Construction and Building Materials 37 (2012) 425–431

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Thermal conductivity of coconut fibre filled ferrocement sandwich panels

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HIGHLIGHTS

- ▶ The potential use of coconut fibre as thermal isolating filler for ferrocement panel walls.
- ▶ Ferrocement sandwich panels filled with coconut fibre exhibit lower thermal conductivity than the extreme cases tested.
- ▶ Ferrocement sandwich panels filled with coconut fibre present lower thermal conductivity than traditional materials.
- ▶ Coconut fibre loading content has some influence on thermal conductivity.

ARTICLE INFO

Article history:
Received 12 December 2011
Received in revised form 10 June 2012
Accepted 21 July 2012
Available online 5 September 2012

Keywords:
Conductivity
Coconut fibre
Thermal comfort
Isolating material
Ferrocement

ABSTRACT

This study evaluates the potential use of coconut fibre as thermal isolating filler for ferrocement panel walls in sandwich configuration of schools and houses' roofing in Puerto Escondido, Oaxaca, Mexico. Thermal conductivity measurements were performed to compare the thermal behaviour of ferrocement panel walls filled with coconut fibre to other typical building materials of the region. Measured thermal conductivities for red clay brick, hollow concrete block and lightweight concrete brick panel walls are 0.93, 0.683 and 0.536 W/m K respectively. Thermal conductivity of the proposed configuration is 0.221 W/m K and that is lower than typical materials used for home-buildings in this region.

1. Introduction

In the coast of southern México, specifically Puerto Escondido, Oaxaca the climate is hot and semi-humid presenting an average daytime temperature of 28 °C but can reach peak temperatures up to 34 °C during the summer. This location is situated 60 m above sea level at geographic coordinates 15°51′43″N, 97°4′18″W in the southern coast of Oaxaca [1,2]. The dominating vegetation type is medium subdeciduous forest and lowland deciduous forest with annual rainfall that normally varies from 500 to 1500 mm [3,4]. In order to have certain comfort under such circumstances, air coolers that normally consume an important amount of energy are used. This energy consumption can be reduced making use of construction materials with biodegradable fibres as an alternative to reduce energy consumption in house living, waste isolating materials and help to preserve ecological surroundings. On the other hand, in the last decade, grow of industrial sector from the construction point of view has experienced a significant development with the inclusion of new materials and advanced properties. This development presents also an important disadvantage in the surroundings since most of the materials used are inorganic and cause environmental contamination for not being degradable [5]. Activities such as rebuild and refurbish buildings and structures generate waste isolating materials and contamination for the environment and to recycle these materials is difficult for developing countries because of their lack of infrastructure to carry out these processes.

In this sense, biodegradable fibres like coconut have taken a growing importance for economical and environmental reasons [6]. Research in previously mentioned organic fibres, either mixed with cement, mortar or concrete indicate that an improvement in some mechanical properties such as impact strength, tension, flexure and bonding [7–11] is achieved. Reduction of 30–40% in cost of the composite material makes them an alternative to be considered. Some studies carried out using Durian and coconut fibres for panel boards have shown promising results, registering low thermal conductivities in the range of 0.054–0.1854 W/m K, making it possible to use them as thermal isolating materials [12–15]. Khedari et al. developed coconut fibre based soil–cement blocks with light weight and low thermal conductivity [16].

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http://dx.doi.org/10.1016/j.conbuildmat.2012.07.053

Now a days ferrocement sandwich panels are attracting attention in the production of building components. Sandwich panels provide an economic method of providing structural requirements and thermal insulation [17–20]. The faces of the sandwich panel provide protection to the core material and withstand the imposed loads acting as tension and compression elements.

Ferrocement encased aerated concrete core sandwich composites have been investigated in terms of ultimate compression and flexural strength and compared to solely aerated concrete. The ferrocement encasement transforms the brittle behaviour of aerated concrete in ductile failure mode reducing weight and increasing flexural and compressive strength [21]. Raj et al. [22–24] have developed bamboo-based ferrocement slab elements for roofing/flooring purpose in low cost housing with good mechanical properties and light weight, while Yao and Li [25] carried out flexural strength studies on bamboo-fibre-reinforced mortar sandwich plates with remarkable improvement.

The work presented in this paper is focused on exploring the potential use of coconut fibre as thermal insulation filler of ferrocement sandwich type panel wall components and compare its performance with panel walls made of typical building materials used in roofing at schools and houses in hot climate of Puerto Escondido Oaxaca, Mexico.

