Straw bale construction in a South American Mediterranean climate:

Insitu measurements and physical test chambers in Chile's Central Valley.

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ABSTRACT: Dwellings in a Mediterranean climate such as that of Chile´s Central valley must provide comfort both during the hot days and cool nights of the summer months in addition to the cold winters. International research and previous work by the author has demonstrated that straw bale construction offers high levels of insulation and can reduce the heating demand of rural dwellings in the region. However the straw's insulating properties must be complimented by the introduction of thermal mass either in the form of thick renders or other building elements in order to avoid problems of overheating during the summer months. To date, over 40 dwellings have been constructed in Straw Bale in Chile. This paper presents the insitu measurements of environmental comfort in a recently completed straw bale house, designed and built by students from the Universidad Andrés Bello, Universidad Austral and Universidad Diego Portales, where thermal mass has been incorporated through the use of stone floors and internal earth render. The house is situated at 1200m above sea level in the coastal range of the Chilean Central Valley with high diurnal thermal oscillation. The results are compared with simultaneous measurements of a neighbouring dwelling of typical timber construction which lacks both sufficient thermal insulation and thermal mass, and analogous measurements of physical test chambers that form a part of the author's ongoing research program into straw bale construction in central Chile.

Keywords: Straw bale, Mediterranean climate, insulation, thermal mass

INTRODUCTION

Chile's Central Valley runs over 480km north-south between the Chilean coastal range and the Cordillera de Los Andes. It is bounded by the transverse valleys of the river Aconcagua (latitude 32.8º South) to the North and that of the river Bio-Bio (latitude 37.2º South) to the South. According to the latest census, that of 2002, over 50% of the Chilean population is concentrated in the region [1]. The climate of the region is classified as Mediterranean [2,3], a warm temperate climate with short cold winters of 4 to 5 months, dry summers with intense insolation and diurnal thermal oscillation averaging around 20ºC in summer and 10ºC in winter (fig.1). Both insolation and thermal oscillation increase with altitude. [2]. As a result dwellings must provide comfort both during the hot days and cool nights of the summer months in addition to the cold winters. Therefore according to bioclimatic principals, construction techniques must include both external insulation to reduce thermal losses in winter and thermal gain in summer, in addition to exposed thermal mass to attenuate and retard thermal oscillations.

TYPICAL RURAL CONSTRUCTION

Historically the construction of dwellings in the region consisted of the pre-Columbian indigenous timber-framed thatched *rukas* of the Mapuche, or following the arrival of the Spanish, *adobe* construction of sun dried earth and straw blocks. Whilst examples of these construction techniques remain, especially in the case of adobe, modern rural dwellings are now typically of platform framed timber construction with timber cladding [4]. Those dwellings built prior to the introduction in 2007 of the Chilean Residential Thermal Building Regulations for walls [5] are rarely insulated and the worst cases are unlined leading to a typical U-value of 3.5W/m^{2}K [3]. Those constructed since 2007 must comply with a maximum thermal conductivity of 1.9W/m^{2}K in the northern sector of the region and 1.7W/m^{2}K in the southern sector [4]. Although Chile was the first Latin American country to introduce thermal building regulations, the requirements of the regulations have been criticized for their inadequacy and relative weakness at both a national [6] and international [7] level. Given average winter temperatures of 10ºC and average minimum winter temperatures of 3.9ºC (fig.1) the lack of sufficient insulation leads to high heating demands and low levels of hygrothermal comfort.

In 2006 it was estimated that three fifths of the population suffered from fuel poverty [8]. In addition a study to define the baseline for the new thermal building regulations concluded that 60% of the population spend the winter with an average internal temperature of less than 15ºC and 94% an average internal temperature less than 20ºC [9]. The same study concluded that 80% of Chilean dwellings suffer problems with condensation and mold growth due to insufficient insulation and high usage of naked flame, unvented gas and paraffin heaters.

