and adobe in energy policy and guidelines. Thermal inertia is an important concept to addresses dynamic situations, climatic change, user's non-controlled behavior, seasonal variation, *etc*. Various uncertainties are also present in certification or simulation and in the building design process; some of them have epistemic origin and are quite difficult to eliminate. For all these reasons, it seems the thermal robustness concept is of interest for use in building design.

## 4. Conclusions

In this paper, simulation studies and monitoring of four different houses in San Pedro de Atacama have been presented. The principal goal of the study is to evidence that adobe and rammed earth construction responds more effectively than block-work or wood constructions to desert climate solicitation, guaranteeing internal stability and comfort. As appropriate for the culture and climate of the ancient San Pedro town, the results' assessment was done using adaptive comfort concepts and calculations. As a principal conclusion, real houses' performance studies confirm the heuristic goodness of earth as a construction material in terms of thermal decrement, thermal lag, insulation properties, and solar radiation gain use. Ventilation, also present, is not the most sensitive variable, if users control it. Only the wood house shows extreme dependence on the external situation, but in this case, infiltration was maintained and not controlled by the user. Another goal of the study is the quantification of comfort improvement obtained in these kinds of houses. The result is better than initially supposed: Adobe and tapial houses are respectively three and four times better than block-work houses.

## Acknowledgments

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## Author Contributions

Massimo Palme wrote final version of the paper and did simulation work. José Guerra did graphical work (architecture drawings) and managed monitoring data. Sergio Alfaro contributes to place monitoring instrument and to talk with families in San Pedro de Atacama.

## Conflicts of Interest

The authors declare no conflict of interest.

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