2. Materials and methods

In this section, a description of materials and details related to fabrication of the panels used in the experimental measurements are presented.

2.1. Properties of materials used in panels

Ferrocement is a construction material composed of reinforced concrete and various layers of steel wire mesh, either electro-welded or hexagonal, distributed uniformly through a transversal section [26]. Normally a mortar rich of cement, sand and water is used. This material is thin (10–35 mm width) and with high resistance and flexibility besides of being a low cost material. Ferrocement constructions present weight reduction compared to traditional building materials.

Panel walls prepared and tested in this study were fabricated of (a) two ferrocement panels, 0.025 m thick, plus long coconut fibres, 0.1 m thick, in sandwich configuration, and the thermal conductivity measured and compared to three typical materials highly used in house building in south of Mexico, like (b) panel wall of hollow concrete block, 0.15 m thick, (c) panel wall of lightweight concrete brick, 0.15 m thick, (d) panel wall of red clay brick, 0.15 m thick, and two additional tests of extreme cases were conducted, (e) panel wall exclusively of solid ferrocement, 0.025 m thick, and (f) two ferrocement panels with air space, 0.1 m thick, in-between, instead of coconut fibre (see Fig. 1).

For mortar preparation in this study, Portland cement type 1 was used since it fulfils all requirements of ASTM C-150-89 standard. Cooperativa La Cruz Azul S.C.L. in Mexico fabricates this cement. Natural sand, clean and free from organic substances, sieved with sieve 8 (2.38) ASTM was used. Average grain size was 0.7 ± 0.145 mm. Water from the main distribution line in the region was taken to prepare the mixture. Mechanical properties of mortar used in this study are summarised in Table 1 [27].

Coconut fibre used as thermal insulator filler in ferrocement panels was bought in the local market. Moisture content, W_m of coconut fibre was determined by Eq. (1) as the ratio of the mass of absorbed water to the total fibre mass. Coconut fibre (0.5 kg) was thoroughly washed in a soap solution for 24 h to eliminate impurities and completely rinsed in tap water, it was let to drip off for 1 h and weighted in a precision scale balance. Then the fibre was sun dried for 5 days and weighted again. Then that fibre was introduced in an electric oven set to temperature of 45 °C for 5 h to be finally weighted.

Table 1
Properties of mortar.

Property	Measured value	International standard
Cement:sand:water	1:3:0.67	–
Compression strength of cylinders	25.29 MPa	ASTM C39/C39M-03
Compression strength of cubes	23.03 MPa	ASTM C109/C109M-02
Elasticity modulus	16.3 GPa	ASTM C469-02
Poisson ratio	0.11	ASTM C469-02

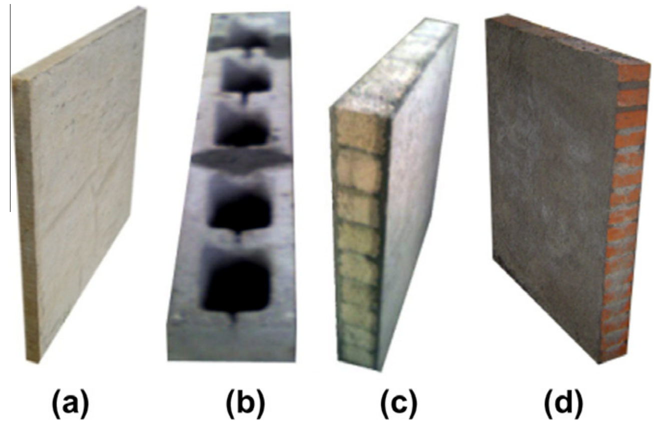

Fig. 1. Materials used for thermal conductivity tests: (a) panel wall of ferrocement, (b) panel wall of hollow concrete block, (c) panel wall of lightweight concrete brick, and (d) panel wall of red clay brick.

Fig. 2. Coconut fibres used in the experiments as thermal isolating material.

Table 2
Physical and mechanical properties of coconut fibre.

Property	Typical value	Ref.
Specific density	1.15 kg/m^3	[28]
Tensile strength	≈150 MPa	[29]
Modulus of elasticity	≈3 GPa	[29]
Thermal conductivity	0.046–0.068 W/m K	[30]

$$W_m = \frac{(M_h - M_o)}{M_h} \times 100 \quad (1)$$

where M_h is the mass of coconut fibre before drying and M_o is the mass of coconut fibre after drying (oven-drying).

