Natural Fibre Insulation in Rural Southern Chile

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ABSTRACT: Thermal insulation is probably one of the most important elements in reducing the heating demands of residential accommodation in a cool temperate climate. However many insulating materials have a large environmental impact and high embodied energy. Research has shown that natural fibres can provide insulation with a lower impact especially when sourced locally. This paper presents a study of the natural fibres with insulating potential available in the micro-region of Araucania Andina in Chile's 9th Region, a temperate region with long cold wet winters and short hot summers. An environmental impact matrix is used to select the materials with the lowest impact, which in turn are subjected to laboratory guarded hot box testing to determine their thermal conductivity. The final results will inform the design of a sustainable construction system for the micro-region. Materials evaluated include cellulose fibre from the forestry industry which is one of the principal sectors in the local economy; straw bales from wheat production, Chile's main agricultural crop of which the region is the second largest national producer; sheep's wool from the region and those further to the south; and two different local species of bamboo, colihue which currently has limited use for furniture and internal finishes and the highly invasive quila which requires constant clearing to reduce the threat of forest fires yet has no current commercial value. Results show that sheep's wool provides the best insulation values, followed by straw bale and interesting that chipped quila bamboo could provide an economic natural insulation with low environmental impacts.

Keywords: Natural Fibre Insulation, Environmental Impact, Thermal Conductivity

INTRODUCTION

Probably the most effective method of reducing heating demands of residential accommodation in a cool temperate climate is the reduction of the thermal conductivity of the building envelope. This is principally achieved through the use of thermal insulation. This insulation can be synthetic or natural in its origin. Examples of synthetic materials include expanded polystyrene, polyurethane, polyester fibre, autoclave concrete and mineral fibres. Although the latter are based on naturally occurring materials, their production involves a significantly large change in their physical state as to consider them synthetic. Examples of natural insulation materials include cellulose fibre, cotton, natural wools such as sheep's wool, straw bale and hemp.

Natural insulation materials can be found in vernacular and indigenous architecture dating back thousands of years such as the use reeds and grasses for example as the thatch on English country cottages or the walls and roofs of the indigenous Mapuche *Ruca* of central Chile. More recent examples include the insulation of timber stud walls with newspapers (cellulose fibre) in the UNESCO Heritage site of Sewell a mining town built in Central Chile in 1905 and straw bale houses dating from the early 20th Century in Sandhills Nebraska, USA. Since the first energy crisis of the 1970´s and then the preoccupation with sustainability that has been steadily growing since the 1990's, interest has now been refocused on these materials that not only save energy in use but also have minimal embodied energy and low environmental impacts in their production.

NATURAL INSULATION MATERIALS IN THE ARAUCANÍA ANDINA

As part of the research project "Sustainable Construction System for Special Interest Tourism in the Araucanía Andina" an inventory of available natural insulation materials was undertaken. The materials identified were Sheep's wool, the endemic bamboos colihue (Chusquea culeou) and quila (Chusquea quila*)*, and straw from cereal crops and cellulose fibre arising from forestry stewardship and timber production.

SHEEP'S WOOL

The hair follicles of sheep comprise of two types of proteins; fibrous proteins and globular proteins. The fibrous proteins are of the keratin subgroup which is characterized by its high sulphur content. Macromolecules of keratin possess a chain of amino acids the most important being cysteine which is responsible for the stability of the fibres. The aliphatic and aromatic residues valine, leucine and phenylalanine, which comprise the side chains of keratin, form hydrophobic regions due to their non-ionic character.

The sheep's wool production of the Araucanía Region represents 7.2% of the national production with a production of 44,184kg in the agricultural productive year of 2009/2010 [1]. The regions directly to the south, Los Lagos and Aysén represent 8.2% and 7.9% of national production respectively. The largest producer of wools is the region of Magallanes in the far south of Chile, 1,400km away, where 56% of Chile's wool is produced.