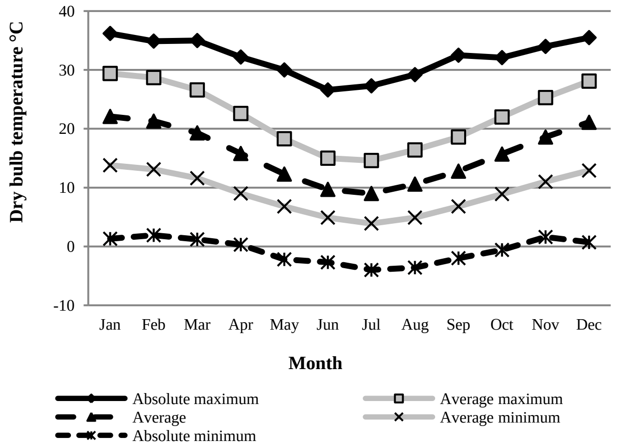

Figure 1: Average dry bulb temperatures, Santiago de Chile 1970-2000 [10].

STRAW BALE CONSTRUCTION

Although construction using straw bales can be traced back to the late 19th century, originating in the Sandhills region of Nebraska USA, this form of building gained popularity following the first energy crisis of the 1970s and examples can now be found in all continents except for Antarctica [11]. No official straw bale register exists in Chile however the author is aware of at least 40 national examples of straw bales constructions. The majority of these examples are located in the Central Valley with the exception of some houses on the Central Coast and one known dwelling near Coyhaique in Patagonia, latitude 45.5 º south.

International research has shown that straw bale construction can achieve walls with a thermal conductivity of between 0.103W/m^{2}K [12] and 0.334W/m^{2}K [12] both a great improvement on the 1.9W/m^{2}K required by the regulations. There however exists little measured and published information on the thermal mass and inertia provided by the internal earth render.

PHYSICAL TEST CHAMBERS

For the past two years, as part of a research project funded by Universidad Andrés Bello internal research funds, the author has been measuring the dry-bulb temperature and relative humidity in three physical test chambers constructed by students at the Casona de las Condes campus of the university, in Las Condes, Santiago de Chile. These three test chambers with an identical internal volume of 8.5m^3 are of three different construction techniques. Two are of platform timber frame construction. The first of which is uninsulted thus representing typical rural residential construction predating the introduction of the Chilean Thermal Building Regulations in 2007 and in addition replicating the conditions of the emergency housing or *mediaguas* constructed following the earthquake of 27th February 2010. The second is insulated with expanded polystyrene, the most commonly used insulation product in the Chilean building industry, to achieve a thermal conductivity of 1.9W/m^{2}K and thereby comply with the Chilean Thermal Building Regulations. This second test chamber represents those rural dwellings constructed post 2007. The third test chamber is constructed with a modified post and beam timber structure infilled with straw bales and finished with an earth render both internally and externally. During the first year of measurements the thickness of the earth renders was 3cm externally and 1 cm internally. Following the results of the first year the internal render was increased to a thickness of 3cm.

The three test chambers are orientated with their longest façade towards the north. This façade contains a window 1m high by 1.5m wide. During the first year these windows had no solar protection. In November 2011 solar protection was designed and installed by students to provide 100% protection between September and April.

Since May 2010 hourly measurements of dry bulb temperature and relative humidity have been recorded using LogTag HAXO-8 Multi Use Temperature/Humidity data loggers suspended centrally at a height of 1.7m above finished floor level.

RESULTS OF PHYSICAL TEST CHAMBERS

Using the data collected from the three test chambers the heating and cooling demand was calculated. A comfort range as defined by Givoni 18ºC-27ºC [13] was used. The results show a clear reduction in heating demand in the straw bale test chamber in comparison with the two timber chambers. The straw bale chamber had a 33% reduction in heating for the period March 2011 - March

2012 when compared to the insulated timber test chamber that complies with Chilean thermal building regulations.

