Heritage earth construction and hygrothermal comfort: The challenge of rebuilding in Central Chile

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Keywords: Adobe, earth construction, straw bale, hygrothermal comfort, heritage buildings.

Abstract. According to the latest official census of 2002, earth construction represented 5.5% of the Chilean building stock. These buildings of traditional construction techniques of unfired earth and straw blocks (adobe), rammed earth (tapial) or wattle and daub (quincha) form a large proportion of Chile's National Monuments and heritage buildings. In addition to their heritage value, these buildings with their high thermal mass, respond well to the climate conditions of both the altiplano of northern Chile and the Central Valley, zones with high diurnal temperature oscillations, with typical daily temperature differences of up to 20ºC. However, following the 2005 earthquake in Tarapacá, northern Chile and that of the 27th February 2010 in Central Chile, a serious rethink has been required as to the retention and restoration of adobe buildings. Public opinion has labelled earth construction as unsafe and most reconstruction to date has taken place with prefabricated timber solutions which lack the necessary thermal mass to respond well to the climatic conditions. At the same time research into the structural integrity, seismic resistance, maintenance and the living conditions provided by earth construction has been undertaken. In this wider context this paper presents the compilation of international and Chilean research into the hygrothermal properties of adobe construction, in addition to the authors insitu measurements of the temperature and relative humidity in two surviving adobe dwellings in the earthquake hit village of Chépica located in Chile´s Central valley. These measurements are compared with those of a dwelling rebuilt with straw bales and earth render in the same location. Based on this information the paper studies the challenge of rebuilding and restoring heritage buildings whilst providing occupants with the necessary levels of environmental comfort.

KEYWORDS: Adobe, earth construction, straw bale, hygrothermal comfort, heritage buildings.

Introduction

History of Earth Building in Chile. Since pre-Columbian times earth construction has played an important role in the vernacular architecture of Northern and Central Chile. The ruins of the town of Tulor Aldea located near San Pedro de Atacama in the North of Chile date from 400BC and show signs of continual habitation until 300AD. The town consists of 26 circular structures constructed using a technique of earth mixed with water and modelled insitu [1] similar to British cob construction. Other examples of pre-Columbian earth construction in Chile include *Quincha* a type of wattle and daub with a timber structure supporting a cane membrane to which an earth-gypsum render is applied; and *Tapial* rammed earth.

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 fibres are added. In Chile the most commonly used natural fibre 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

1200mm 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 [2] and forms a large proportion of Chile's National Monuments and heritage buildings especially in the Central Valley and the altiplano of the north.

Earthquakes and Regulations. The earthquake of the 1st December 1928 with a seismic movement of 8.3 [3] destroyed much of the city of Talca in central Chile, a city previously predominantly of adobe construction. This lead directly to the drafting of the first Chilean Building Regulations the "*Ordenanza General de Urbanismo y construcciones*," which classifies adobe as a "Class F" material, limiting the maximum height of unrestrained walls to 3.5m [4]. Following the earthquake that struck Tarapacá in Northern Chile on the 13th June 2005 registering a seismic moment of 7.9 [3], a national committee "*el Comité "Adobe*"" was formed to review the safety of building with earth construction. Consisting of representatives from the Ministry of Housing, the national professional association of architects *El Colegio de Arquitectos*, the national construction institute *El Instituto de la Construcción* and various universities, the committee concluded that under no circumstance should buildings be built or rebuilt using load bearing earth construction and that earth construction should only be used when forming a non load bearing infill within a structure that can be shown to comply with the Chilean standard for the seismic design of buildings NCh 433 Of.96 [5]. The final report also recommended the creation of financial support for research into earth construction. The prohibition of load-bearing adobe was included in the building regulations but the financial support did not materialize.

The latest earthquake, that of the 27th February 2010 which struck central Chile with a seismic moment of 8.8 [3] has once again raised doubts as to the suitability of adobe construction in a seismic region. 62% of the dwellings destroyed were of earth construction, as were 30% of those suffering major or minor damage [6]. Whilst advocates of earth construction have highlighted that poor maintenance and subsequent self built extensions and structural changes were the cause of much of the damage and destruction, the mass media and public opinion has labelled adobe as a high risk building material, the use of which should be prohibited [7].

Climatic Conditions in Central Chile. Chile's Central Valley, bordered by the coastal range to the west and The Andes to the east, runs directly north-south between the latitudes of 32.8º south and 37.2º south. The climate is classified according to the classification of Wladimir Köppen as Csb, a warm temperate climate with warm dry summers [8] often referred to as Mediterranean due to the presence of this climate in that region. Average daily maximum temperatures in the summer reach 30°C with an average winter minimum of 4°C [9]. Diurnal temperature oscillations average 18°C in summer and 11°C in winter [10]. In order to respond to these temperatures and oscillations, dwellings in this climate must provide sufficient exposed thermal mass in addition to external insulation.