A 24 h water absorption test was carried out firstly weighting on a scale balance the fully dried coconut fibre and immersing it in 20 °C water at 15 min time intervals up to 24 h in a flat bottom container. Water absorption is expressed as the percentage of the weight of water absorbed by the coconut fibre by the dry weight of the coconut fibre. Water absorption, O is then calculated by using the following equation:

$$O = \frac{(M_2 - M_1)}{M_1} \times 100 \quad (2)$$

where O is the water absorption (%), M_1 is mass of coconut fibre before immersion (g), and M_2 is the mass of coconut fibre after immersion (g)

After dried, coconut fibre was chopped in 9 cm long as indicated in Fig. 2 and its diameter was measured with a calibrated micrometre saw gauge resulting an average of 0.51 mm. More than 100 individual fibres were measured in this way for a representative value. Physical and mechanical properties typical of coconut fibre, taken from references, are indicated in Table 2.

Table 3
Dimensions of panel walls tested.

Panel wall	Dimensions (m) length, height, width
Ferrocement only	1, 1, 0.025
Ferrocement (0.05 m) + air space of (0.1 m)	1, 1, 0.15
Ferrocement (0.05 m) + coconut fibre (0.1 m)	1, 1, 0.15
Hollow concrete block	1, 1, 0.15
Lightweight concrete brick	1, 1, 0.15
Red clay brick	1, 1, 0.15

Table 4
Ferrocement reinforcement specifications.

Mesh type	Specification
Electrowelded mesh 6*6/10*10	Wire diameter of 3.43 mm and yield strength of 588.4 MPa
Square mesh of expanded metal gauge 26	Weight 0.635 kg/m^2, 0.32 mm thick and yield strength of 235.35 MPa

2.2. Fabrication of ferrocement panels

Fabricated panels under study and their dimensions are indicated in Table 3. Ferrocement panel walls were prepared using a wooden form of 1 m × 1 m and thickness of 0.025 m for panel casting. This form was built with specific precautions to facilitate the removal of the panel wall after hardening. In this case mortar matrix was a mix composed primarily of ordinary Portland cement, sand and water with a proportion of 1:3 of cement–sand and 1:0.67 of cement–water as indicated previously. Firstly a mortar layer 0.025 m thick was uniformly distributed in the wooden form. Then an electrowelded mesh 6*6/10*10 and a square mesh of expanded metal gauge 26 were installed, as indicated in Table 4. Ferrocement panel was removed from the wooden form within 24 h after casting. A second ferrocement panel was built following the same procedure. Ferrocement panels were stored in the laboratory atmosphere and covered with a wet cloth using water sprinkled twice a day for curing.

2.3. Fabrication of coconut filled ferrocement panels

For the sandwich type ferrocement configuration a wooden box frame of 1 m × 1 m and thickness of 0.15 m was built and mounted on top of a ferrocement panel (0.025 m thick). Then coconut fibre previously weighted was introduced in the space of the wooden box and after that a second ferrocement panel (0.025 m thick) was positioned on top to get the component panel indicated in Fig. 3. Finally, ferrocement faces were two-sided mortar rendered. Ferrocement sandwich component panels were tested after 28 days. Fig. 3a and b shows the ferrocement panels filled with coconut fibre and indicate their dimensions.

2.4. Fibre loading vs thermal conductivity

In order to test the effects of coconut loading fibre content on thermal conductivity, three ferrocement panel walls were made, each one with coconut fibre weights of 5.76 kg, 3.15 kg and 2.6 kg corresponding to coconut fibre high, coconut fibre medium and coconut fibre low content respectively. The coconut fibre previously weighted, was distributed randomly in the wooden box by hand applying some pressure as shown in Fig. 4a. This procedure makes possible to have a constant coconut fibre thickness in-between the ferrocement layers previously prepared. Worth of mention is that fibre orientation effects were not included in this study. Fig. 4b represents how the coconut fibre filled ferrocement panel wall in sandwich configuration looks like after mortar rendering finish.

2.5. Thermal conductivity measurements on ferrocement panels filled with coconut fibres

Thermal conductivity measurements of panels used in this study were carried out on a home made hot plate conductivimeter. Dimensions of the apparatus are indicated in Fig. 5. In its basics, this apparatus is a box one side open, in which heat is generated by means of an electric heating system. The walls of the box are thermally isolated with a ceramic fibre material.