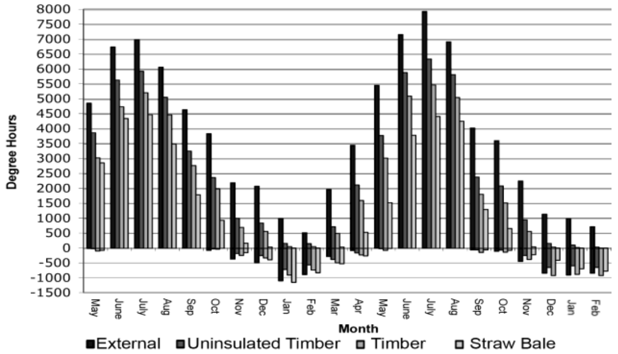

Figure 2: Heating (+) and cooling (-) degree hours of physical test chambers

Overheating in the test chambers can be noted during the summer months. During the first summer (December 2010 – March 2011) the straw bale test chamber experienced more hours over 27ºC than the timber chambers. Following the introduction of solar protection and additional thickness of internal earth render it can be noted that this overheating was reduced and that the straw bale test chamber had a lower cooling demand in the summer months than that of the insulated timber chamber.

CASE STUDY HOUSE: CASA CALEU

In order to validate the theoretical results of the physical test chambers the author undertook measurements of a recently completed straw bale house in Central Chile.

LOCATION

The house is a second home located on the outskirts of the small village of Caleu, situated 60km North West of the capital Santiago de Chile, high in an eastern lateral valley of the central coastal range. At an altitude of around 1200m above sea level the diurnal thermal oscillation is at the higher end of those experienced in the region.

CONSTRUCTION AND MATERIALITY

The house was designed and built over a period of a year 2010-2011 by architecture students from the Universidad Austral, Max Ovalle; the Universidad Andrés Bello, Pedro Anguita; the Universidad Diego portales, David Aceituno and Juanpablo Mhor; along with the qualified architect Francisca Infante and independent builder, Francisco Ilabaca. The students lived onsite during the design and construction process modifying the design according to the knowledge gained insitu. This included definition of the orientation of the house, location of windows for specific views and sun angles, positioning of terraces to enjoy breezes, as well as defining the bioclimatic strategies for the construction.

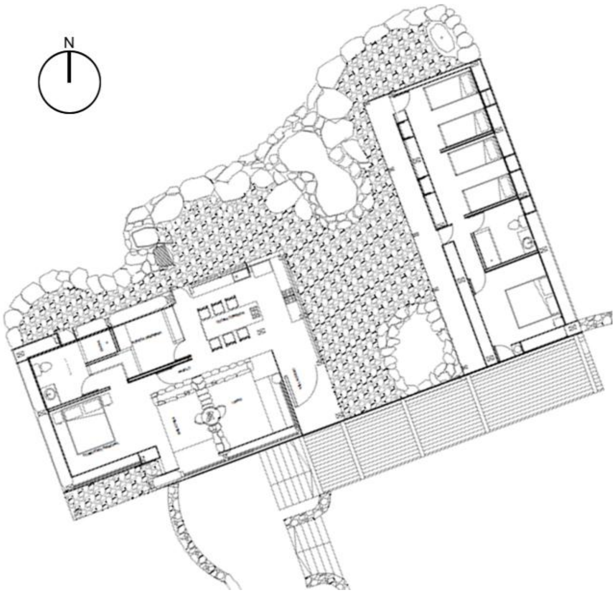

Figure 3: Plan of case study house, Caleu, Metropolitan Region, Chile. Timber post and beam structure with straw bale infill.