Hygrothermal Properties of Adobe Construction

Adobe is made up from natural materials, earth and straw. Given that these can vary depending on local soil conditions and that their proportions in the mix are not standardized, it can be difficult to state a fixed coefficient of thermal conductivity for adobe. However studies show that there exists a strong correlation between the thermal conductivity of earth construction as a function of its density (fig.1).

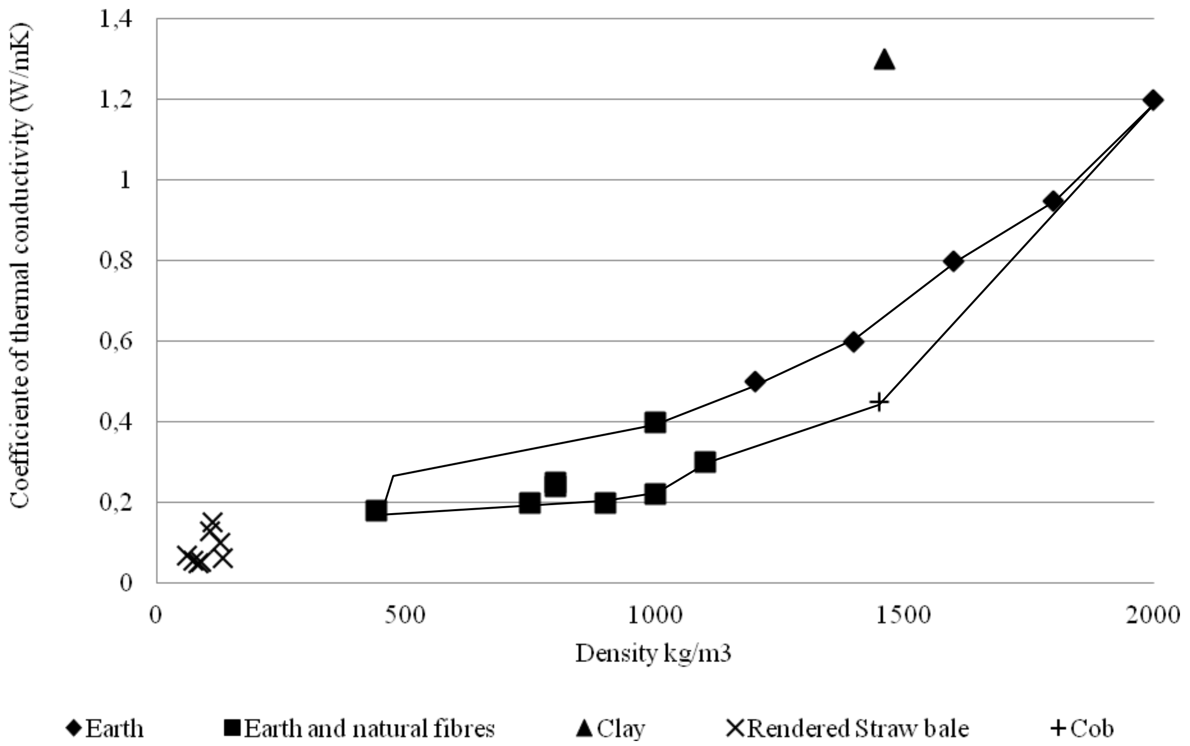

Figure 1: Correlation between density and thermal conductivity [11, 12 & 13].

Laboratory tests conducted according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 90-75) methodology for the measurement of stead state U-Values have shown an adobe wall of 10" (254mm) finished externally with a ¾" (19mm) earth render and internally with ½" (12.7mm) wet plaster finish can achieve a u-value of 1.493W/m^{2}K, whilst a 14" (355.6mm) adobe wall achieved a u-value of 1.073W/m^{2}K. [14] Measurements using a guarded hot plate conducted according to the Chilean standard NCh850 of83 show a steady state U-value of 1.163W/m^{2}K for a 300mm thick adobe wall [15]. Adobe has a volumetric heat capacity of between 1.153J/m^{3}K and 1.285J/m^{3}K [12]. Given this high thermal mass some argue that steady state U-values do not fully represent the thermal conductance of adobe and earth construction. Measurements of effective U-values have shown that a 10" (254mm) adobe wall can vary between 1,329W/m^{2}K and 0,284W/m^{2}K depending on orientation [14]. The high thermal mass has the advantage of equalizing and offsetting thermal oscillations. Studies by the New Mexico Energy Institute showed in preliminary measurements that the internal surface temperature of an adobe wall of ≤300mm tends towards the daily average external dry bulb temperature. In comparison, the internal surface temperature of walls ≥300mm tends toward the seasonal average external dry bulb temperature [14].

