

STRAW BALES, A POSSIBLE SOLUTION FOR HYGRO-THERMALLY COMFORTABLE DWELLINGS IN CHILE'S CENTRAL VALLEY: PHYSICAL TEST CHAMBERS AND IN SITU MEASUREMENTS

Christopher J. Whitman^a

ABSTRACT

Dwellings in a Mediterranean climate, such as that of Chile's Central Valley, must provide hygro-thermal comfort both during the cold winters, and the hot days and cool summer nights. Straw, once a material common in Chile's indigenous and vernacular architecture, could meet these demands when coupled with sufficient thermal mass in the form of earth renders and floor finishes. This article presents measurements of dry bulb temperatures and relative humidity, both in physical test chambers and Chilean straw bale homes. The results of these measurements confirm that straw bale construction could provide hygro-thermal comfort with heating demands 28% less than those of constructions that meet the Chilean thermal building regulations. Straw bale, therefore, could provide a viable solution for comfortable, energy efficient, rural dwellings in Chile's Central Valley. Whilst over 40 private straw bale projects have been completed in Chile to date, restrictions applying to projects receiving government subsidies prevent this technology being available to those who need it most.

KEYWORDS

straw bale, hygro-thermal comfort, residential, energy efficiency, Chile

1. INTRODUCTION

1.1 Context

1.1.1 Chile's Central Valley

Chile's Central Valley stretches over 480km running 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 32.8° South) to the North and that of the river Bio-Bio (latitude 37.2° South) to the South. According to the census of 2002, over 50% of the Chilean population is concentrated in the region [1]. The Valley enjoys a Mediterranean climate similar to that

^aLaboratorio de Energía e Iluminación, Facultad de Arquitectura, Arte y Diseño, Universidad Andres Bello, Campus Casona de Las Condes, Fernández Concha 700, Las Condes, Santiago de Chile. Tel:+56 2 661 8792 chriswhitman@hotmail.com.

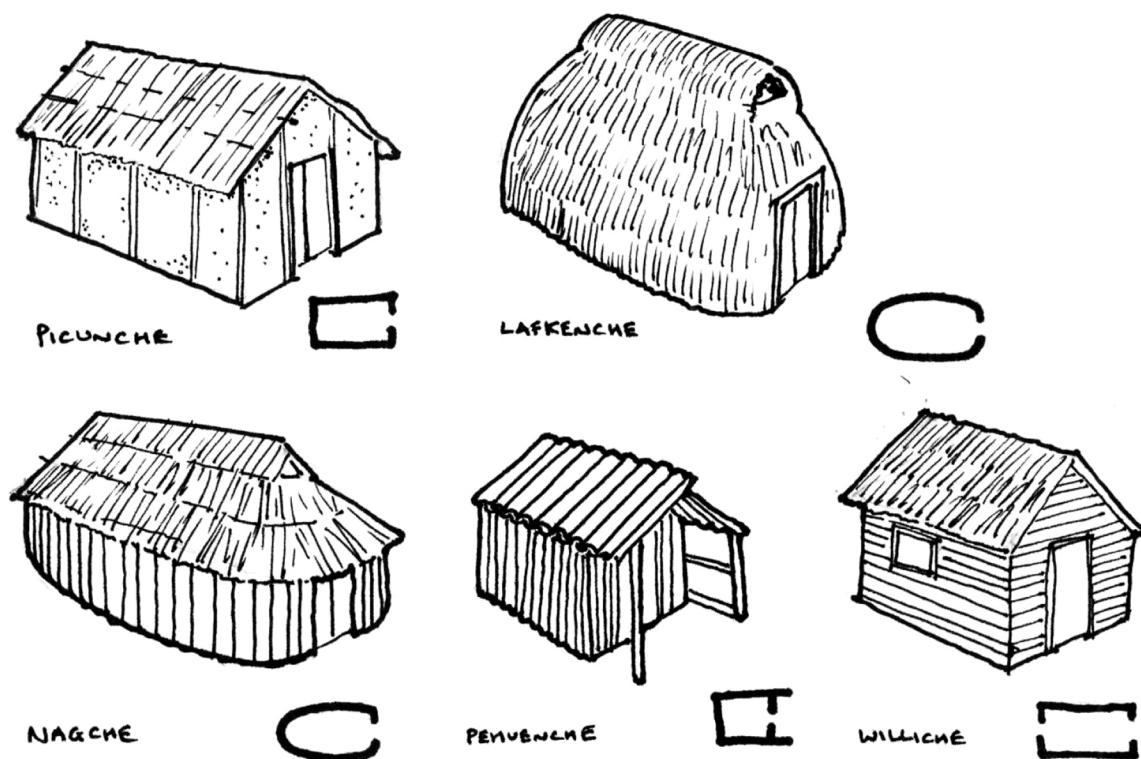
of California, Cape Town, South West Australia and countries bordering the Mediterranean itself. This temperate climate is characterised by its dry warm to hot summers and short cool wet winters of 4–5 months [2]. Its altitude of between 300 and 800m above sea level, and its clear skies lead to intense insolation and diurnal thermal oscillation averaging around 20°C in summer and 10°C in winter. Both insolation and thermal oscillation increase with altitude. 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 principles, 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.

1.1.2 Indigenous and vernacular architecture in Central Chile

Historically, the construction of dwellings in the region consisted of the pre-Columbian indigenous timber-framed thatched *rucas* of the Mapuche. These single roomed constructions vary in their materiality depending on the specific sub region (Fig. 1).

In the north of the Central Valley, the *Picunche* tribes built their homes from wattle and daub, the *Lafkenche* from the coast, to this day use local reeds and grasses, whilst the *Nagche* from the central plains build their walls from vertical timbers. The *Pehuenches* from the Andean foothills are the only Mapuche tribe that do not thatch their rucas, opting instead for a construction of hollowed logs or canoes used as large tiles. Further south, the *Willeche* use thatch for the roof but the walls are constructed of horizontal timbers, and there is the introduction of windows.

FIGURE 1. The architecture of the different tribes of the Mapuche, Chile's indigenous people [3].



With the arrival of the Spanish in 1537 came the introduction of the unfired earth brick or Adobe. This building technique consists of earth to which natural fibers are added. In Chile the most commonly used natural fiber is straw. The earth-straw mix is formed into bricks or adobes in wooden moulds. The adobes are then left to dry in the sun. Adobes are used as both load-bearing solid masonry construction, bedded with an earth mortar, with walls typically between 600mm and 1,200mm thick, and as an infill between timber structure forming thinner walls and partitions. Both systems are traditionally finished with an earthen render. In time adobe became the predominant construction technique in Chile's Central Valley and remained so until the beginning of the 20th Century. According to the latest national census of 2002, earth construction represented 5.5% of the Chilean building stock [1] and forms a large proportion of Chile's National Monuments and heritage buildings.

1.1.3 Current Rural Construction Techniques

Whilst examples of both indigenous Mapuche architecture and colonial adobe construction can still be found in rural Chile, the majority of rural dwellings are now built of platform-framed timber construction with timber cladding. A survey undertaken by the author of the typical rural village of Rungue, 50km north of the capital Santiago de Chile, found that only 7% of the buildings were of adobe, and these are concentrated in the historic core of the village. Of the remaining buildings 67% are of platform framed timber construction. Those built prior to the introduction of Chilean thermal building regulations in 2007 are almost all uninsulated, in the worst case without internal lining, leading to typical thermal conductivity U-values of $3.5\text{W/m}^2\text{K}$. Those constructed since 2007 must comply with a maximum thermal conductivity of $1.9\text{W/m}^2\text{K}$ in the northern sector of the region and $1.7\text{W/m}^2\text{K}$ in the southern sector [4]. Although Chile was the first Latin American country to introduce thermal building regulations, their requirements have been criticized for their inadequacy and relative weakness at both a national [5] and international level [6]. Given average winter temperatures of 10°C and average minimum winter temperatures of 3.9°C , the lack of sufficient insulation leads to high heating demands and low levels of hygro-thermal comfort.

1.1.4 Chilean Housing Deficit

1.1.4.1 The Quantitative Housing Deficit. Even before the earthquake that struck central Chile on the February 27, 2010, Chile's quantitative housing deficit was not insignificant. According to the 2002 census, 15% of the urban population were recorded as living in self built shelters or homeless [7], a figure that rises to 37.64% of the total Chilean population when those sharing dwellings are included [8]. Of this figure the rural homeless population represents 19%. According to the National Survey of Shantytowns undertaken by the charity 'Un Techo para Chile,' in 2007 there existed in Chile 533 shantytowns housing 28,578 families. Of these 73% were located in central Chile (5-9th and Metropolitan Regions) [9].