The sale of wool in the Chile is via wholesale and retail markets. In the Araucanía Region its sale is principally via retails markets with raw white wool prices varying between $300 and $400 Chilean pesos per kilo. Washed and carded white wool retails around $10.000 pesos per kilo. Currently in Chile sheep's wool is not sold as a commercialized building product, however internationally there exist companies that have developed wool as a commercial product in order to find new markets to maintain the local economy faced by falling wools prices and competition from synthetic fibres in the fabric industry. Such companies include; Black Mountain Insulation Ltd. and Thermafleece in the UK; Naturlaine in France; and Terra Lana, Green Sheep and Woolcote in New Zealand. In the UK 100mm thick sheep's wool insulation from Thermafleece retails at £5.79/m^2 [2] compared to £2.14/m^2 for mineral wool insulation [3].

BAMBOOS

The bamboos of Chile are of the genus *Chusquea* of which there exist approximately 150 species in Latin America [4], 11 of which can be found in Chile. In the temperate rainforests of the micro region Araucanía Andina there are two endemic species, colihue (*Chusquea culeou*) and quila (*Chusquea quila*). Table shows its presence in southern-central Chile in the zone between the 5th and 11th Regions. The figures show that quila is the most abundant species. Unlike Asian bamboos both colihue and quila are solid stemmed.

Table 1: Presence of endemic bamboos in the area between the 5th and 11th Regions of Chile

Species	area (hectares)
Chusquea culeou (Colihue)	305,382.3
Chusquea quila (Quila)	396,507.1
Chusquea cummingii (Quila chica)	179,207.3
Chusquea uliginosa (Tihue)	18,838.7
Total	**899,935.4**

Both species follow supra-annual flowering and seeding patterns. After a period of between 5 and up to 70 years of vegetative state, during which production is focused on foliage and root structure, there follows a short period of flowering and seed production after which the plant dies. Given that this occurs in almost all of the individual plants of given populations at the same time, large tracts of forest undergrowth die simultaneously increasing risks of forest fires. Both species and in particular quila are seen as a plague and threat to both commercial forestry and conservation.

COLIHUE (*Chusquea culeou*)

Figure 1.- Colihue (Chusquea culeou)

Colihue is a straight growing bamboo which does not branch (fig 1.). It grows to a height of up to 6m with an average cane diameter between 13 and 16mm [5]. In its chemical composition lignin represents 23.9% and cellulose 72.4% [5]. Currently colihue is used in Chile as garden canes, for furniture making and as a decorative internal finish for walls and ceilings. The canes are also used for placing dynamite charges in mining installations, this being the most common use of colihue in Chile with the state copper mining company CODELCO ordering 800.000 canes per year [6]. Prices range from $60 Chilean pesos for canes 1m in length up to $800 pesos for widths greater than 25mm. Although colihue is sold commercially it is not cultivated, instead it is collected wild from forests with machetes, with between 100 and 200 canes being harvested per day depending on cane stem width [6].

QUILA (*Chusquea quila*)

Figure 2.- Quila (Chusquea quila)

Unlike colihue, quila branches, is more crooked and has a smaller diameter (fig.2). In its chemical composition lignin represents 18% and 48 % cellulose. As it forms dense clumps it is commonly believed to attract rodents, this in addition to the previously mentioned flowering pattern and associated fire risk has led to quila being classified as a nuisance. Its irregular form makes it less attractive for functional and decorative applications than colihue.

STRAW BALE

Wheat remains the most important crop in Chile with 245,277 hectares planted in the productive year 2011-2012. When other straw producing crops such as barley and oats are included the total planted area rises to 399,816 hectares [7]. The cereal production in the Araucanía Region represents 48% of this figure [7]. In Chile in general straw is not ploughed back into the soil due to the time needed for decomposition prior to reseeding, therefore agricultural fires are the most common method of disposing of this waste material. As previously mentioned straw bales have been used as a construction material since the beginning of the 20th Century. Examples of straw bale construction can be found in all continents except Antarctica [8]. International testing has shown that straw bales have a coefficient of conductivity between 0.054W/mK and 0.15W/mK and a rendered straw bale wall has a thermal conductivity of between 0.103W/m^{2}K and 0,334W/m^{2}K [9].