The hygroscopic properties of adobe help minimise condensation problems within the dwelling when internal finishes are vapour permeable [11].

Hygrothermal Performance of Adobe Construction in Central Chile. The thermal mass of adobe is well suited to mitigate the summer diurnal thermal oscillations of up to 20°C and high temperatures of over 30°C especially when used in conjunction with shaded external spaces common in the colonial architecture of Central Chile. The same cannot be said for typical modern rural construction in Central Chile which lacks both the thermal mass and the external shaded spaces. A study conducted in 2009 of the typical rural village of Rungue found that only 7% of the buildings were of adobe, these being concentrated in the historic core of the village. Of the remaining buildings 67% were of platform framed timber construction [13]. Similarly, of the 748 certified designs from which those claiming reconstruction subsidiaries can choose, 80% are of either platform framed or balloon framed construction [16]. These lightweight construction techniques lack thermal mass and so suffer from overheating in the summer months.

In 1985 a project to improve the hygrothermal conditions of timber emergency housing or *mediaguas,* built in Central Chile following the 1985 earthquake, measured dry bulb temperatures before and after modifications. These modifications consisted of a 39mm earth and straw render, applied externally to a wire mesh itself the by-product of beer bottle cap production. In addition a ceiling of timber boards was installed with a small amount of earth and straw applied to its upper side. These modifications aimed to introduce thermal mass, increase air-tightness and provide a ventilated roof space. The project's measurements showed that with these modifications it was possible to reduce the amplitude of the thermal oscillation by a total of 9°C, with 6°C lower at the peak and 3°C higher at the trough, and with an retardation of 2 hours (figs 2&3) [17].

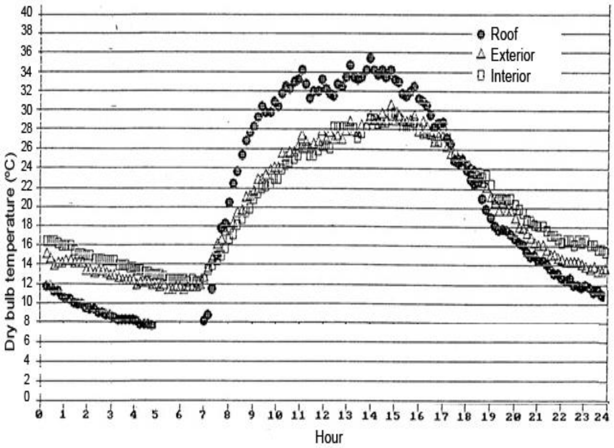

Figure 2: Dry bulb temperatures of emergency timber timber dwelling,Los Cerrillos, Santiago de Chile. As measured. 23rd January 1988

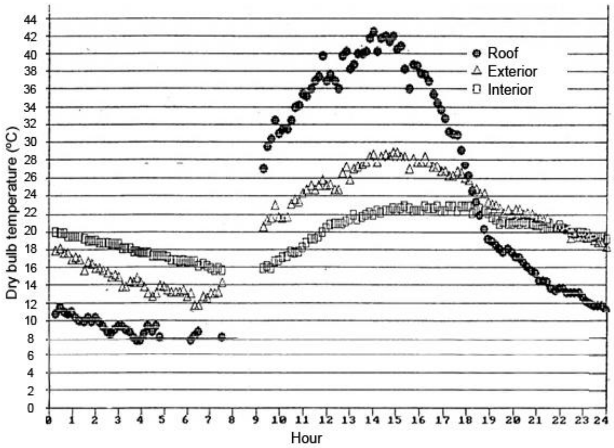

Figure 3: Dry bulb temperatures of emergency dwelling with addition of 39mm earth render, Los Cerrillos, Santiago de Chile. As measured 25th March 1988.

Case Study Chépica

Founded in 1875, the rural town of Chépica is located in the VI Region of Chile, 130km south of the capital Santiago de Chile. Typical of many towns in Chile's Central Valley the historic core is arranged around the Plaza de Armas and retains many of the original adobe buildings. Many of these buildings were severely damaged in the earthquake of the 27th February 2010. Whilst some required immediate demolition others have been restored and yet others await restoration.

As part of the research project "*Restauración y reconstrucción de viviendas de adobe en el valle de Colchagua; Un desafío técnico y patrimonial*," dry bulb temperatures, relative humidity and internal radiant surface temperatures were measured on the 25th April 2012 in two surviving adobe dwellings, Casa Enrejada (fig. 4) and Casa Pampa de Lima (fig. 5). The results of these measurements are presented below.

Figure 4: Casa Enrejada, Chépica, VI Region Chile.

