Paper Nº548: Heat Flux Measurements and Indoor Temperatures in Wood-based Test Cells

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Abstract

In 2007 the Brazilian housing deficit encompassed 7.223 million units. The greatest part of this deficit is located in urban areas and in the northeastern and southeastern regions of the country. On the other hand, Brazil has a high agricultural and foresting potential. The adequate use of wood-based panels as building elements could contribute to rationally take advantage of such potential, as wood is a renewable material and a possible alternative to meet the huge demand for new homes. The purpose of the present paper is to analyze the heat flux obtained through different wood-based panels of small-scale test cells of 1m×1m×1m of internal volume in Curitiba, Brazil, characterized by a subtropical climate with high daily and annual amplitudes of the air temperature. Altogether five different wood-based test cells were built, which indoor air temperatures were monitored during winter and summer periods: wood-cement panel; “Wall” panel; plywood; agglomerated wood panel and OSB panel. Reference material for comparisons was a prototype made with ordinary ceramic bricks, plastered on both sides. Air temperature measurements were carried out with data-loggers, heat flux plates were attached to the north facade of each test cell, while solar radiation was measured with an experimental solarimeter.

Key words: Heat flux measurements, wood panels, thermal performance.

1. Introduction

A whole range of issues should be considered when planning adequate housing for the low-income population, starting with the appropriate siting of the building, the definition of the building system itself and its construction steps and, finally, with the evaluation of the finished building (pre- and post-occupancy evaluations). In tropical and subtropical climates, the thermal performance evaluation of low-cost dwellings should be mainly related to the optimization of indoor comfort conditions, as HVAC systems are very rarely employed. Nevertheless, from the financial point of view, the improvement of thermal comfort conditions in low-cost housing should not result in substantial increases in the final building costs.

Concerning the existing Brazilian deficit of about 7 million housing units, the need to redefine low-cost housing policies has lead to several research projects throughout the last decades, aimed at the evaluation of building systems for the low-income population. According to the *Ministério das Cidades*, in 2007 the Brazilian housing deficit encompassed 7.223 million units. The greatest part of this deficit is located in urban areas and in the northeastern and southeastern regions of the country. Over 10 million units of existing low-cost dwellings require basic infrastructure and about 84% of the families earn up to three minimum wages (about US$ 700 a month).

On the other hand, Brazil has a high agricultural and foresting potential. Exotic forests such as *Pinus ssp* and *Eucalyptus ssp* adapted well to tropical and subtropical climatic conditions, which characterize the Brazilian territory, mainly due to advanced foresting technologies. As a result, mainly pine and eucalyptus are grown (93% of the harvest). Productivity in this field may reach up to ten times the output of temperate climates [1].

In this scenario, wood-based construction panels can offer several advantages such as: cost reduction, reutilization of wood wastes (from lumber industries, for example), possibility of having lightweight constructions (suitable to many climatic regions in Brazil), possibility of a straightforward assembly in low-cost housing projects, among other factors.

The purpose of the present paper is to analyze the heat flux obtained through different wood and plywood panels of small-scale test cells of 1m×1m×1m of internal volume. Altogether five different wood and plywood test cells were built, which indoor air temperatures were monitored during the winter and spring, 2007: wood-cement panel; “Wall” panel; plywood; agglomerated wood panel and OSB panel (Oriented Strand Board). Reference material for comparisons was a prototype made with ordinary ceramic bricks, plastered on both sides. Air temperature measurements were carried out with data-loggers, heat flux plates were attached to the north facade of each test cell, while solar radiation was measured with an experimental solarimeter, which is explained in Section 5.

2. Evaluated panels

The concept of wood-cement panels is to take advantage of benefiting features both of wood and cement [2]. In this case, resistance and stiffness can be enhanced by the composite to a higher degree than in separate components, along with a reduced mass density. Cement will transmit loads to wood particles at the same time protecting those from ambient exposure. Wood, by its turn, will enhance tensile strength, contributing to reduced mass density and costs. Specially as wall material, cement-wood panels can be a substitute to conventional masonry in building elements not subjected to loads [3]. The analyzed panels consist of a mix of cement, water and *Pinus ssp* wood flakes with a cement-wood ratio of 4/1. Due to limitations of the press machine (SIEMPELKAMP – 40kg.cm^{-2}), the desired wall surface of 1m² was modulated in four 50cm × 50cm small panels with an average thickness of 17mm, which were later glued together with Purweld 645.

The "WALL" panel is produced in Brazil by Eternit (www.eternit.com.br). It consists of a five-layered lightweight sandwich element to be used in facades, partition walls etc. The composition of the panels used in the prototype is as follows: internal and external reinforced cement layers 3mm thick, two 3mm thick wood sheets and a 28mm thick laminated wood filling. The industrialization of such panels occurs at high temperatures. The manufacturer informs that the panel has improved thermal and acoustic properties, when compared to conventional wood-based panels. Eternit donated "Wall" panels for thermal evaluations. The analyzed panels had originally the dimensions 120cm × 210cm and were cut to fit a similar modulation of the wood-cement (four 50cm × 50cm small panels with an average thickness of 40mm, which were later glued together to form the 1m² surface area).