CELLULOSE FIBRE- FORESTRY WASTE

In 2011 according to the Ministry of Agriculture 2.349.250 hectares of forestry plantations existed in Chile, of which 63% were of Monterey Pine (*pinus radiate*) and 32% eucalyptus [10]. When waste from native forests is included the total biomass waste produced by the forestry industry in 2008 was 4.749m^3 not including forest thinning. Of this 10.7% was located in the Araucanía Region and a further 58.4% in neighbouring regions [11]. Currently this waste is used in biomass boilers and research is underway to explore its potential in the production of refined biofuels. International testing shows that cellulose fibre or wood wool produced from forestry waste has a coefficient of conductivity between 0.04W/mK and 0.06W/mK.

ENVIRONMENTAL IMPACT OF INSULATION PRODUCTION

The method used for the evaluation of environmental impact is based on that developed by Leopold et al. in 1971 [12] in which numerical values are allocated according to the impact produced, in this case by the production process of thermal insulation. The natural insulation materials described above were compared with the most common synthetic insulation materials used in by the Chilean construction industry, these being Expanded Polystyrene, Polyurethane foam and Glass Fibre.

Expanded Polystyrene

Expanded polystyrene is s petrochemical. Only 4% of world oil production is used for the manufacture of plastics and expanded polystyrene represents 2.5% of this figure. The main impacts in the production of this material are: the liberation of airborne contamination in the form of NO_x, CO, VOCs and PM_{10} which cause acid rain, smog and breathable carcinogens: spillages during production lead to contamination of ground and water courses: and the production of dangerous by-products and residues. The polymerization of styrene is irreversible and the final product is not biodegradable. Its useful life span is between 35 and 50 years.

Polyurethane

The principal impacts of the production of polyurethane are: the release of toxic gases SO_2, SO_4, NO_x, HCFC, CFC and VOCs: as with polystyrene, spillages can cause irreversible contamination to ground and water courses and related animal and plant life: the final product is not biodegradable with a useful life span of between 50 and 70 years. Its production produces a large quantity of dangerous residues.

Sheep's wool

The principal airborne emissions arise from the transportation of the sheep and their wool. In order to avoid infestations and degradation it is necessary to treat the wools with sodium borate (borax), however this is not considered a dangerous residue. The product is biodegradable and has a useful life span of more than 50 years.

Quila and Colihue

Airborne emissions could result from transportation and from the use of adhesives or agglomerates. Depending on the origin of these additives these could have negative impacts on ground and water contamination. The product is biodegradable and has an expected useful life span of 30 to 50 years.

Straw bales

In the production of cereals airborne pollution can be caused by through the disturbance of dry earth and resulting $PM_{10.}$ Being a monoculture, single crop farming cereal production can have negative effects on biodiversity. However straw is a by-product of cereal production and therefore the principal pollution arising directly related to the straw bales arises from their transportation. The product is biodegradable and historic examples of straw bale buildings show a useful life span of more than 100 years.

Forest waste

The environmental impact of forestry depends much on its stewardship. Impacts can be reduced via avoidance of monoculture plantations and sustainable management.

Forest waste produces airborne emissions from arising from its transportation and, as with the bamboos, possible additional contamination could arise from adhesives and agglomerates. The end product is biodegradable and has an expected useful life span of between 30 and 40 years.

Table 2: Environmental Impact Matrix. Weighting of environmental impacts of insulation materials.(L)Low impact, (M) Moderate impact, (H) High impact (+) positive impacts.

Material	L	M	H	+
Ex. Polystyrene	8	46	6	11
Polyurethane	8	28	6	6
Glass Fibre	7	23	10	10
Sheep's wool	8	13	1	16
Bamboos	4	30	2	13
Straw bale	10	14	1	13
Cellulose fibre	5	33	5	16

The materials with the lowest environmental impact are sheep's wool followed by straw bale and bamboos.

Following this evaluation sheep's wool, quila and colihue were chosen for thermal conductivity testing. Testing of straw bales was not undertaken due to the availability of international test results.