Figure 5: Casa pampa de Lima, Chépica, VI Region Chile

As part of the reconstruction work following the earthquake the architects Patricio Larraín and Eduardo Rodway have been working with state funds on the rebuilding of dwellings in Chépica and the neighbouring villages of Lolol and Auquinco. The designs by the architects use earth rendered straw bales in place of adobe to maintain the thick-walled architectural tradition. The straw bales are used as infill between a post and beam timber frame. The timber frame complies with the Chilean standard for the seismic design of buildings NCh 433 Of.96. The rear walls of the dwellings are of mineral wool insulted timber frame construction. Straw bale was not used for the rear walls due to pre-envisaged occupant extension of the properties following official hand-over. Although state funded projects normally demand the use of conventional or certified building materials, straw bale was in this case accepted due to special dispensations arising from the projects' locations within designated "heritage polygons". Dry bulb temperature, relative humidity and radiant temperature readings were recorded in one of these projects in the neighbouring village of Auquinco also on the 25th April 2012. The owners of this dwelling have extended the house using un-insulated reinforced concrete construction. When questioned as to their choice of building material they expressed the opinion that concrete was more "solid" than the straw bale construction and acknowledged that the thermal properties of the material had not been a consideration. The presence of the two construction techniques in the same dwelling provided the possibility of comparative measurements.

iButton dry bulb temperature and relative humidity data loggers were installed at a height of 1.7m above finished floor level in all three dwellings to record at half hourly intervals for five weeks between the 25th of April and the 6th of June 2012. These results are presented below.

Figure 6: Dwelling rebuilt with straw bales, Chépica, VI Region, Chile.

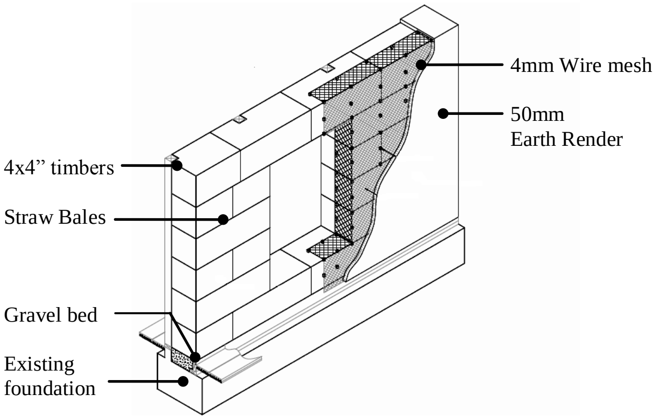

Figure 7: Axonometric of construction

Insitu Measurement Results

Dry Bulb Temperature (°C) and Relative humidity (%)

The diurnal temperature oscillations experienced during the 5 weeks of measurements are presented below (table 1). The largest diurnal external thermal oscillation recorded was 20.1°C whilst the same day the internal oscillation within the dining room of the Casa Enrejada was only 3.5°C due to the high thermal mass of the adobe walls.

Table 1. Diurnal Temperature Oscillations [°C] 25 April – 6 June 2012

	Exterior	Pampa de Lima Shop	Pampa de Lima Corridor	Enrejada Dining room	Enrejada Empty room	Straw Bale Living Room	Straw Bale Bedroom 1	Straw Bale Bedroom 2
Average	8,8	4,3	7,5	1,4	1,6	4,3	4,4	4,2
Max.	20,1	11,5	17,5	3,5	4,5	18,2	10,2	12,7
Min.	1,5	1,0	1,5	0,5	0,4	1,4	1,0	1,2

The dry bulb temperatures and relative humidity measured with the iButton data loggers are presented below (figs. 8-11) in the form of Pyscometric Charts (PC) with Givoni-Milne overlays. In the case of the living room of the Straw Bale house in Aunquinco, the measurements taken whilst the wood burning stove was lit are marked in red.