Directly following the earthquake a further 80,000 emergency shelters called "mediaguas" were constructed by the Chilean government, the military and charitable foundations, of which by the October 31, 2012, 56% had been permanently rehoused [10].

1.1.4.2 The Qualitative Housing Deficit. In addition to the quantitative housing deficit, Chile also suffers from one that is qualitative. Many Chilean households spend winter with an average indoor temperature of 15°C and high levels of relative humidity. Hence 80% of the housing stock suffers from problems of condensation and mould growth [11]. The poor quality housing stock also directly contributes to airborne contamination due to the use of

inefficient wood burning stoves. Many of the larger cities of the central valley have been declared zones saturated by breathable airborne contamination of PM10 (particulate matter $\geq 10\mu\text{m}$). In the city of Rancagua (VI Region) 28% of the contamination is attributed to wood fired space heating, whilst further south in the city of Temuco (IX Region), this figure rises to 93% [12].

1.2 Straw bales—an agricultural waste product

During the agricultural productive year 2010-2011 Chile planted 271.415 hectares of wheat, 105.643 of oats, 20.184 of barley and 25.121 of rice [13]. Assuming that 60% of the straw is baled and an average yield of 2,690kg per hectare [14], this would equate to the production of around 34.5 million straw bales or 2.3 bales per capita. Currently in Chile the straw from these cereal crops is viewed as a waste product and in many cases is burnt in the fields further adding to carbon emissions and poor air quality. Concerns over the already saturated air pollution in the capital Santiago led in 2009 to the prohibition of agricultural fires during the winter months between the 1st of May and the 31st August in the VI Region, the region to the windward side of the capital. However in 2009 alone 360 prosecutions were brought for infringement of this law.

1.2.1 Straw bales—a low cost insulation material

International research has shown that straw bales can provide walls with a U-value of between 0.334 and 0.103 W/m²K (Table 1). This wide range of U-value results can be attributed to different straw types, dissimilar bale compaction and varying test methods. In the case of the guarded hot plate test undertaken by IDIEM of the Universidad de Chile in 2003, the sample consisted of 35mm lengths of straw compacted by hand into a miniature bale, a method that does not represent the compaction and density obtained with a mechanical baler. However even taking this worst case scenario, an earth rendered straw bale wall would have a thermal conductivity of 0.641 W/m²K. This value is a third of the maximum conductivity permitted by the Chilean building regulations which require only 1.9 W/m²K. The majority of the international test results show a far greater reduction in thermal conductivity with average values around 0.2 W/m²K almost ten times better than the Chilean regulations.

Furthermore, laboratory testing has shown that rendered straw bales can provide a fire resistance of between F60 [22] and F90 [23] (Table 2) and acoustic separation of 59.8 dB(A) (Table 3).

In 2009 the cost of straw bales in the countryside near the capital, Santiago de Chile, ranged between \$1000 Chilean pesos and \$1500 Chilean pesos (2-3US\$). To achieve an equivalent u-value of 0.2 W/m²K with the cheapest available insulation, expanded polystyrene of 10kg/m³, a thickness of 200mm would be required costing approximately \$5280/m² Chilean pesos (US\$11/m²). The straw bales also have the added advantage of forming the main body of the wall, thereby requiring less additional materials than expanded polystyrene to form a finished wall.

2. HYPOTHESIS

If straw was viewed as a resource instead of a waste product, the straw from grain crops could be used for straw bale construction, providing an alternative to the current poorly insulated platform framed timber construction in the rural communities of Chile's Central Valley. This

TABLE 1. Results of International Thermal Conductivity Testing of Straw Bales [15, 16, 18, 19, 20, 21 &22].

Author	Date	Location	Method	Straw Type	Bale dimension mm	Moisture content %	Density kg/m ³	U Value W/m ² K	λ W/mK
McCabe. J.	1993	University Arizona	Guarded hot plate. Single bale	Wheat	580	8.4	133	0.103	0.054 edge 0.061 flat
Acton. R.U.	1994	Sandia Labs	Thermal Probe Single Bale	Not listed	460	Not listed	83.3	0.118	0.05 flat
Watts. C., Wilkie. K., Thomson. K. and Corson J.	1995	Nova Scotia	Hot plate. in-situ	Not listed	460	Not listed	Not listed	0.2	0.097
Not listed	1996	Oak Ridge National Lab	Hot Box full wall	Wheat	460	20	112	0.334	0.15
Not listed	1997	CEC	Hot Box full wall	Rice	580	11	107	0.218	0.13
Stone. N.	1997	Architectural Testing Labs-Fresno	Hot box	Not listed	580	Not listed	Not listed	0.218 0.172	0.13–0.07
Not listed	1998	Oak Ridge National Lab	Hot Box Full wall	Not listed	480	13	128	0.208	0.099
Wimmer. R.	2001	BMVIT. Vienna	ISO 8301	Not listed	Not listed	Not listed	Not listed	Not listed	0.038
Wimmer. R.	2001	BMVIT. Vienna	ÖNORM B6015	Not listed	Not listed	Not listed	Not listed	Not listed	0.034
Andersen. J.M. and Andersen. B.M.	2004	Statens Byggeforskn- ingsinstitut. Denmark	Hot box. Single bale	Not listed	385 365	Not listed	75 90	0.208- 0.196	0.057–0.060 0.052 flat 0.056 edge
Goodhew. S. and Griffiths. R.	2004	University of Plymouth	Thermal probe	Not listed	360	Not listed	60	0.18	0.067
Not listed	2006	Deutsches Institut für Bauttechnik	Not listed	Not listed	Not listed	Not listed	Not listed	Not listed	0.08 flat 0.052 edge
IDIEM, Universidad de Chile	2003	Santiago de Chile	NCh 850 Guarded hot plate	Wheat cut to 35mm	400x 400x 35	Not listed	Not listed	Not listed	0.28
IDIEM Universidad de Chile	2009	Santiago de Chile	NCh 851 Hot box	Trigo	300x 400	Not listed	Not listed	0.2–0.3 0.15–0.2	0.06–0.09

TABLE 2. Results of International and Chilean Fire Testing of Straw Bales [22, 23 & 24].

Author	Year	Location	Standard	Construction	Minutes	Result
SHB Agra	1993	Scandia, Nueva México, EEUU	ASTME E-119		30	Approved
				Rendered	120	Approved
Universidad de California	1996	California, EEUU	ASTME E-119	Rendered	60	Approved
Santa Fe, Fire Dept.	2000	Nueva México, EEUU	1093°C	Unrendered	30	Failed
				Standard timber wall	35	Burnt
				Rendered	40	Approved
GrAT Wein	2001	Viena, Austria	Alemán F90	Rendered	90	Approved
AUSBALE	2002	Australia	Australian Bushfire code AS 3959	Rendered	No esp.	Qualified as "incombustible" Approved
DCAT	2006	Texas EEUU	ASTME E-119	Earth Render	60	Approved
				Lime-cement Render	120	Approved
Universidad Técnica de Braunschweig	2007	Alemania	DIN EN 1365-1:1990-10	Earth Render 30mm	38	Approved
EXPO Zaragoza	2008	Zaragoza, España	UNE-EN 1364-1:2000	Earth Render	91	Approved
IDIEM, Universidad de Chile	2009	Santiago de Chile	NCh 935/1	400mm bale Cement Render	120	Approved
IDIEM, Universidad de Chile	2009	Santiago de Chile	NCh 935/1	300mm bale Cement Render	60	Approved

TABLE 3. Results of International and Chilean Acoustic Testing of Straw Bales [25 & 26].

Author	Year	Lugar	Norma	Construction	Reduction dB(A)
C J. Mas and E Carr Everbach	1995	Swarthmore, EEUU	Not listed	Wheat straw bales. 20" thick	58,9
J. Van de Linden	2003		ISO 140-3	Straw bales with earth render	55
J. Glassford	2006	Sídney, Australia	Not listed	Straw bales. Finish not listed.	54–55
R. Deverell, S. Goodhew, R. Griffiths and P de Wilde		Genesis Centre, Somerset, UK	ISO 140:4-1998	Straw bales. Finish not listed	48–50
IDIEM, Universidad de Chile	2009	Tunquén, Chile	NCh 2785	Straw bales with 30mm of plaster	45

alternative for rural dwellings would have a reduced heating demand, lower green house gas and air borne pollution emissions, and provide improved hygro-thermal comfort. In addition, the use of this waste material would reduce the additional greenhouse gas emissions arising from agricultural fires.