According to Iwakiri [4], agglomerated panels are created from small wood particles, which are bonded together with urea-formaldehyde resin based adhesives. Such particles are randomly distributed and the panel is consolidated under high pressure and temperature. Normally the panel is composed of three layers, the external layers having the smallest particles, which will guarantee a better panel finishing. The inner layer will have a bigger particle size, which by its turn will add improved resistance to the composite. The wood panels and products manufacturer Berneck (www.berneck.com.br) donated the agglomerated panels for thermal evaluations. Similarly to both the wood-cement and the "Wall" panels, the original dimensions of 185cm × 220cm were cut to fit the modulation of four 50cm × 50cm small panels (average thickness of 15mm, which were later glued together to form the 1m² surface area).

Plywood is manufactured with an odd number of layers, each layer consisting of one or more sheets of veneer (thin sheets of wood), which are glued together [5]. The plywood panel is generally hot-pressed in hydraulic presses. The application of both heat and pressure, as in the case of agglomerated panels, will cure the glue in a matter of minutes. The analyzed panel is for external use, consisting of seven layers, glued with a synthetic resin, based on a phenol-formaldehyde resin. The Brazilian Association of Mechanically Processed Wood Industry (*Associação Brasileira da Indústria da Madeira Processada Mecanicamente – ABIMCI*) donated the plywood panels for thermal evaluations. Similarly to the aforementioned panels, the original dimensions of 160cm × 220cm were cut to fit the modulation of four 50cm × 50cm small panels (average thickness of 15mm, which were later glued together to form the 1m² surface area).

OSB panels are fabricated in a cross-oriented pattern similar to plywood. They are composed of thin rectangular-shaped wood strands arranged in layers at right angles to each other, which are laid into mats to form a panel [6]. The mat pattern offers structural strength to the panel. OSB panel are bonded together with waterproof adhesive and, similarly to both the agglomerated wood panel and the plywood, heat-pressed. The wood panel manufacturer Masisa (www.masisa.com) donated the OSB panels for thermal evaluations. The original dimensions of 122cm × 244cm were cut to fit the modulation of four 50cm × 50cm small panels (average thickness of 15mm, which were later glued together to form the 1m² surface area).

3. Preparation of the test cells

For the heat flux measurements and also for the assessment of indoor temperatures in a small-scale prototype, five different test cells were built for each panel configuration, each having an internal volume of 1m³. Reference for comparisons was a test cell, made of hollow ceramic bricks, plastered on both sides and white-painted. All test cells had an internal volume of 1m³, with 1m² wall panels on each facade.

All test cells were sited, aligned according to an east-west axis. Tetra Pak milk packages were opened and sewn together, in order to form an insulation sheet underneath the roof of each test cell, which consisted of 6mm fiber cement tiles. Test cells were white-painted, as a further means of standardizing, so that differences in thermal behavior would be exclusively related to the employed wall panel.

4. Heat flux and indoor temperature measurements – equipment and procedures

The equipment used for determining heat flux through each panel configuration consisted of two copper constantan heat flux plates, developed at the *Laboratório de Meios Porosos e Propriedades Físicas de Materiais* – LMPT, Universidade Federal de Santa Catarina, Brazil. Each plate was attached to the inside and to the outside surface of the panel, respectively, and connected to a PC. The external plate was painted white.

The internal and external surface temperature of each panel was measured with thermocouples and also with HOBO H08 dataloggers, for comparisons. Styrofoam circles were used on top of the thermocouples and the HOBO temperature sensors to avoid convective and radiative heat exchange.

A 'solarimeter' was used in order to estimate global radiation (sky, solar and reflected from the ground) striking the wall surface, whereas another solarimeter was placed horizontally to estimate global horizontal radiation during the experiment. The concept of the solarimeter is presented in Cheng et al. [7]. It is based on the assumption that differences between the temperature measured on a black aluminum plate and the concurrent air temperature closely correlate to the intensity of solar radiation striking the surface. Both solarimeters were built and field comparisons were made between estimated radiation from solarimeters and measured radiation data from a standard Pyranometer at the local meteorological station.

Externally, ambient temperature was measured with a HOBO H08 temperature logger, which was placed inside a small PVC cylinder approximately 15cm in diameter and 40cm long. The PVC cylinder served as a naturally ventilated solar radiation shield and was supported vertically. Additionally, in order to avoid long wave radiation gains, the logger itself was covered on the outside with aluminium foil. Inside the test cells, air temperature was measured with HOBO H08 temperature loggers, which were enclosed in a plastic cup to prevent possible moisture infiltrations in the logger. Experimental set-up is shown in Figures 1-3.