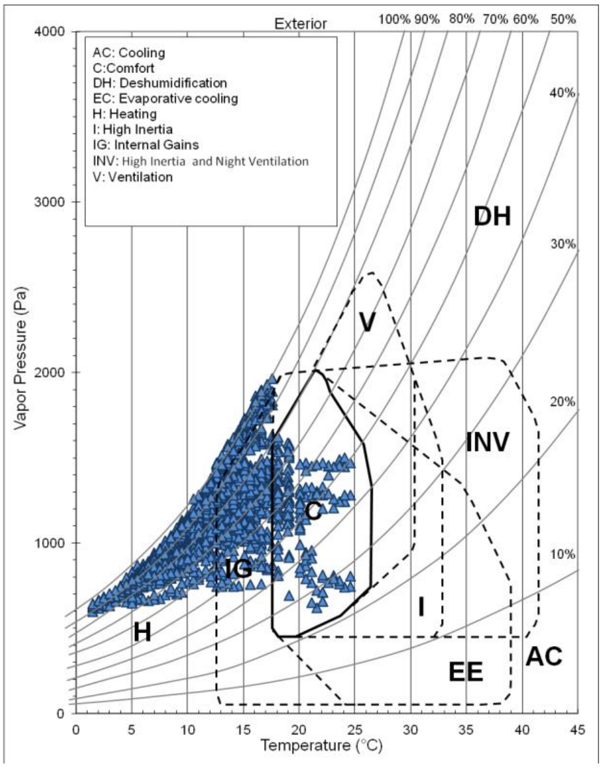

Figure 8. Exterior

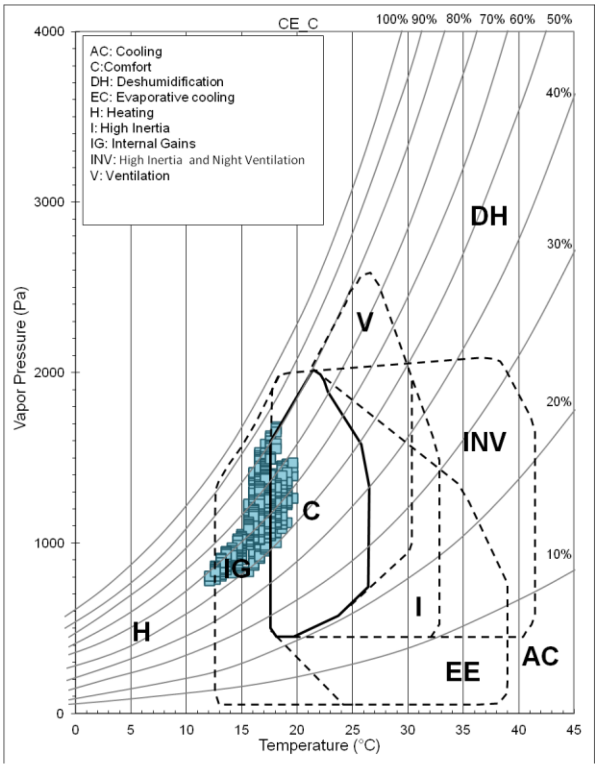

Figure 9. Casa Enrejada Dining Room

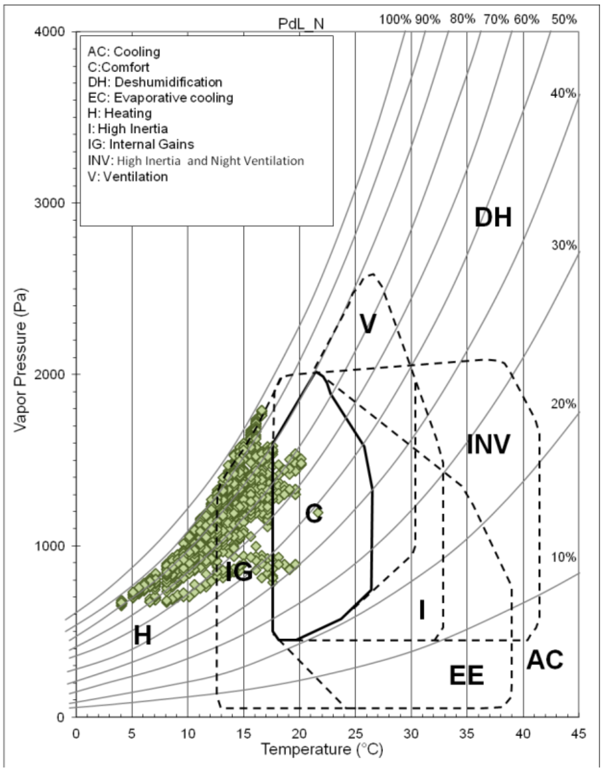

Figure 10. La Casa Pampa de Lima, shop

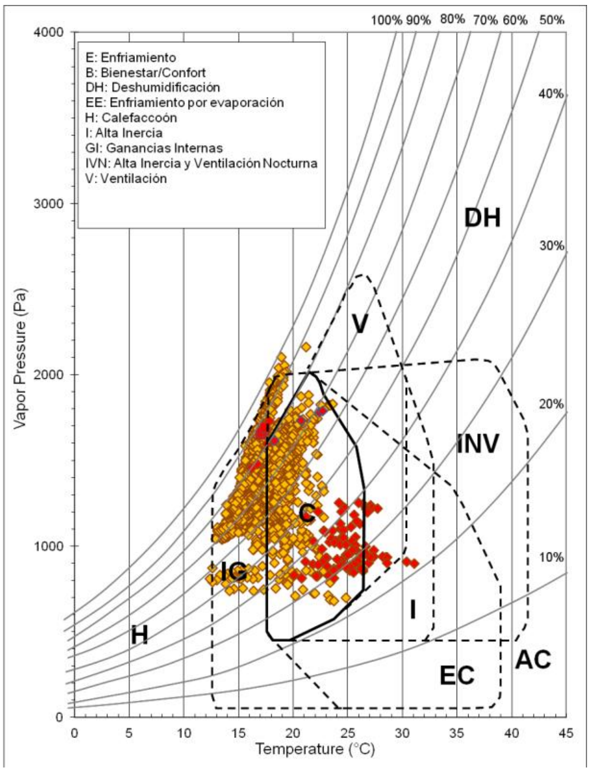

Fig.11 Auquinco, Straw Bale living Room (with stove in red)

Radiant Surface Temperatures. The dry bulb temperatures and relative humidity of the three dwellings measured on the 25th of April 2012 were all approximately equal to external conditions due to the presence of open doors and windows in all three cases. Temperatures were between 18-

20°C and relative humidity 35-52%. Despite similar dry bulb temperature readings, the thermal sensation of the two adobe dwellings was quite distinct from that of the straw bale and timber construction of the third. All four researchers present (2 staff and 2 students) noted