This is a primary apparatus that uses steady state conduction heat transfer as principle and allows determining thermal conductivity by ASTM C 177 using the following equation:

$$\lambda = q * L/(A\ \Delta T) \tag{3}$$

where q is heat flow rate through the specimen in W, λ is the thermal conductivity of the specimen in W/m K, ΔT is the temperature difference through the specimen in K, L is the thickness of the specimen in m and A is the area of cross section in m^2. It is worth to mention that if the specimen is a laminar compound, contains porous or voids where heat can be transferred by convection, radiation and/or conduction then λ, in Eq. (3), is the apparent thermal conductivity of the specimen.

For thermal conductivity determination, panel walls are mounted on the open side and closing the box completely. A constant heat flow of 100 W was supplied to the specimen of area 1 m^2 through a controlled power supply and wire resistance attached to a 6 mm AISI 1018 hot plate. Temperature measurements reported in this study were carried out using a total of eight thermocouples of the type TMC6-HD smart sensors (−40 °C to 100 °C) connected to a 12-bit HOBO12 Data Logger system that includes HOBOware software and standard NIST calibration kit and stores 43,000 readings, at a sampling rate of 1 s–18 h, four located in the hot face and four in the cold face of the panel wall to determine the thermal conductivity by Eq. (3). Thermocouple positions are indicated in Fig. 6 below.

Four testing replicates were carried out on each panel wall in this study. Temperature measurements were taken every 10 min for a period of 75 h (about 450 data points). Registered temperatures from the four sensors in the hot side and four sensors in the cold side were plotted and only the range of steady state was taken to get the mean temperature of that sensor. After that, an average from the four sensors in the hot side was calculated. The same procedure was taken for the four sensors in the cold side. The temperature gradient was calculated as hot-side average temperature minus cold-side average temperature, and used to calculate the thermal conductivity of the panel wall measured. It should be mentioned that more than 100 points in the steady state were taken to calculate the mean temperature registered in every sensor for each panel wall.

A schematic of the thermal conductivity system is illustrated in Fig. 7 and the set up of the conductivity tests is shown in Fig. 8.

In the home-made conductivimeter in our facilities, thermal conductivity measurements were carried out on a fibreglass blanket GC-920 (GC Insulation Inc.) of 1 inch thick and density of 48 kg/m^3 at 25, 50 and 100 °C. Recorded thermal conductivity values were compared to thermal conductivity values provided by the manufacturer. Results are shown in Fig. 9. The steady state on the hot side of the specimen was reached after 10 h, as is shown in Fig. 10. During the test, temperature values were registered every 10 min. It is important to mention that registered values used to determine thermal conductivity of the material tested correspond to the steady state.

3. Results and discussion

3.1. Moisture content and water absorption of coconut fibre

Moisture content loss in the coconut fibre used in this study is presented in Table 5. It is noticed that coconut fibre loss 73.4%

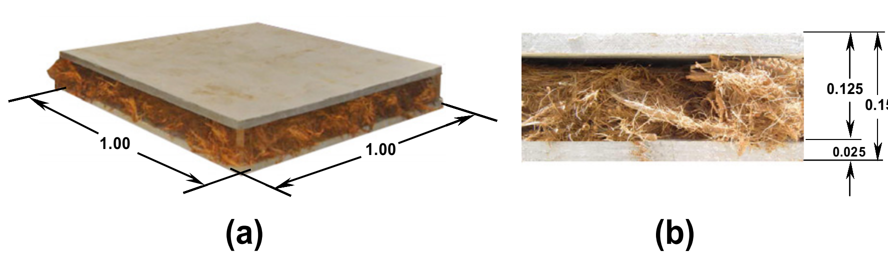

Fig. 3. Ferrocement panels in sandwich configuration with coconut fibre filled: (a) isometric view and (b) details of transversal section.

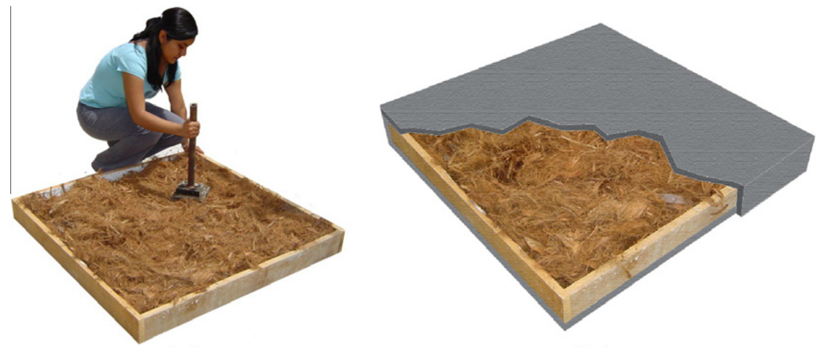

Fig. 4. (a) Coconut fibre pressed in the wood form and (b) mortar rendered coconut filled ferrocement panel in sandwich configuration.