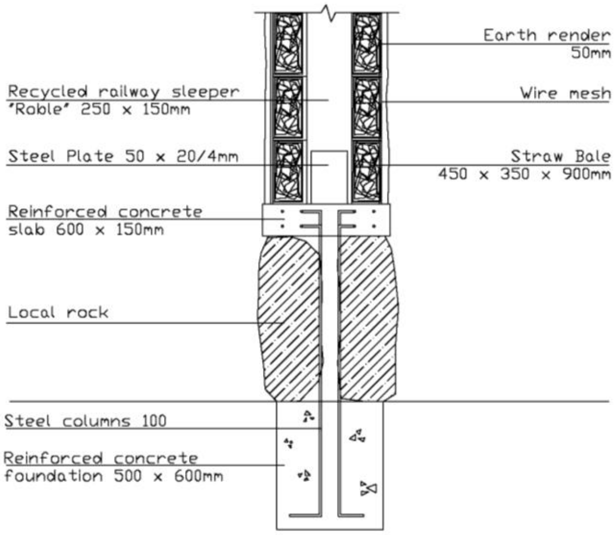

Figure 4: Section through wall. Construction detail

Owing to the climatic conditions previously discussed it was acknowledge the need for high levels of insulation and exposed thermal mass. Straw bale construction was chosen for the walls with an earth render to both protect the bales and provide thermal mass. Additional thermal mass was introduced in the form of stone floors and stone dwarf walls. The detailing of the dwarf walls could prove problematic in winter due to the lack of insulation and thermal bridging at this point (fig.4). The roof is an inverted green roof planted with species endemic to the site. Once established these plants will require only the water provided by the winter rains and humidity present naturally in the atmosphere avoiding additional irrigation and use of potable water. The plants, a mixture of grasses and low shrubs will provide shade to the roof surface thereby reducing direct solar gains.

Materials were where possible sourced locally. The stones and rocks for retaining walls, dwarf walls and floors were collected by hand from the site and surrounding hillsides. The main timber structure is of poplar sourced and felled by the students on a neighbour's smallholding 1km from the site. Exposed secondary timber beams are of recycled timber, a mixture of "*Roble"* Chilean oak *(Nothofagus obliqua)*, and *"Coihue"* Dombey's Southern Beech *(Nothofagus dombeyi)* both source at architectural salvage yards in Qunita Normal, Santiago de Chile 60km from the site but en route from the home of some of the students. The straw bales were sourced from a neighbouring smallholding and the earth for the earth render was taken directly from the site.

INSITU MEASURMENTS

On Sunday the 27th of November 2011 the author visited the house with the students and the owners to take measurements of dry bulb temperature, relative humidity, and internal radiant surface temperatures. In addition to reading taken on the day, three LogTag HAXO-8 Multi Use Temperature/Humidity data loggers and two additional LogTag HAXO-8 Multi Use Temperature data loggers were installed, at a height of 1.7m above finished floor level, to take dry bulb temperature and relative humidity measurements every ten minutes in the living room, master bedroom and a second bedroom of the house. Measurements of external conditions were taken, as were those of an adjacent neighbouring uninsulated timber cabin that predated the construction of the straw bale house. The results of these measurements are presented below.

RESULTS

DRY BULB TEMPERATURE

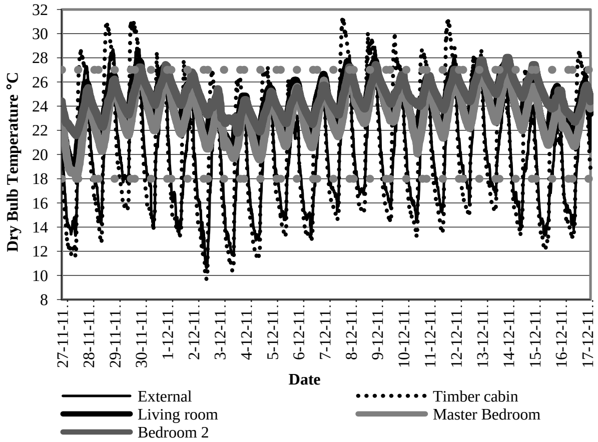

Figure 4: Summer Dry bulb Temperatures as measured 27 November – 17 December 2011

The internal dry bulb air temperatures of the case study house (fig.5) remain almost constantly within the thermal comfort zone as defined by Givoni [13] with only a few hours passing beyond the higher limit of 27ºC. The house shows good insulation at night. In the worst case maintaining 20.5ºC whilst external temperatures dropped to 10.5ºC. The amplitude of the thermal oscillation is reduced from an average external oscillation of 12ºC to an internal oscillation of 5ºC. In comparison the uninsulated timber cabin amplifies the oscillation to an average 15ºC.