3. METHODOLOGY

To test this hypothesis test chambers were constructed to compare the hygro-thermal performance of straw bale construction in comparison to typical rural construction. In addition, in situ measurements were undertaken in a Chilean straw bale dwelling. In parallel, in order to understand the reality of building with straw bales in Chile, Chilean architects with experience of straw bale construction were interviewed.

3.1 Physical test chambers

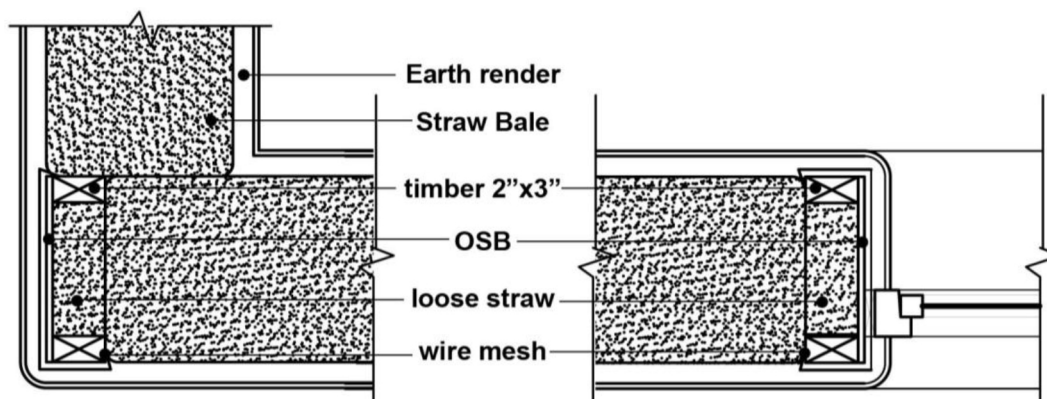
3.1.1 Design of physical test chambers

3.1.1.1 Definition of materials for comparison. In order to define the typical rural construction of the central valley of Chile, a survey was undertaken of a typical small town, Rungue, situated 50km north of Santiago just off the Pan American Highway. The survey concluded that 65% of the residential construction was timber framed with timber cladding. In addition, a review was made of the 121 certified housing designs introduced by the government for rebuilding following the February 2010 earthquake. Of these, 75% are timber framed or of timber based structural insulated panels [10]. Given that many of the rural dwellings were built prior to the 2007 building regulations, it was decided to construct three physical test chambers:

- Un-insulated timber construction to simulate rural housing pre 2007 and emergency housing “*mediaguas*” constructed immediately following the earthquake.
- Insulated timber construction, insulated with expanded polystyrene to comply with Chilean building regulations (U-Value $1.9 \text{ W/m}^2\text{K}$), to simulate rural housing constructed post 2007 and the government certified housing solutions for rural reconstruction.
- Earth rendered straw bale laid on edge, with “modified post and beam” timber structure [Fig. 2].

To reduce the variables, the roofs of the three test chambers were all of 9mm orientated strand board (OSB), 80mm of expanded polystyrene to provide a thermal conductivity of $0.47 \text{ W/m}^2\text{K}$ as required by Chilean building regulations [4], roofing felt and finished with black bituminized corrugated roofing, a common material for low cost housing in central

FIGURE 2. Plan of straw bale test chamber corner and window jamb construction detail.



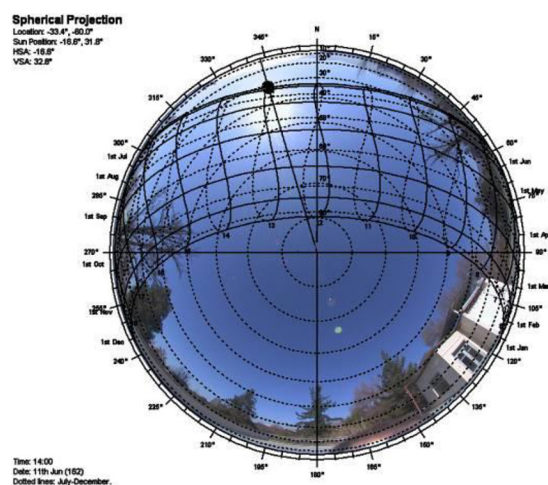
Chile. The windows were single glazed 3mm float glass, in accordance with Chilean building regulations, which do not require double glazing when the glazed area does not exceed 25% of the vertical surface area of the dwelling [4]. The floor of the test chambers is 3mm polyethylene sheeting supported on the existing concrete slab of the selected site. The floor of the test chambers is un-insulated as Chilean building regulations require only ventilated floors to be insulated.

3.1.1.2 Physical dimensions. An internal volume of 2,450mm long \times 1,560mm wide by 1,800mm high at the eaves rising to 2,470mm at the apex was chosen based on the modular bale size. This allowed sufficient internal space for comfortable working during construction whilst not exceeding budget constraints. As the wall thickness varies for each of the three constructions, gross floor area and external surface area vary but the internal air volume remains constant.

Each test chamber has a north facing window formed by three fixed timber framed 3mm single glazed windows, each 500mm wide \times 1,000mm high, giving a total fenestration area of 1,500mm \times 1,000mm. During the period May 2010–November 2011, no solar protection was provided. Following a review of the first year of results solar shading was designed and installed by students to provide 100% solar shading from the spring to the autumn equinoxes. There is a door 700mm wide \times 1,800mm high for access in the western elevation.

3.1.1.3 Site selection. Various possible sites within the university's Campus Casona de las Condes were reviewed with regard to solar exposure, over-shadowing, security, and minimum disruption to other academic and administrative activities. As a result of this review, the roof terrace of the Library building was selected. A photograph was taken with a Nikon Coolpix digital camera fitted with a fish-eye lens and a solar chart overlaid to evaluate solar access (Fig. 3). This exercise confirmed minimal overshadowing of the site, with minimal shade from trees in winter until 10:00am and after 16:00pm in summer. Winter sun angles were used to calculate the separation between test chambers to ensure that one would not cast a shadow on another.

FIGURE 3. Site photo taken with Nikon Coolpix digital camera fitted with fish-eye lens, with solar chart for Santiago overlaid.



3.1.2 Material costs

All construction materials were purchased at the same time in December 2009 from a local builder's merchant, except for the straw bales which were sourced locally on the outskirts of Santiago. Material costs are presented in Table 4. The material costs of the straw bale test chamber were marginally lower than those for the un-insulated timber chamber. Labour costs were not calculated as construction was undertaken by students.

3.1.3 Construction of physical test chambers

The construction of the three test chambers took place between November 2009 and May 2010 during the summer months (Fig. 4). Owing to the lack of rainfall during this season

TABLE 4. Material costs for the three physical test chambers.

Construction type	Overall cost US\$*	Cost per m ² net area US\$*
Straw Bale. Straw bales laid on edge 360mm; timber, straw filled structural elements as described earlier; 30mm earth render (both sides); lime wash; <i>single glazed, timber framed, windows; timber door, roof of OSB; expanded polystyrene insulation sufficient to meet with Chilean Thermal regulations; roofing felt</i>	548	140
Un-insulated Timber. Structure consisting of 2" × 3" softwood timbers; softwood timber siding 15 × 125mm; white exterior emulsion paint; <i>single glazed, timber framed, windows; timber door, roof of OSB; expanded polystyrene insulation sufficient to meet with Chilean Thermal regulations; roofing felt</i>	555	142
Insulated Timber—Expanded Polystyrene. Timber structure consisting of 2" × 3" softwood timbers; softwood timber siding 15 × 125mm; white exterior emulsion paint; <i>single glazed, timber framed, windows; timber door, roof of OSB; expanded polystyrene insulation sufficient to meet with Chilean Thermal regulations; roofing felt</i>	631	161

*exchange rate at time of purchase—US\$1 = \$554,700 Chilean pesos
Materials in italics are common to all three test chambers

FIGURE 4. Finished physical test chambers as measured May 2010–November 2012.

there was no need to protect the bales during construction. The construction was undertaken by 4th year Industrial Design undergraduates as part of their course “laboratory Practice.” The construction team represents an unskilled workforce not uncommon in rural Chile. The timber constructions were painted white with ordinary exterior quality water-based emulsion paint; their joints were not sealed as this is not common practice in rural Chilean construction.

The straw bale test chamber was finished with a 30mm thick earth render using recycled “adobe,” earth blocks, from a historic house in Pirque, South West of Santiago, that was demolished following severe structural damage in the February 27, 2010, earthquake. The earth render was applied by hand directly to the straw bales in two coats. The few cracks in the render were repaired prior to the application of the whitewash.