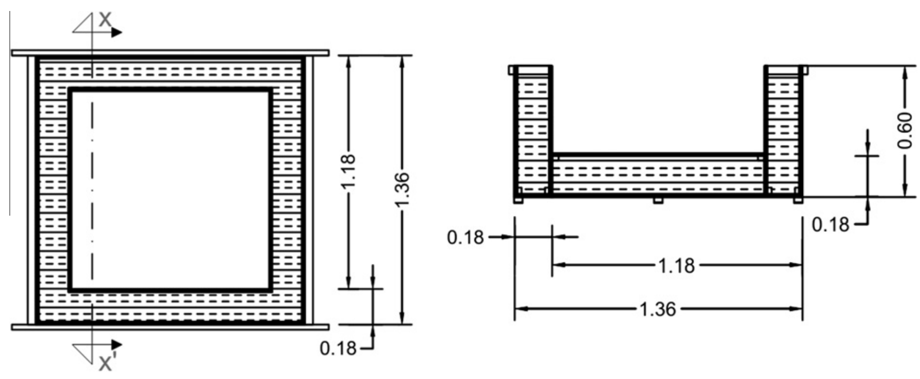

Fig. 5. Hot plate apparatus for thermal conductivity tests: (a) top view and (b) front view.

water during the first 5 days exposed to sun (average of 28 °C ambient temperature) and then after 5 h in the oven at 45 °C further 13% for a total of 86.4%. Thus coconut fibre used for panel walls remain with 13.6%. Further drying of coconut fibre until the change in mass between successive weighing was less than 0.1%, to a moisture value of 3.04%.

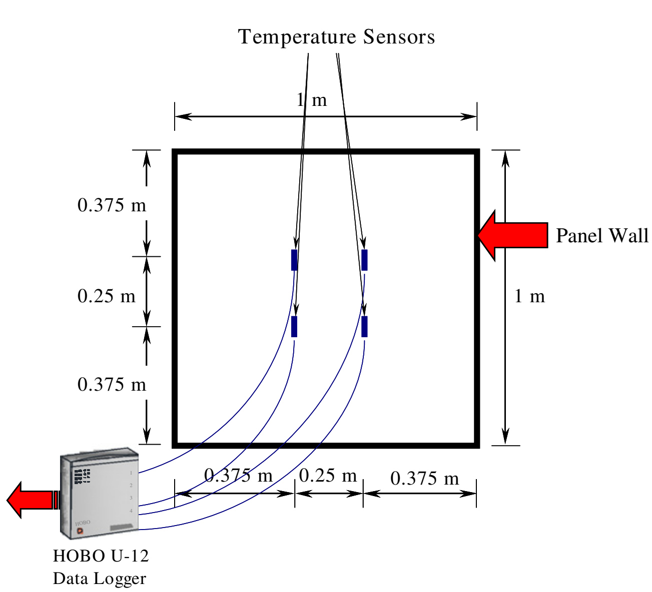

Fig. 6. Positions of thermocouples type TMC6-HD smart sensors.

It should be emphasised that panel walls of ferrocement in sandwich type filled with coconut fibre provide enough protection to minimise humidity concerns since the coconut fibre is in-between the walls of ferrocement. In the same way, while authors of this paper are aware of the change in thermal conductivity values with temperature, it must be mentioned that this thermal conductivity study is focused on conditions typical of roofing in the area of study (Puerto Escondido Oaxaca).

Fig. 11 shows the water absorption capacity of coconut fibre used in this study. It is observed that coconut fibre absorbs 240% water in a period of 24 h to reach a constant value.

3.2. Thermal conductivity of panel walls

The thermal conductivity of coconut filled ferrocement sandwich panels was measured and their potential as thermal insulators to be used as components for house living was assessed and compared to thermal conductivities of traditional building materials of the area of study. Bearing in mind that in the construction industry, achieving room temperatures in the thermal comfort range by using ecological and thermal insulation materials is of paramount importance and although the authors are aware that many other parameters interact together such as air velocity, humidity and heat variations (depending on the latitude) are key factors, the steps followed in this study are enough to determine whether coconut fibre filled ferrocement sandwich panels can be used as thermal insulating materials for hot tropical climates.