THERMAL INSULATION REQUIRMENTS IN THE ARAUCANIA ANDINA

In 2000 Chile became the first Latin American country to introduce thermal building regulations for new build residential. However the requirements of the regulations have been criticized for their inadequacy and relative weakness at both a national [13] and international [14] level. The maximum permitted U-values for the region are 1.6W/m^{2}K up to 1500m above sea level and 1.1W/m^{2}K for higher locations. In addition to the legally required thermal building regulations there exists the Chilean Standard NCh1079 of 2008 which has recommended maximum U-values which are more stringent than the regulations and are 0.5W/m^{2}K for altitudes up to 600m and 0.3W/m^{2}K for higher altitudes.

THERMAL CONDUCTIVITY TESTING: GUARDED HOT BOX

METHODOLOGY

The testing of the thermal conductivity of the materials was undertaken according to the Chilean Standard NCh851.of83 Thermal Insulation- Determination of thermal conductivity coefficients by the method of the guarded hot box. The guarded hot box method was chosen rather than guarded ring due to the non-homogenous nature of the materials. The tests were undertaken by the Centre for Research in Construction Technology (Centro de Investigación en Tecnología de la Construcción) CITEC of the Universidad Bio Bio in Concepción, a Laboratory certified by the technical division of the Chilean Ministry of Housing and Urbanism (MINVU).

The materials selected to be tested were. Sheep's wool washed and carded (fig.3), colihue laid perpendicular to heat flow (fig. 4), quila laid perpendicular to heat flow (fig. 5) and quila chipped with a mobile garden shredder (fig. 6). Chipped colihue was not tested due to the hardness of the material.

Figure 3.- Sheep's wool washed and carded. Test panel before closing with second MDF panel. Figure 4.- Colihue perpendicular to heat flow

Figure 5-. Quila perpendicular to heat flow. Figure 6.- Quila chipped with garden shredder. Test panels before closing.

In order to comply with the Chilean standard which states that samples should be reasonably presented with flat, parallel faces five sample panels were constructed, 4 with a softwood frame 1375mm x 1555mm x 90mm faced with 9mm MDF leaving a space of 1293mm x 1473mm x 90mm. this space was then filled with the selected insulations (figs. 3-7). The fifth panel consisted of two 9mm MDF boards nailed together to allow the deduction of their conductivity in the calculation of the coefficient of the insulation materials. The densities were those achieved via manual compaction.

The five filled panels were tested in the guarded hot box. The guarded hot box (fig. 8) consists of three chambers each one open on one side.

The first box is heated with an electric resistance heater, the second is chilled and the third protects the second box to ensure that all the thermal energy produced passes through the test panel. The heat flow produced and determined by the electrical input in the measurement chamber, passes through a known area of the test panel which is placed between the measurement chamber and the cold chamber.

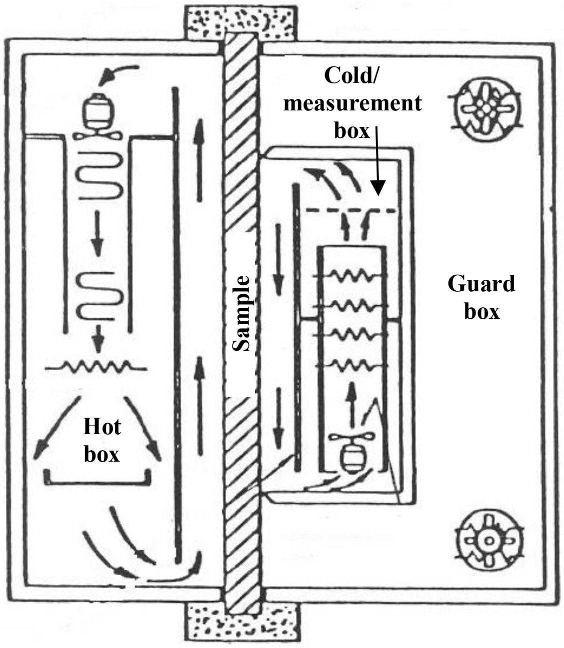

Figure 8- Plan of guarded hot box (NCh851.of83)