3.1.4 Measurements

Using Logtag HAXO-8 Temperature and Humidity Recorder (maximum temperature 85°C), measurements of dry bulb air temperature (°C) and relative humidity (%) began in May 2010. The Logtag recorders were suspended centrally in each test chamber 1.7m above finished floor level and were programmed to record readings at hourly intervals.

Measurements of external dry bulb air temperature (°C) and relative humidity (%) were recorded by the La Crosse Technology 2317 weather station of the Laboratory of Energy and Lighting. Results of these measurements are presented in section 4.1.1 as psychometric charts according to Givoni (Figs. 6–9) [27].

3.1.5 Calculation of Heating and Cooling Demand

Based on the recorded dry bulb temperatures, the heating and cooling demand in degree hours for the three physical test chambers was calculated using a comfort range as defined by Givoni 18°C–27°C [27]. Results of this calculation are shown as monthly figures in section 4.1.2 (Fig. 10).

3.1.6 Error analysis

- a. Only one set of test chambers was tested. Owing to the range of thermal properties presented in Table 1 this may lead to some concern. However, as previously mentioned, even according to the worst case scenario, the rendered straw bale walls would have a thermal conductivity of only a third of that of the test chamber that complies with Chilean Building Regulations.
- b. Owing to the varying wall thicknesses of the three construction types it was necessary to allow variation of external surface area and gross floor area in order to maintain an equal net floor area and internal volume. The external walls therefore receive varying quantities of solar radiation; however, the surface area of the roof which receives the majority of solar exposure remains constant in the three chambers.
- c. The three test chambers each have a north facing window, 1500mm wide by 1000mm high, orientated towards the sun. In accordance with typical rural constructions in the central valley of Chile these initially had no solar protection. It is known however that this is not good design practice and that the lack of solar protection in the summer months gives rise to overheating. As previously mentioned solar shading was installed in November 2011. The impact of this solar protection can be seen in the reduced cooling demand (Fig.10) for the second and third summers (November – March 2012 and 2013).
- d. The windows are fixed lights and no simulation of ventilation was included in the test. This lack of ventilation will result in higher indoor temperatures than those that would occur in a real situation where natural ventilation is provided by opening windows.
- e. During April, May and June 2012 two of the Logtag HAXO-8 Temperature and Humidity Recorders ceased to function. Measurements were resumed in July 2012.

3.2 In situ measurements: Case Study Casa Caleu

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

3.2.1 Description of Case Study (Fig. 5)

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 1,200m above sea level, the diurnal thermal oscillation is at the higher end of those experienced in the region.

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 in situ. 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.

Owing to the climatic conditions of the region, it was acknowledged that there was a 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. 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 small-holding 1km from the site. Exposed secondary timber beams are of recycled timber, a mixture

FIGURE 5. Case Study house Casa Caleu, Caleu, Metropolitan Region, Chile.



of “Roble” Chilean oak (*Nothofagus obliqua*), and “Coihue” Dombey’s Southern Beech (*Nothofagus dombeyi*), both sourced 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.

3.2.2 Measurements

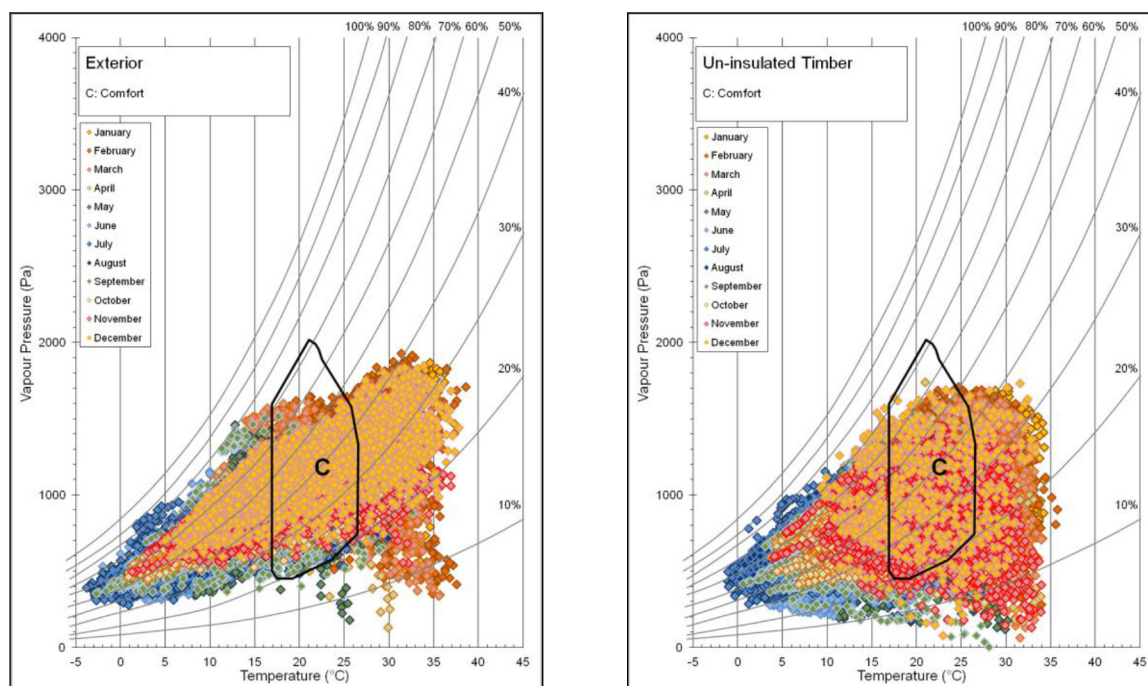
On Sunday the 27th of November 2011 the author visited the house with the students and the owners to take measurements of dry bulb temperature, relative humidity, and internal radiant surface temperatures. In addition to readings taken on the day, three LogTag HAXO-8 Multi Use Temperature/Humidity data 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 un-insulated timber cabin that predated the construction of the straw bale house. Data logger measurements were recorded from the 27th November 2011 until 17th December 2011 (early summer) and from 9th August 2012 until 9th September 2012 (late winter). The results of these measurements are presented below in section 4.2.

4. RESULTS

4.1 Physical Test Chambers May 2010 to December 2013

4.1.1 Dry bulb temperatures and relative humidity

FIGURES 6 & 7. Psychometric chart according to Givoni of external conditions and un-insulated timber test chamber. Temperature and relative humidity as measured May 2010–December 2013.



FIGURES 8 & 9. Psychometric chart according to Givoni of insulated timber test chamber and straw bale test chamber. Temperature and relative humidity as measured May 2010–December 2013.

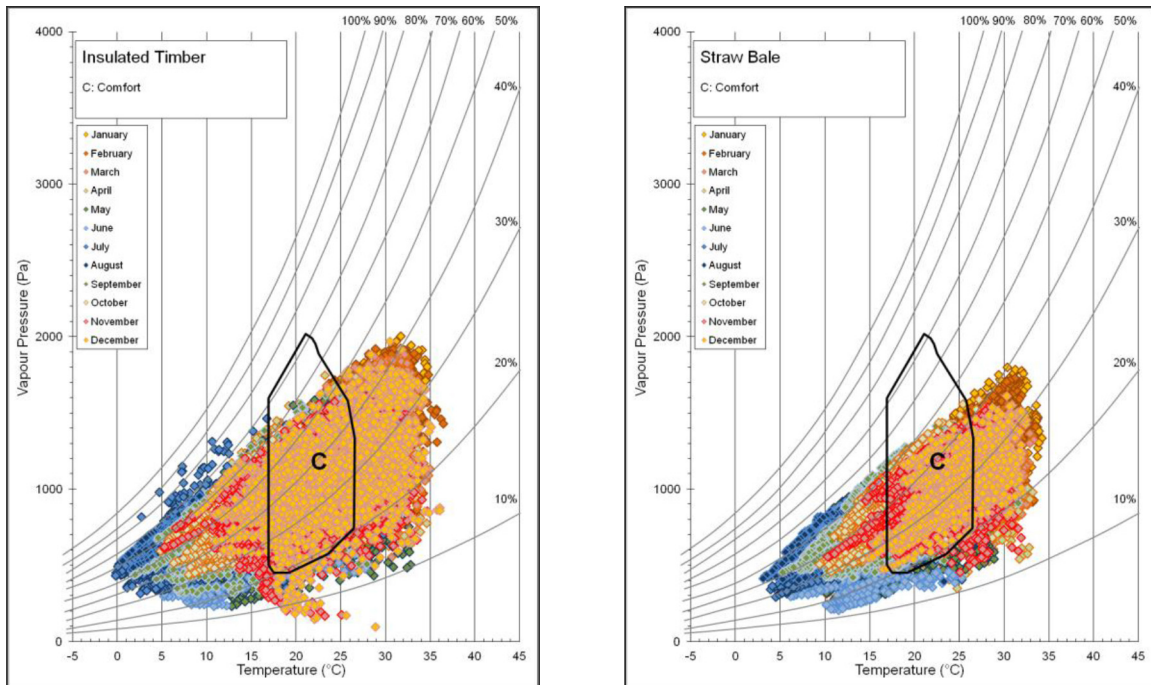


TABLE 5. Daily oscillation of dry bulb air temperature, measured May 2010–December 2013.