Thus, Fig. 12 shows thermal conductivity results of the materials tested. It can be seen that ferrocement sandwich panels filled with coconut fibre present lower thermal conductivity (0.221 W/

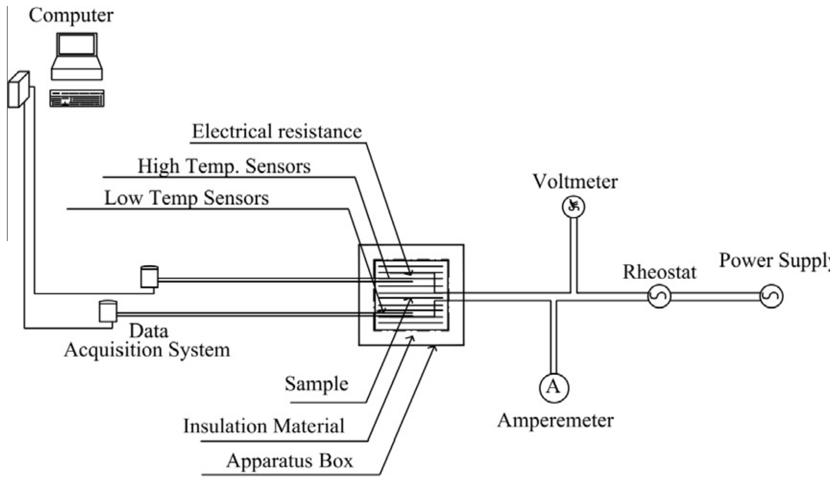

Fig. 7. Thermal conductivity system.

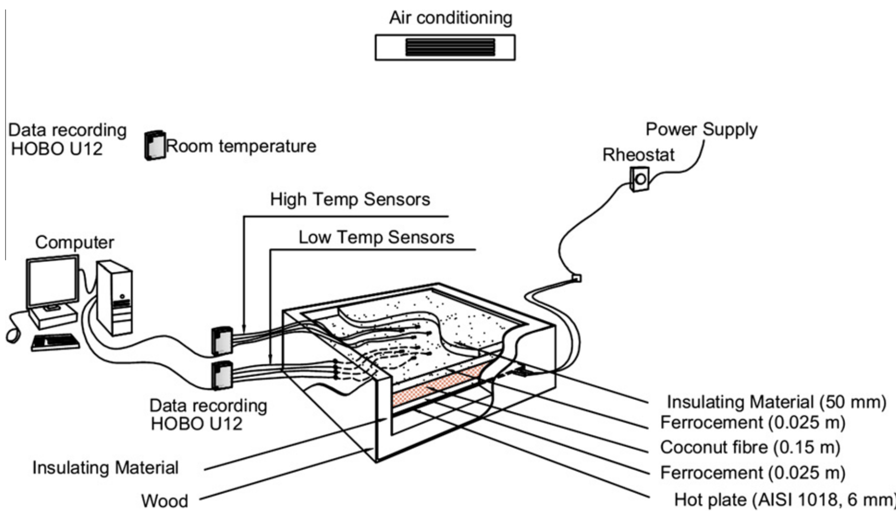

Fig. 8. Experimental configuration of the thermal conductivity test.

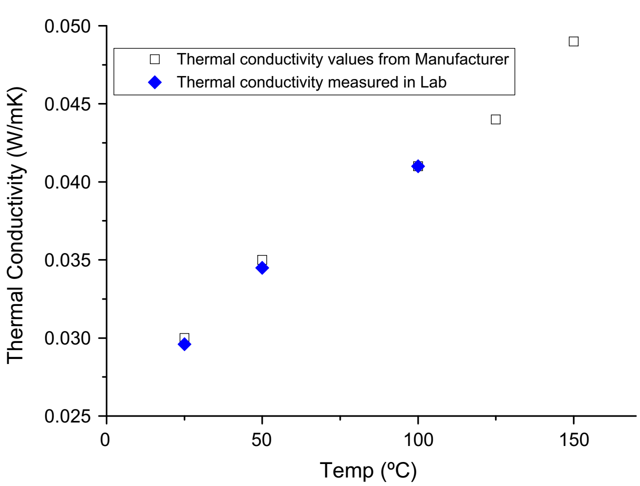

Fig. 9. Calibration of home-made conductivimeter using a fibreglass blanket.