that the adobe dwellings felt cooler than the straw bale construction. The radiant surface temperatures measured (fig. 11) uphold this subjective observation, with the adobe walls showing the adobe surface temperatures between 1°C and 4°C lower than the internal air temperature. The earth rendered straw bale walls show surface temperatures up to 1°C warmer or equal to that of the air.

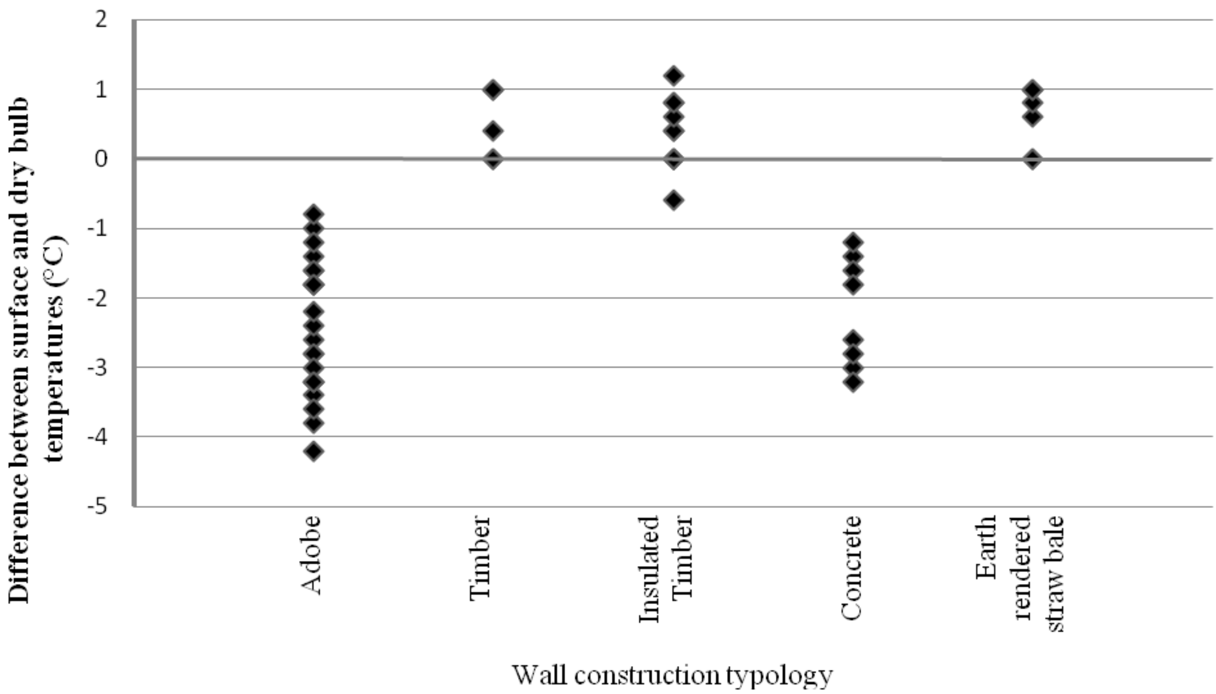

Figure 12: Difference between measured radiant surface temperatures and dry bulb temperatures (°C) as measured in 3 dwellings in Chépica,25th April 2012 .

Density of Adobe from Casa Pampa de Lima Chépica. Samples of adobe and earthen renders were taken from the Casa Pampa de Lima, one of the adobe dwellings. The samples were then cut into regular blocks, measured and weighed. With these measurements their density was calculated. (Table 2.)