	Un-insulated Timber	Insulated Timber	Straw Bale	External
Min °C	2.2	2	1.2	2.5
Average °C	12.8	12.5	7.8	16.8
Maximum °C	21.7	21.0	16.3	27.1

4.1.2 Heating and cooling demand

Based on the recorded dry bulb temperatures, the heating and cooling demand in degree hours for the three physical test chambers was calculated using a comfort range as defined by Givoni 18°C–27°C [27]. Results of this calculation are shown as monthly figures in Figure 10. Heating hours are presented as positive and cooling as negative.

4.2 In Situ Measurements: Casa Caleu

The results of the LogTag HAXO-8 Multi Use Temperature/Humidity data loggers are presented in Figures 11–14 compared with a comfort range as defined by Givoni 18°C–27°C [27].

5. DISCUSSION

5.1 Results of Physical Test Chambers

The psychometric charts show that the temperatures and relative humidity in the straw bale test chamber are more stable and are grouped closer to the comfort range than those of the

FIGURE 10. Monthly heating (+) and cooling (-) demand in degree hours. Based on dry bulb temperatures as measured May 2010–December 2013.

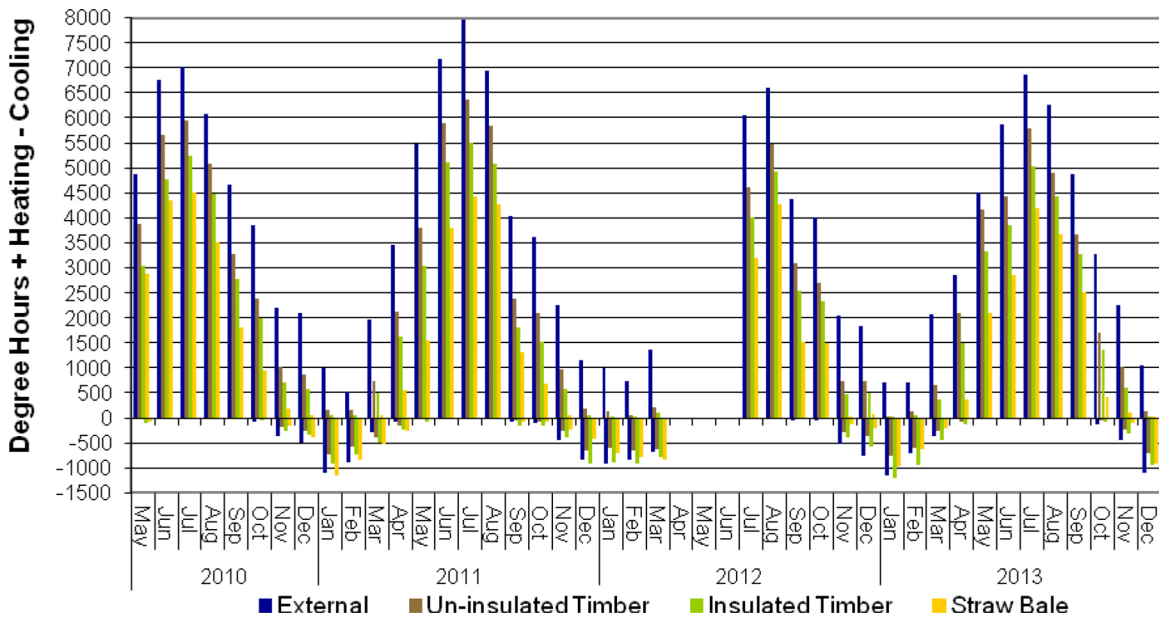


FIGURE 11. Dry bulb temperatures (°C) as measured in situ 27.11.11 – 17.12.11.