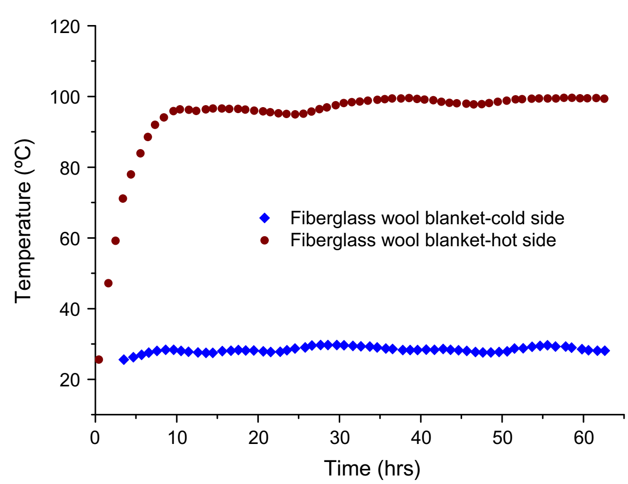

Fig. 10. Steady state on the calibrating material.

m K) than traditional materials such as hollow concrete block (0.683 W/m K), lightweight concrete brick (0.536 W/m K) and red clay brick panel walls (0.93 W/m K) respectively.

The results also indicate that ferrocement sandwich panels filled with coconut fibre exhibit lower thermal conductivity than the extreme cases tested (solid ferrocement panels (0.696

Table 5
Moisture content of coconut fibre.

Wet coconut fibre weight	1.94 kg
Coconut fibre weight after 5 days sun dried	0.515 kg
Coconut fibre weight after 5 h oven dried at 45 °C	0.448 kg
W_m after 5 days sun dried	73.4%
W_m after 5 h oven dried at 45°	13.0%
W_m to constant mass	3.04%

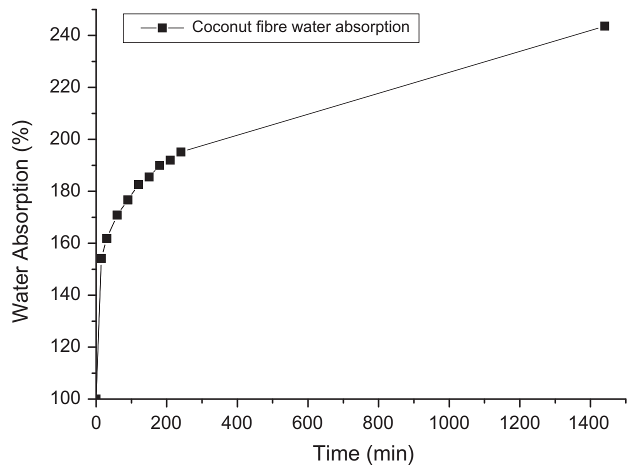

Fig. 11. Water absorption of coconut fibre used in this study.

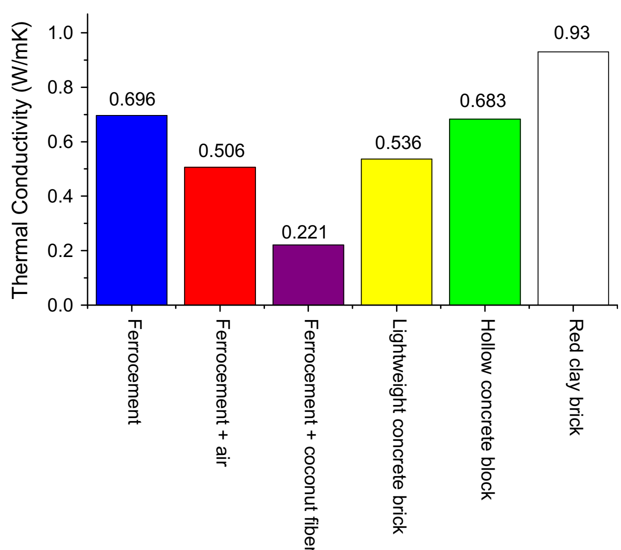

Fig. 12. Thermal conductivity results.

W/m K) and ferrocement panels with air substituting coconut fibre (0.506 W/m K)).

Fig. 13 also indicates that coconut fibre loading content (low, medium and high) corresponding to 2.6 kg, 3.15 kg and 5.76 kg respectively, has some influence on thermal conductivity. Increasing coconut fibre loading from low to medium means a reduction in thermal conductivity from 0.313 to 0.233 W/m K.