Establishing the electrical power dissipated (ø=heat flow), the area (A) of the test panel through which the heat passes and the difference in temperature between the chilled face (T1) and the heated face (T2) of the test panel, it is possible to calculate the thermal conductivity U_e by the formula:

$$Ue = \frac{ø}{\mathrm{A(T2 - T1)}}$$

With the same information of electrical power dissipated and area, but considering the difference in air temperature between the chilled chamber (Ta1) and the heated chamber (Ta2) it is possible to calculate the global thermal conductivity U by the formula:

$$U = \frac{ø}{\mathrm{A(Ta2 - Ta1)}}$$

The thermal conductivity of the two MDF panels was obtained from a test using the Guarded Ring methodology according to Chilean Standard NCh850 of. 83. The obtained value together with the U values obtained from the guarded hot box tests, were used to calculate the coefficient of conductivity λ of each material according to the Chilean Standard NCh893of.91. Using the formula:

$$\mathrm{R} = Rsi + \frac{e1}{\lambda 1} + \frac{\mathrm{e2}}{\lambda 2} + \frac{\mathrm{en}}{\lambda \mathrm{n}} + Rse$$

Where
R= Resistance
Rsi = Internal surface resistance = 0.12 m^2K/W
Rse = External surface resistance = 0.12 m^2K/W
e = thickness of material
λ = Coefficient of conductivity of material

The calculated λ are presented below.

Each of the test panels was weighed and the density of the insulation calculated. The densities are presented together with the coefficient of conductivity are presented below.

Using the calculated coefficients of conductivity λ, the thickness required to achieve the maximum U-value as recommended by the Chilean Standard NCh1079 of.2008 was calculated assuming a panel construction faced internally and externally with MDF. These thicknesses are presented below.

RESULTS

Table 2: Test results of thermal conductivity (λ) density of different natural insulation materials (D) and thickness required to achieve a u-value of 0.3W/m^2K

Material	λ (W/mK)	D (kg/m^3)	t (cm)
Sheep's wool	0.045	38.8	13.8
Quila Perp.[1]	0.210	225.2	64.5
Quila chipped	0.065	122.2	19.9
Colihue Perp.[1]	0.161	463.2	49.5
Straw bale[2]	0.054	133	16.6
Wood fibre[3]	0.038	50	11.7
Ex. Polystyrene[4]	0.043	10	13.2
Polyurethane[4]	0.026	40	8.0
Glass Fibre[4]	0.04	18	12.3

1. Perpendicular to heat flow. 2. McCabe J, (1993) [9]. 3. www.steico.com [15]. 4. Instituto de la Construcción (2006) [16]

CONCLUSION

From the results it would appear that of all the locally available natural insulation materials wood fibre has the lowest thermal conductivity; however this material has the highest environmental impact when compared to the other natural materials. Its current use as biomass and its potential for future development of biofuels increases its economic value and reduces its attractiveness as a viable insulation material.

Sheep's wool, with a coefficient of conductivity of 0.45W/mK is the second lowest and achieves the recommended U-value in just 13.8cm. It is also the lightest of the natural insulation materials and so would be the ideal solution for roof insulation. The cost of washed and carded wool is currently prohibitive, however if raw wool was bought and large scale production of wool prepared specifically for the building industry was developed this cost would be reduced.

Straw bale has the third lowest conductivity, achieving the required U-value with only 13.2cm. However due to the format of the bales it is necessary to use the entire bale in order to maintain the density. This increases wall thicknesses to around 40-50cm.

Perhaps the most interesting result is that of the chipped quila bamboo. With a coefficient of thermal conductivity of 0.065W/mK it achieves the recommended U-Value in less than 20cm. In addition it grows locally, has no current use or economic value and if not cleared increases the risk of forest fires. Given its density of $122kg/m^3$ its application would make more sense as an infill for wall construction. Further research is however required to define if additives are required to prevent settlement and self-compaction over time.

Based on these results the authors will design a sustainable construction system for the Special Interest Tourism infrastructure for the micro-region of Araucania Andina. The system will have wall panels insulated with chipped quila bamboo and roof panels insulated with sheep's wool, two natural insulation materials from the region. This will improve the energy efficiency and thermal comfort of the installations, whilst at the same time generate a local economy based on the production of these materials.

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