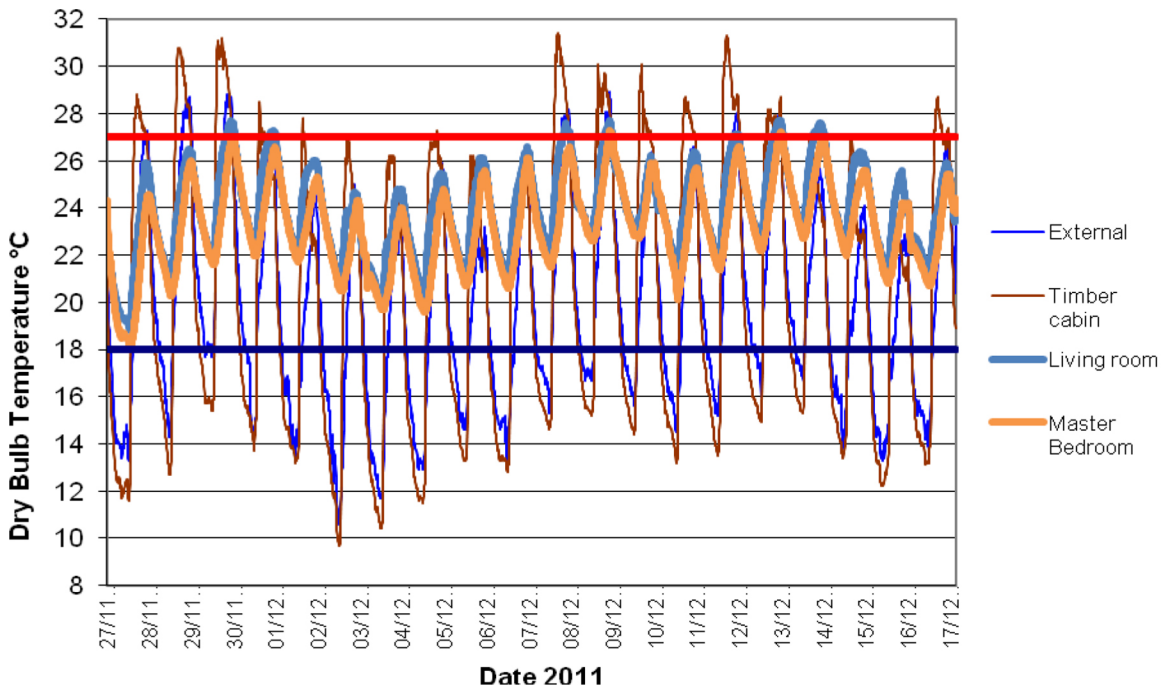


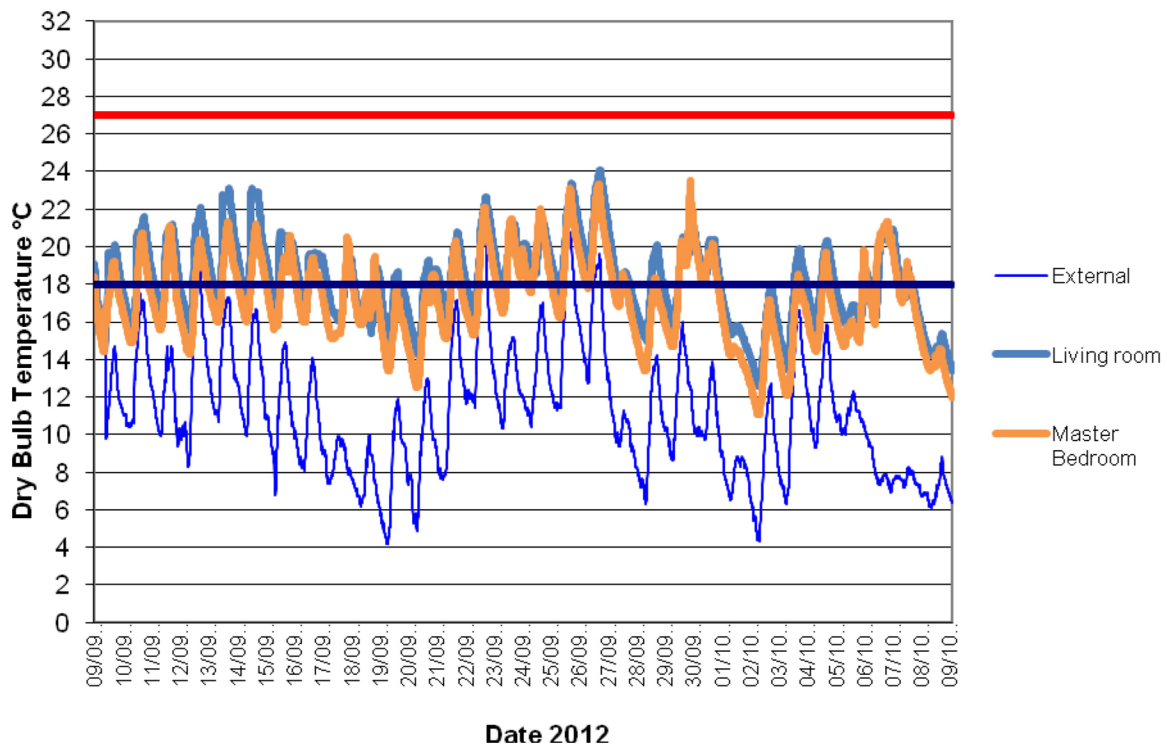
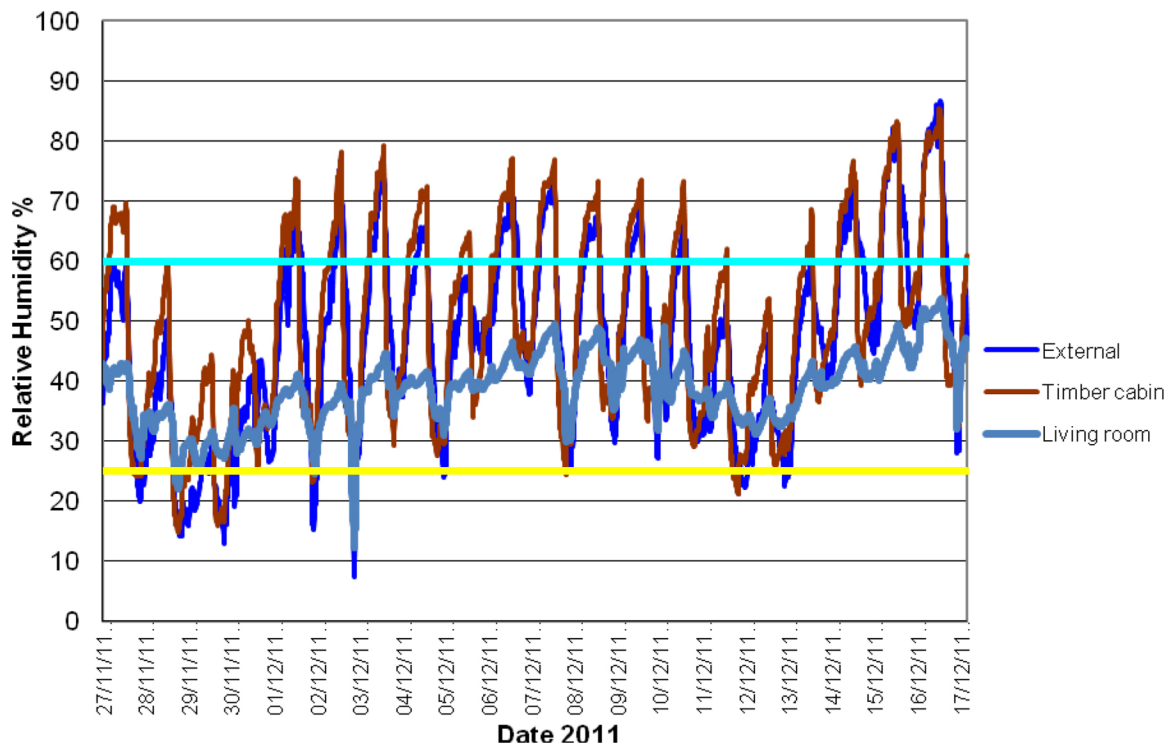
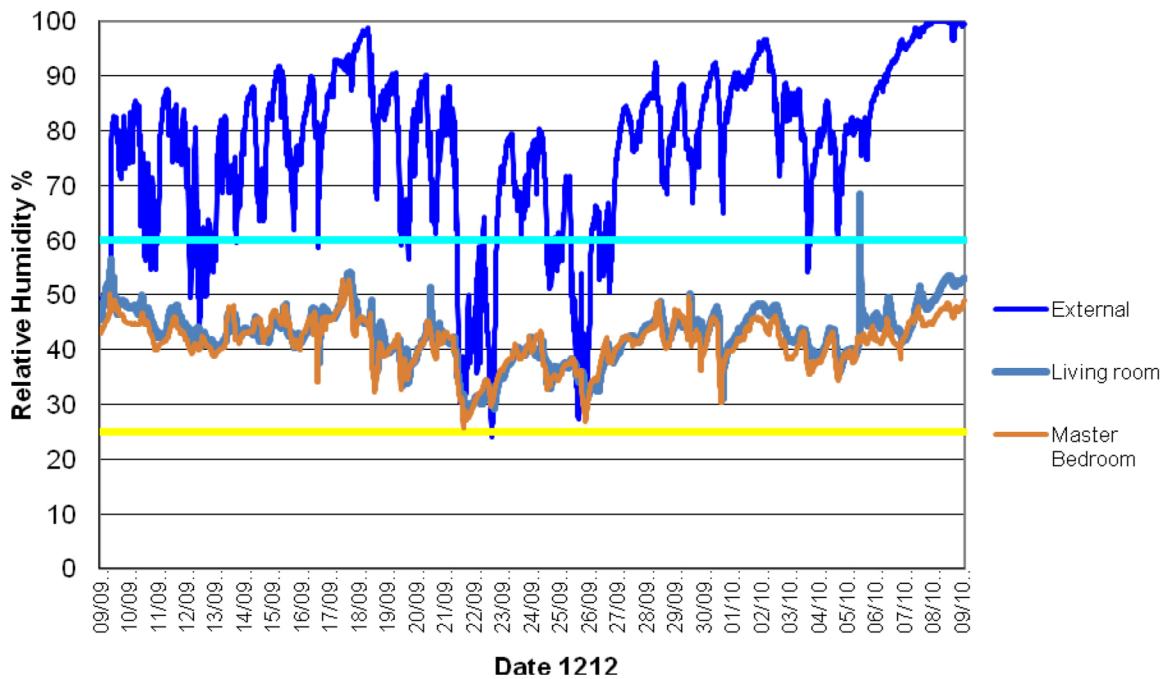
FIGURE 12. Dry bulb temperatures (°C) as measured in situ 09.09.12 – 09.10.12.**FIGURE 13.** Relative Humidity (%) as measured in situ 27.11.11 – 17.12.11.

FIGURE 14. Relative Humidity (%) as measured in situ 09.09.12 – 09.10.12.



other two test chambers. Temperatures never drop below 3.3°C whilst outdoor temperatures drop to minus -3.8°C . Periods of extreme heat and dryness are also avoided. The most notable difference in the charts is seen in the relative humidity which in the straw bale chamber never rises above 60% humidity. Whilst bearing in mind that the test chambers do not have any of the humidity creating activities encountered in real dwellings, this low humidity is an important factor considering that the 80% of Chilean dwellings suffer problems of condensation [11]. A direct comparison of the diurnal thermal oscillation shows that the insulation provided by the straw bales in conjunction with the thermal mass provided by the earth render produces temperatures much more stable than those of the other test chambers (Table 5) with an average daily temperature oscillation of only 7.8°C in comparison to that of the average diurnal external temperature oscillation of 16.8°C .

The calculation of heating and cooling demand shows that the heating demand of the straw bale chamber is significantly reduced as shown in Figure 10. On average during the year the heating demand is 29% less than that required by the test chamber insulated to comply with the Chilean thermal building regulations. The average cooling demand is 32% less. During the first summer due to the lack of solar protection the cooling demand of the straw bale test chamber was 9% more than that of the insulated timber chamber; however, following the introduction of solar protection to all three test chambers, and additional internal render to the straw bale chamber, the cooling demand for the straw bale chamber in comparison to that of its insulated timber counterpart was 26% less during the second summer and 43% less during the third summer. The cooling demand of all the test chambers could be further reduced with the introduction of a ceiling with ventilated roof void and the use of free cooling through nocturnal ventilation [27]. In reality few rural Chilean dwellings have air conditioning and so this cooling demand represents the hours of discomfort from overheating

as opposed to a real energy cost. The trend of the graph in Figure 10 shows that although Santiago de Chile has a Mediterranean climate it still has a largely heating based demand curve. It should however be considered that during the months November to May this demand is almost 100% during the middle of the night and heating is rarely used during these months.