Table 2: Density (D) Coefficients of thermal conductivity (λ) of adobe and earthen renders, Casa Pampa de Lima. Conductivity values are extrapolated from those presented in figure 1.

Element	D [kg/m^3]	λ [W/mK]
Adobe	1580	0.64-0.79
Internal Render	1315	0.40-0.58
External Render	1320	0.40-0.58

The walls of Casa Pampa de Lima are 700mm thick. Using the higher values for thermal conductivity, the wall consisting of 660mm of adobe with a 30mm external render and a 10mm internal render would have an approximate U-value of 0.920 W/m^{2}K. Assuming a coefficient of thermal conductivity (λ) of 0.15W/mK for straw bales [18] the walls of the dwelling in Auquinco would have a U-value of 0.334 W/m^{2}K. To comply with Chilean building regulations new dwellings in Chépica must have a U-value of no greater than 1.9 W/m^{2}K. Therefore, both the adobe dwellings and the straw bale construction provide greater thermal insulation than new-build dwellings.

Occupants' Opinions. The occupants of the three dwellings were asked for their opinions regarding the temperatures of their dwellings. A summary of their responses is presented below (table 3.) Those of the two adobe dwellings concurred that the rooms of adobe construction were pleasantly cool in summer but that they were difficult to heat in winter as a result of the adobe walls and the high ceilings. In the case if the Casa Enrejada daily life occurs in the lean-to corridor space which has a lower ceiling and an external wall of timber construction. The main adobe built dining room is used only for family occasions and entertaining guests. The other main adobe built rooms are unoccupied or used for storage due to concern over their structural integrity. The occupants are awaiting the release of government funds for the restoration of these spaces. In the case of the Casa Pampa de Lima daily life takes place in the concrete outbuildings surrounding the patio. Again the lean-to corridor space is used as a living room but in this case the doors to the patio are constantly left open to aid a quick escape, such is the fear that remains over two years since the earthquake. The main adobe built rooms are used for storage or lie abandoned. In comparison the occupant of the dwelling rebuilt with straw bale expressed her surprise at the warmth of her dwelling in the evenings. She did not report problems of overheating. As the house was completed in November she had as yet not spent a winter in her new home and therefore could not comment on winter temperatures, however during the second visit on the 8th of July 2012 she informed the author that she had installed a wood burning stove the previous week. The temperatures recorded whilst this stove was functioning are marked in red (fig.10) and show indoor temperatures reaching over 30°C.

Tabla 4. Respuestas de las entrevistas con las dueñas de casa viernes 8 junio 2012

	Thermal Sensation[1]		Clothing used[2]		Windows open[3]		Stale air		Draughts		Use of Heating
Winter [W] Summer[S] / Dwelling	W	S	W	S	W	S	W	S	W	S	
Casa Enrejada, Adobe	2	4	1,2	0,6	X	X	Yes	No	Yes	Yes	May-Aug. PM
Casa P. de Lima, Adobe	1	4	0,9	0,6	AM	AM	No	No	No	No	May-Sept. PM
Auquinco Straw Bale	4	4	1,0	0,6	N	N	No	No	No	No	Installed in June

1. Range: 1= cold; 4= comfortable; 7= Hot
2. Clo: 0,6=summer clothes; 0,9= with jumper; 1,2= with thick jumper or overcoat
3. AM=Morning; N=Noon; PM=Afternoon X=Never

Conclusion

The findings of this paper would suggest that adobe earth construction provides better hygrothermal comfort during the summer months in Central Chile than that provided by the predominant platform framed timber construction. The results of dry bulb temperature measurements show that the adobe rooms experience much smaller diurnal temperature oscillations with stable temperatures (table 1 & fig 8). However half of these temperatures tend towards the low range of the hygrothermic comfort zone or completely below it. The measurements taken in the straw bale house, a construction with less thermal mass and greater thermal insulation, are equally stable but in general fall within the comfort zone.

It is probably, based on the density measurements, that the adobe walls of the Casa de Pampa de Lima have a thermal conductivity of 0.920W/m^{2}K, two time better than that required by the Chilean Thermal Building Regulations. However the high thermal mass of adobe produces a low thermal sensation in the cold winter months due to the low radiant surface temperatures, a fact confirmed by the dwellings inhabitants. In the olden days the use of open hearths and fires left burning all through winter warmed this thermal mass which in turn maintained the heat. Today the sporadic use of heaters means that they must first heat the wall surfaces before warming the air, an effect that reduces both the energy efficiency of heating systems and the thermal sensation within these rooms. A possible solution suggested by Dr. Baruch Givoni during his visit to Chile in 2002, would be to introduce a thin layer of thermal insulation to the internal wall surfaces. This layer should be thin enough so as not to reduce the positive benefits of the thermal mass in summer, yet sufficient to raise the radiant surface temperature. It is interesting to note that this solution is identical to the use of tapestries in stone buildings in medieval Europe.