A further increase of coconut fibre from medium to high content means a thermal conductivity reduction from 0.233 to 0.221 W/m K. This indicates that a further increase in coconut fibre loading from this point on may provide little thermal conductivity reduction. Results suggest that coconut fibre form insulating chains

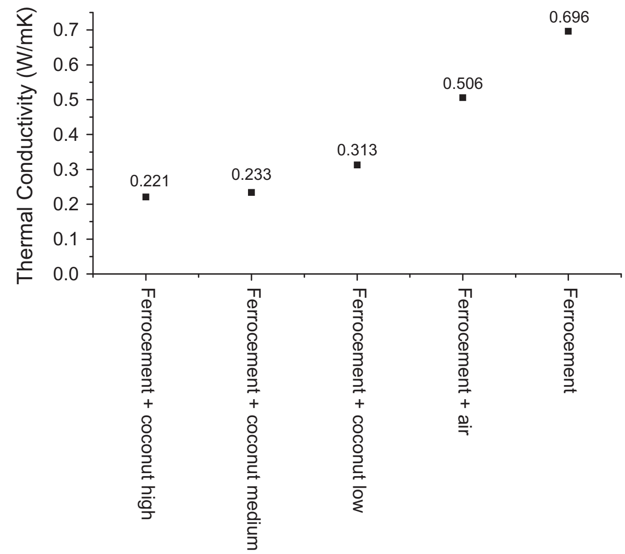

Fig. 13. Coconut fibre loading effect on thermal conductivity of ferrocement sandwich panels.

and as the fibre loading content increases, the chance of formation of fibre insulating chains increases and air space in-between ferrocement panels is less. As a consequence, a higher thermal gradient is measured and since Fourier's law indicate that this is inversely proportional to thermal conductivity, then a lower thermal conductivity value is obtained.

3.3. Cost of panel walls

Direct cost by square metre in US dollars for the panel walls under study is determined according to Mexican market and exchange rate (14.24 Mexican pesos/dollar) of the day. It is worth of mention that the cost associated to all materials used to build the panel walls are considered, including mortar rendering, man labour and necessary equipment. For the sake of brevity a summary is shown in Table 6.

Table 6
Cost analysis for panel walls tested.

Panel wall type	Remarks	Unite price ($US/m^2)
Lightweight concrete brick	52 lightweight concrete bricks (12 × 7 × 24 cm), mortar rendered with mixture cement:sand (1:5), cost includes labour and equipment needed	$ 19.78
Hollow concrete block	13 hollow concrete blocks (20 × 10 × 40 cm), mortar rendered with mixture cement:sand (1:5), cost includes labour and equipment needed	$ 17.84
Red clay brick	64 annealed red clay bricks (7 × 14 × 28 cm), mortar rendered with mixture cement:sand (1:5), cost includes labour and equipment needed	$ 23.46
Ferrocement + coconut fibre (sandwich type)	Two ferrocement panels (25 cm tic each) filled with coconut fibre, two sheets of electrowelded mesh 6*6–10*10, two sheets of expanded metal gauge 26, annealed wire rods 9.5 mm (3/8″), mortar rendered with mixture cement:sand (1:3), cost includes labour and equipment needed	$ 20.44

Results indicate that the most expensive option is a panel wall made of red clay brick while the cheapest option is a panel wall of lightweight concrete brick. Even though coconut fibre filled ferrocement panel walls in sandwich configuration is not the cheapest option it still must be considered since it provides better thermal comfort at a competitive price.

4. Conclusions

The work presented in this paper is limited to measure thermal conductivity on ferrocement sandwich type panel wall components filled with coconut fibre and compare its performance with component panel walls made of typical building materials in southern Mexico. From the results of this study, the following main conclusions can be drawn:

- Coconut fibre filled ferrocement panels can be used as insulating material for house living with lower thermal conductivity than typical building materials used in southern Mexico such as lightweight concrete brick, hollow concrete block and red clay brick panel walls.
- A simple and systematic procedure of making ferrocement filled with coconut fibre as sandwiched panels is presented.
- As fibre loading content of coconut filled ferrocement panels is raised, thermal conductivity is reduced down to a certain limit.
- The coconut fibre is an ecologically friendly and sustainable option to build roofs and panels in hot tropical weather.

It is important to mention that thermal conductivity values reported in the literature for building materials mostly do not agree well with their thermal performance working as panel walls. Thus, thermal conductivity values of component walls reported in this paper become more valuable. Undergoing work is focused on bioclimatic design and thermophysical behaviour of roofing made of ferrocement sandwich type configuration filled with coconut fibre to be used for thermal comfort at schools and homes in Puerto Escondido Oaxaca, Mexico. These results will be presented in a future paper.

Acknowledgements

Authors acknowledge National Council for Science and Technology (Conacyt), Secretary of Public Education (SEP) and CIIDIR-IPN for the financial support given for this research.

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