RELATIVE HUMIDITY

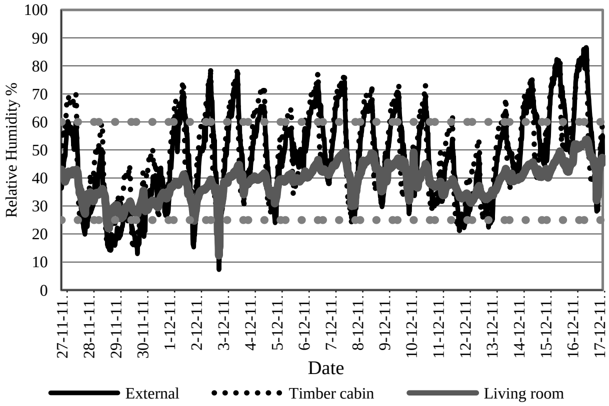

Figure 6: Summer Relative Humidity as measured 27 November – 17 December 2011

Internal relative humidity measurements (fig.6) in the house are more stable than both external measurements and those of the timber cabin. Except for a couple of hours when readings dropped below 25%, reading remained within the range of 25-60% relative humidity. External relative humidity varied between 9-85% and that of the timber cabin was almost equal to external measurements at all times.

INTERNAL RADIANT SURFACE TEMPERATURES

Table 1: Internal Radiant Surface Temperatures. As measured on the 27th November 2011. (DB- Dry bulb air temperature)

	DB(ºC)	Surface temperature (ºC)					
Room		North	East	South	West	Ceiling	Floor
Living	23	N/A	21.4	21.0	22.0	23.4	21.2
Kitchen	23	22.8	22.6	N/A	22.8	23.4	21.6
Master B.	23	22.8	21.2	21.0	22.4	25.0	21.8
En Suite	23	22.4	22.8	22.6	22.8	23.8	21.6
Bed 2	22	22.4	23.2	22.2	22.2	23.8	21.4
Bed 3	22	22.8	23.2	23.4	23.6	24.8	21.6
Bed 4	22	23.6	23.6	23.4	22.6	25.6	21.4
Bathroom	22	23.6	24.0	23.8	23.2	25.4	22.2
Hall	22	22.0	23.8	22.2	22.2	22.8	22.6
External	26						

The internal radiant surfaces temperatures of the walls were on average closely related to the dry bulb air temperature of the room. Ceiling temperatures were higher than the air temperature. As the vegetation on the inverted green roof has not yet become established the desired shading effect is not yet in place. The direct solar gain on the roof could explain these higher temperatures. The stone floors have a lower surface temperature than the dry bulb air temperature.

Whilst studying the walls with the use of a thermographic camera, a significant temperature difference was discovered at the wall-ceiling junction (figs.7&8). In this location a mixture of earth and straw had been packed to fill the gaps between rafters rather than cut straw bales. The increased thermal conductivity of this material and higher external temperature explains this difference in surface temperature.

Figure 7: Photograph of wall ceiling-junction.

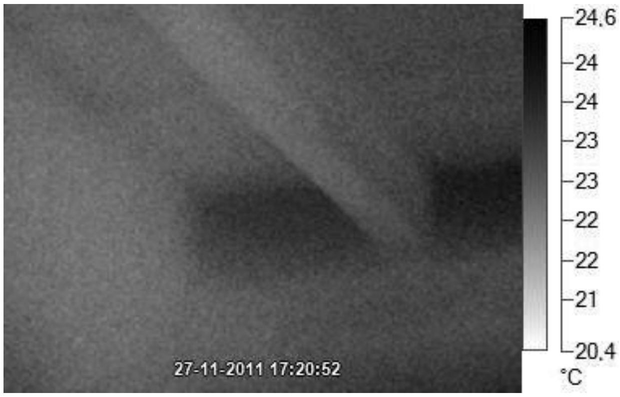

Figure 8: Thermographic image of identical wall-ceiling junction showing radiant surface temperature.

CONLUSIONS

The insitu measurements at the case study house and those of the physical test chambers show that straw bale construction can provide hygrothermal comfort in the Mediterranean climate of Chile's Central Valley when sufficient thermal mass is incorporated into the design in the form of earthen renders and stone floors. The thermal oscillations are significantly reduced by this thermal mass, with the insitu measurements in Caleu showing over a 50% reduction in diurnal temperature changes.

The temperature measurements of the physical test chambers demonstrate that the increased thermal insulation offered by the straw bales can reduce the heating demand by 33% during the winter months when compared to a platform framed timber construction insulated to Chilean thermal building regulation requirements. Currently the author is scheduling a further site visit to the case study house to undertake insitu measurements in winter to validate these results.

ACKNOWLEDGEMENTS

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