The seismic resistance of the heritage earth construction must however be resolved in order to permit the continued use and habitation of these buildings whilst not putting their inhabitants at any great risk than those in modern dwellings. This challenge must be met with regular maintenance programs in addition to strategies for structural reinforcement such as those that have been pioneered in Peru [19].

Earth rendered straw bale construction could offer an interesting alternative to adobe construction for both reconstruction and new build dwellings. Whilst maintaining something of the aesthetics of the heritage adobe architecture, with thick walls, earthen renders and irregular surfaces, the increased thermal insulation provided by the straw bales and the decrease in thermal mass improves hygrothermal comfort at the same time as allowing the use of a timber post and beam structure designed to resist seismic movements.

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References

[1]. M. Bahamóndez Prieto and E. Muñoz González. Sitio Arqueológico Tulor 1: Consideraciones para su Conservación y Caracterización de Materiales. Conserva, Revista del Centro Nacional de Conservación y Restauración, N°1 Santiago de Chile (1997). 49-90

[2]. Instituto Nacional de Estadistica de Chile, Censo Nacional 2002, Santiago de Chile. (2002) [Online] Available: http://www.ine.cl/cd2002/ [21 April 2012]

[3]. Servicio Sismológico, Departamento de Geofísica, Universidad de Chile [Online], Available: http://www.sismologia.cl/seismo.html [19 April 2012]

[4]. Ministerio de Vivienda y Urbanismo Ordenanza General de Urbanismo y Construcción. Santiago de Chile. (1992)

[5]. Comité “Adobe”. Informe técnico, Instituto de la Construcción, Santiago de Chile. (2005).

[6]. Ministerio de Vivienda y Urbanismo. Plan de Reconstrucción, 4th Ed. Santiago de Chile (2011). [Online], Available: http://www.minvu.cl/opensite_20111122105648.aspx [26 April 2012]

[7]. M. Sarrazin. Carta al Director, La Tercera Edición digital. 21/04/2010 - 04:00. [Online], Available: http://latercera.com/contenido/896_253076_9.shtml [27 April 2012]

[8]. M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, World Map of the Köppen-Geiger climate classification updated. Meteorol. Z., 15, (2006). 259-263. [Online], Available: http://koeppen-geiger.vu-wien.ac.at/present.htm [23 April 2012]

[9]. C. Castillo Fontannaz. Estadistica Climatologia, Toma 1. Dirección Meteorológica de Chile, Santiago de Chile. (2001)

[10]. H. Russo, G. Rodríguez, H. Behm, H. Pavez, J. MacDonald, and M. Testa, Architecture and Construction- Climatic Dwellings for Chile and Recommendations for Architectural Design, Chilean Standard NCh 1079 of 77 (2008)", Institución Nacional de Normalización, Chile (2008)

[11]. G. Minke. Building with earth: design and technology of a sustainable architecture. Birkhäuser Basel (2009)

[12]. S. Goodhew, and R. Griffiths, Sustainable earth walls to meet the building regulations. Energy and Buildings. vol 37 (5) (2005) 451-459.

[13]. C.J. Whitman and D. Fernández. The viability of improving energy efficiency and hygro-thermal comfort of rural social housing in central Chile using straw bale construction. In 2nd International Conference on Sustainable Construction Materials and Technologies, Ancona, Italy, June 28-30 (2010).

[14]. P.G. McHenry, Adobe and Rammed Earth Buildings: Design and Construction. Wiley, New York (1984).

[15]. G. Barrios, Tecnología del Adobe: Optimización por ensayos empíricos. Universidad Católica de Chile, Santiago de Chile. (1987) 92

[16]. Ministerio de Vivienda y Urbanismo, Proyectos Tipo Evaluados 12-04-2012, Santiago de Chile (2012). [Online] Available: http://www.ine.cl/cd2002/ [28 April 2012]

[17]. G. Armijo, Experiencias de mediciones de comportamiento térmico en mediaguas mejoradas con barro. Programa de construcción con Ayuda Mutua financiado por GTZ y organizado por Cáritas –Chile después del terremoto de 1985. Universidad Central, Santiago de Chile (1985)

[18]. N. Stone, N. Thermal Performance of Straw Bale Wall System, Ecological Building Network (2003), [Online] Available: http://www.ecobuildnetwork.org/pdfs/Thermal_properties.pdf [3rd March 2010]

[19]. D. Quiun, A. San Bartolome, L. Zegarra, and A. Giesecke, Adobe Reforzado con mallas de alambre: Ensayos de Simulación sísmica y aplicación a construcciones reales. Pontificia Universidad Católica del Perú. (2005)