5.2 Results of In Situ Measurements

The summer internal dry bulb air temperatures of the case study house (Fig.11) remain almost constantly within the thermal comfort zone as defined by Givoni [28] with only a few hours passing beyond the higher limit of 27°C. In winter the temperatures group around the lower end of the comfort range with night time temperatures falling below 18°C (Fig.12). No heating was used during the measurement period as the house was unoccupied. In general the house shows good insulation, in the worst cases maintaining 20.5°C in summer and 12°C in winter whilst external temperatures dropped to 10.5°C and 4°C respectively. The amplitude of the thermal oscillation is reduced from an average external oscillation of 12°C to an internal oscillation of 5°C. In comparison the un-insulated timber cabin amplifies the oscillation to an average 15°C.

Summer internal relative humidity measurements (Fig.13) 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%, readings 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. In the winter the internal relative humidity measurements stay constantly within the 25–60% range whilst the external conditions reach up to 100% relative humidity.

6. THE CHALLENGE OF IMPLEMENTING STRAW BALE CONSTRUCTION IN CENTRAL CHILE

In order understand the challenges that straw bale construction faces in Chile, three Chilean architects with varying degrees of experience of straw bale construction were interviewed.

6.1 Interviews with Chilean Architects with experience of Straw Bale Construction

6.1.1 Jorge Broughton: www.arquitecturaenfardos.cl

The Chilean architect and building contractor Jorge Broughton has more than 20 straw bale design-and-build projects completed in the last 12 years and is a regular organiser of straw bale building workshops in Santiago and the Metropolitan area. Previous to 2008 all Broughton's projects had been private single family dwellings. In that year Broughton began working on the proposals for a social housing project in Lampa, Chile. At this point Broughton came into contact with the Technical Department (DITEC) of the Ministry of Housing and Urbanism. All projects receiving Chilean government subsidies must be constructed with materials certified by DITEC. Certification requires national test certificates of fire, acoustic and thermal performance from national laboratories certified by DITEC, international test results are not accepted. Due to the lack of these test certificates Broughton was unable to proceed with the use of straw bale in this project.

Following the 27th February 2010 earthquake there was a government call for prefabricated housing designs. Broughton designed a 60m² straw bale house in the hope that, owing to the urgency to provide comfortable shelter following the earthquake, the need for certification

might be relaxed. The design envisaged the recycling of the timber from the emergency temporary *mediagua* dwellings as internal partitions. The straw bales were to be rendered with a primary coat of earth render to be made from recycling adobes from collapsed houses, finished with a cement and earth top coat. Unfortunately, despite the fact that Broughton had commissioned and received test certificates for the straw bales in 2009, the design was not accepted for consideration by the Ministry of Housing and Urbanism.

Broughton is currently working as part of the technical committee of the Chilean branch of the “*Red de construcción en fardos de paja*” Straw Bale construction Network. The committee hope to enter into talks with the Ministry of Housing and Urbanism to pave the way for a Straw Bale code and certification of the construction technique.

6.1.2 OWAR Arquitectos: www.owar.cl

Between 2008 and 2010 OWAR Arquitectos worked in conjunction with the North American architect Evan Sellmyer Pruitt on the design and construction of a large single-family house “Casa Coya” in Machalí, VI Region, Chile. The house has a timber frame in-filled with straw bales and is finished with an earth render. Except for minor cracking around a few window openings in the then recently completed earth render, the house withstood the 27th February 2010 earthquake undamaged. Based on this experience OWAR Arquitectos believed that straw bale could offer a solution to the reconstruction in rural Chile. In particular they were drawn to the similarity in the spatial qualities of straw bale constructions and traditional Chilean adobe architecture, qualities that they identified as important in the cultural identity of many of the affected communities. With this in mind they developed the designs for a wall prototype that could be reconstructed in place of collapsed adobe walls, with a 500mm concrete block plinth to protect the bales from ground water and large overhanging eaves or external passageways also a typical feature in traditional Chilean rural architecture.

Armed with this design and the idea of building a number of prototypes that locals could copy, Owar Arquitectos approached the local councils of Lolol in the VI Region and Molina, further south in the VII Region. Due to concerns over the “un-traditional” nature of straw bale construction and inflated construction budgets from local contractors Lolol declined to pursue the project.

In a parallel project for a private country estate in Almahue, San Vicente de Tagua Tagua, Owar proposed the rebuilding of the estate boundary walls in straw bales on concrete block foundations, bound by nylon ties and topped with a clay tile coping. The client was enthusiastic and initial material costs came in below budget. However on the receipt of tender returns from local builders it became clear that large additional costs were being added due to the “unknown” nature of the construction technique. Faced with a much lower tender return for a “traditional” fired brick option the client abandoned the straw bales. A related project on the same estate, to rebuild an historic adobe barn with straw bales, fell through when it was discovered that the client’s insurance company did not insure the existing adobe constructions and refused to pay out.

6.1.3 Patricio Larraín and Eduardo Rodway

Working within the framework of the Chilean Ministry of Housing’s Programme for the Reconstruction of Historical Buildings (Programa de Reconstrucción Patrimonial) following the 27th February 2010 earthquake, the two young Chilean architects, Patricio Larraín and Eduardo Rodway identified straw bales as a possible solution to rebuilding historic adobe dwellings in the centre of the rural villages of Chépica and Lolol in the 6th Region of Chile. As

with Owar Arquitectos, Larraín and Rodway were drawn to similarity in the spatial qualities of straw bale constructions and traditional Chilean adobe architecture. They also speculated that local residents, opposed to rebuilding in adobe due to a fear of repetition of structural failure in future earthquake, might accept a constructive system with a primary timber structure. Based on this assumption the two developed an adaptable timber frame system with straw bale infill which reused existing building features such as doors, windows, roof tiles when salvageable from the damaged dwellings. Whilst Larraín and Rodway were correct in their assumption that the residents would be willing to experiment with straw bale construction, their proposals met with the same initial resistance from the local authorities and the Ministry of Housing as faced by Broughton. However, since the dwellings in question were located within areas designated by the Ministry of Housing as conservation areas (Polígonos Patrimoniales), areas where building regulations were to be relaxed in favour of conservation of historical features, there existed a loophole in the requirement for the use of materials certified by registered Chilean laboratories. Using the international research results compiled by the author and the results of the physical test chambers then available, Larraín and Rodway were able to convince the authorities to allow them to build with straw bales. Currently nine dwellings have been completed in the village of Chépica, with a further eight in the village of Lolol.

The interviews with local architects with experience of straw bale construction show that there exists interest in building with straw bales. The barriers that exist to the implementation of this construction technique are primarily a lack of knowledge both within the housing ministry and with local house builders. Although there now exist national test certificates for fire resistance and thermal and acoustic performance, it is still difficult to apply the construction technique to housing built with government funds, as straw bales are not included in the Ministry of Housing's list of certified materials. Hopefully the work of the Chilean Straw Bale Construction Network will help pave the way for its inclusion. The relaxation of Building Regulation requirements in the rebuilding of conservation areas does, however, provide the possibility for the use of straw bales. Education and certification appear to be the two most critical requirements needed in tackling the barriers that prevent the application of straw bale construction in rural social housing.

7. CONCLUSION

Based on the results from the physical test chambers it would appear that straw bales could provide an affordable method for building rural dwellings with material costs for wall construction approximately 13% less than those for the typical insulated timber construction [Table 4]. In addition, straw bale construction would provide internal temperatures more stable than those currently provided (Table 5, Fig. 9, 11 and 13); with lower internal relative humidity (Fig. 9, 12 and 14) and a reduced heating demand (Fig. 10); with an average annual heating demand saving of 29% when compared to a construction compliant with the Chilean building regulations. Straw bale construction benefits from an affinity to the traditional adobe architecture of Chile's Central Valley, while at the same time finding a constructive use for an agricultural waste product.

The interviews with Chilean architects with experience of working with straw bale construction highlight that the largest barrier to the implementation of straw bale construction in rural central Chile is the inexperience and a lack of knowledge of this construction technique. The work of "*Red de Construcción en Fardos de Paja*" Chilean Straw Bale Construction

Network www.construccionconfardosdepaja.cl will hopefully allow in the future the building of hygro-thermally comfortable, energy efficient rural dwellings built with government funding. Turning agricultural waste into homes, straw may once again become an important protagonist in rural Chilean architecture.

ACKNOWLEDGMENTS

This research has been made possible by the internal research fund Jorge Millas, of the Dirección de Investigación y Doctorado, of the Universidad Andres Bello. The author wishes to thank Daniela Fernández Holloway for her support and help with the early stages of the research project and the following students of the course “Práctica de Laboratorio” of the Laboratorio de Energía e Iluminación for their help in the design, construction and maintenance of the test chambers 2009- Andrea Guerra & Carla Veloso; 2010 Francisca Bermedo, Carolina Bravo, Eduardo Garcés, & Paula Guerra; 2011 Sofia Alvarez, Samuel Bravo, Andrés Delano, Jorge Diaz, José Durán, Natalia González, Fernanda Henriquez, Pía Larraguibel, Teresa Monreal, Francisca Olivares, Javiera Olivares, Matias Oyarzun & Natalia Vicencio. The authors also wish to thank the architects and builders of the case study house Max Ovalle, Pedro Anguita, David Aceituno, Juanpablo Mhor, Francisca Infante and Francisco Ilabaca, in addition to the owners of the house *Casa Caleu* for allowing the measurement of their second home.

REFERENCES

1. Instituto Nacional de Estadística de Chile. Censo Nacional 2002, Síntesis de Resultados. [Internet] Santiago de Chile: INE; 2003 Mar. [Cited 2012 Dec 4]; Spanish. Available from: http://www.ine.cl/Publicado/Publicacion/2010/12/20121203013749_sintesisencensal-censo2002.pdf
2. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World Map of the Köppen-Geiger climate classification updated. Meteorologische Zeitschrift [Internet]; 2006 [cited 2012 Mar 20]; 15(3): 259-263. Available from: <http://koeppen-geiger.vu-wien.ac.at/present.htm>
3. Ministerio de Obras Públicas (MOP). Guía de Diseño Arquitectónico Mapuche para edificios y espacios públicos [Internet]. Santiago de Chile: MOP; 2003 Dec. [cited 2012 Dec 4] Spanish. Available from: <http://www.arquitecturamop.cl/Patrimonio/Paginas/default.aspx>
4. Ministerio de Vivienda y Urbanismo (MINVU). Manual de aplicación: reglamentación térmica: Ordenanza General de Urbanismo y Construcciones artículo 4.1.10. Santiago de Chile: MOP 2006. Spanish
5. Bustamante W, Cepeda R, Martínez P and Santa María H. Eficiencia energética en vivienda social: un desafío posible. In Propuestas para Chile: Concurso Políticas Públicas 2009. Santiago de Chile: Pontificia Universidad Católica de Chile 2009: 253-282 Spanish
6. Caldera Sánchez A. Building Blocks for a Better Functioning Housing Market in Chile, OECD Economics Department Working Papers [Internet] OECD Publishing 2012 [Cited 2012 Mar 22]; 943. Available from: <http://www.oecd-ilibrary.org/>
7. Ministerio de Vivienda y Urbanismo (MINVU), Comisión de Estudios Habitacionales y Urbanos (CEHU). Déficit Urbano-Habitacional: una mirada integral a la calidad de vida y el hábitat residencial en Chile. Santiago de Chile: MINVU 2009. Spanish
8. MINVU. División Técnica (DITEC) Atlas de la evolución del déficit habitacional en Chile 1992-2002. Santiago de Chile: MINVU 2006. Spanish
9. Un Techo para Chile, Centro de Investigación Social (CIS). Catastro Nacional de Campamentos 2007 [Internet] Santiago de Chile: Un Techo para Chile 2007 [Cited 2010 Oct 28] Spanish. Available from: http://www.untechoparachile.cl/cis/images/stories/Publicaciones/Catastro_2007.pdf
10. MINVU. Avance en la entrega de soluciones habitacionales. Programa de Reconstrucción en Vivienda. Informe 31 octubre 2012 [Internet] Santiago de Chile: MINVU 2012 [Cited 2012 Nov 20] Spanish. Available at: http://www.minvu.cl/opensite_20111122104351.aspx

11. Proyecto Fomento de la Eficiencia Energética (CNE/GTZ). Determinación de línea base “anual” para la evaluación de la inversión en eficiencia energética en el sector residencial invierno 2007 – verano 2008. Santiago de Chile: Comisión Nacional de Energía 2008. Spanish
12. Sistema Nacional de Información Ambiental SINIA. Cobertura zonas declaradas saturadas y latentes. [Internet] Santiago de Chile: Ministerio del Medioambiente 2011 [cited 2011 Aug 29] Spanish Available from: <http://www.sinia.cl/1292/w3-propertyvalue-15480.html>
13. Oficina de Estudios y Políticas Agrarias. Estadísticas de superficie sembrada de cultivos anuales 2010-2011. [Internet] Santiago de Chile: Servicio Agrícola y Ganadero 2011 [Cited 2011 Aug 29] Spanish Available from: <http://www.odepa.gob.cl>
14. Lee C, Grove J. Straw Yields from Six Small Grain Varieties 2003-4 and 2004-5 growing seasons. [Internet]- Lexington USA: University of Kentucky 2005. [Cited 2010 Nov 8] Available from: http://www.uky.edu/Ag/GrainCrops/Research/Research_pdf/SmallGrains_StrawYields2005.pdf
15. Stone N. Thermal Performance of Straw Bale Wall System. [Internet] Ecological Building Network 2003 [Cited 2012 Dec 4] Available from: http://www.ecobuildnetwork.org/images/stories/ebnet_pdfs/Thermal_properties.pdf
16. Commins, Stone. Tested R-value for Straw Bale Walls and Performance Modeling for Straw Bale Homes. [Internet] ACEEE 1998 [Cited 2012 Dec 4] Available from: <http://eec.ucdavis.edu/ACEEE/1998/pdffiles/papers/0104.pdf>
17. Wimmer R, Hohensinner H, Janisch L, Drack M. Heat Insulation Performance of Straw Bales and Straw Bale Walls. [Internet] GrAT – Vienna: Center for Appropriate Technology Vienna University of Technology 2001 [Cited 2012 Dec 4] Available from: http://www.osbbc.ca/Resources/Documents/Technical/heat_insulation_performance_strawbales.pdf
18. Munch-Andersen J, Andersen B M. Straw Bale Houses design and material properties, Danish Building and Urban Re-search. Denmark: Statens Byggeforskningsinstitut 2004.
19. Goodhew S, Griffiths R. Sustainable earth walls to meet the building regulations. Energy and Buildings 2006;37(5):451-459.
20. Deutsches Institut für Bautechnik. Wärmedämmstoff aus Strohballen “Baustrohballen”. [Internet] Bandau, Germany: Deutsches Institut für Bautechnik 2009 [Cited 2012 Dec 4] German. Available from: <http://www.baubiologie.cz/slama/AbZ-Nr.-Z-23.11-1595.pdf>
21. Rodríguez Vivanco CS. Construcción con Fardos: una alternativa para la Región de la Araucanía, Thesis (Title of construction Engineer) Temuco, Chile: Universidad de la Frontera, Facultad de Ingeniería, Ciencias y Administración, Departamento de Ingeniería de obras civiles, 2007. Spanish
22. Bustamante M. Letter to Jorge Broughton 25th August 2009 confirming test results, IDIEM- Universidad de Chile. Unpublished
23. Intertek Testing Services NA, Inc. 1-Hour Fire Testing of a Non-Loadbearing Strawbale Wall, according to ASTM 119-05a. [Internet] Texas, USA: Intertek Testing Services NA 2006. [Cited 2012 Dec 5] Available from: http://www.ecobuildnetwork.org/images/stories/ebnet_pdfs/Non-Bearing_Clay_Wall.pdf
24. Theis B. Straw Bale fire Safety, A review of testing and experience to date. California, USA: Ecological Building Network (EBNet) 2003
25. Mas CJ, Carr Everbach E. Acoustical Characterization of Straw Bales as Structural Elements, Journal of Acoustical Society of America [Internet] 1995. 98(5); 2879-2879 [Cited 2012 Dec 5] Available from: http://asadl.org/jasa/resource/1/jasman/v98/i5/p2879_s2
26. IDIEM. Informe N° 578.663 Índices de Reducción Acustica, Universidad de Chile. Santiago de Chile: IDIEM 2009. Spanish
27. Bustamante W, Rozas Y, Cepeda R, Encinas F and Martínez P. Guía de diseño para la eficiencia energética en la vivienda social, Santiago de Chile: Pontificia Universidad Católica de Chile 2009; 65 Spanish
28. Givoni B. Climate Considerations in Building and Urban Design. New York: Van Nostrand Reinhold 1998