Local soil albedo (grass surface) was estimated to be 0.25-0.30, by using both solarimeters facing the sky (upwards) and the ground (downwards), respectively, during a series of measurements under clear-sky conditions in summer (March 19-25, 2008).

Indoor temperature measurements were carried out during two 6-days periods: in winter, from August 9 through August 14, 2007; and in summer, from March 3 through March 8, 2008. Data loggers were hung in the geometric center of each test cell and had a recording time of five minutes.

Figure 1: Set-up: HOBO data logger, Heat flux plate, thermocouples and solarimeter.

Figure 2: Set-up: Ambient temperature measurements and set of test cells.

Figure 3: Internal temperature measurements with HOBO logger enclosed in a plastic cup.

Measured data were then sampled hourly. The purpose of the indoor temperature monitoring was to compare the thermal performance of the wood-based panels to that of the most common building material used in Brazilian low-cost housing, which is the hollow ceramic brick, plastered on both sides, by means of indoor temperature measurements in small test cells of identical geometric features and with the same roofing system.

The heat flux measurements in each wall panel took place during a series of clear-sky days in spring 2007: wood-cement (November 1); OSB (November 10); plywood (November 21);

agglomerated wood (November 22) and "Wall" panel (November 23).

On those days, the necessary equipment set was installed between 7 and 8am, as it had been observed, during the temperature monitoring period in winter, that around this time of the day indoor and outdoor temperatures in all test cells tend to approximate (after that time frame, outdoor temperatures will tend to rise more sharply than indoors). Heat flux and temperature data had a recording time of five minutes, with a sampling time of one hour. After installment, only measurements taken between 9am and 2pm were considered for analysis. Those measurements allowed us to estimate the average thermal resistance of each panel under normal use conditions (naturally exposed) on a relatively sunny day. The maximum global horizontal radiation during the monitored days ranged 850-1100W.m^{-2} and on the wall surface 270-620W.m^{-2}.

5. Climatic conditions

With regard to the climate of Curitiba (25º31'S, 917m elevation), average temperatures in summer lie between 17 and 20ºC and in winter between 12 and 14ºC [8]. Annual average temperature is about 16ºC. Daily amplitudes may vary between 0,5 and 25,7K, and the average swing is 10,5K. Absolute humidity ranges between about 4 to 18 g.kg^{-1}, with an average of about 11 g.kg^{-1}. Annual precipitation is around 1600mm.

6. Results and Discussion

From the heat flux measurements, the resulting thermal resistance can be obtained from the ratio between surface temperature variations inside and outside the panel and the heat flux through the panel. Thermal conductivity is then calculated by dividing average thickness (measured) by the calculated thermal resistance. Figure 4 exemplifies the thermal resistance for the wood-cement panel, in five minutes intervals.

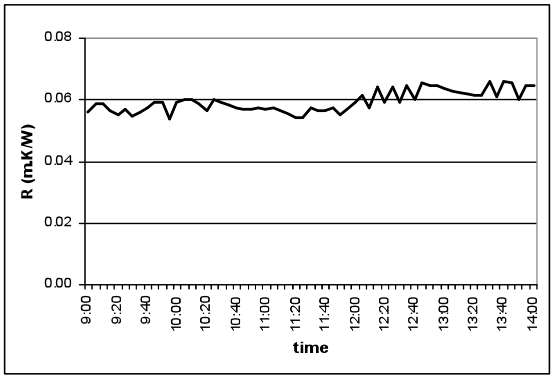

Figure 4: Thermal resistance of the wood-cement panel in m².K.W^{-1}.

A relatively stable pattern is observed in the graph (coefficient of variation CV of 5%), showing an average thermal resistance of 0.059m².K.W^{-1} (standard deviation 0.003), which yields a thermal conductivity of 0.29W.m^{-1}.K^{-1} for the panel thickness of 17mm. This value is higher than average conductivity for wood-cement boards (Table 1), according to the Brazilian Thermal Performance Norm [9]. However the reference value refers to low-density wood-cement mixes. A higher density in this case will be responsible for an increased thermal conductivity. Comparing obtained conductivity to that of high-density wood boards (*Pinus ssp*) and to normal concrete, it lies within a reasonable range. Table 1 also presents results for the other panel configurations: "Wall" panel; plywood panel; agglomerated wood panel and OSB panel.

Table 1: Measured thermal properties and standard values.

Material	**Average Density [kg.m^{-3}]**	**Density [kg.m^{-3}] Reference**	**Reference Conductivity [W.m^{-1}.K^{-1}]**	**Conductivity (measured) [W.m^{-1}.K^{-1}]**
Wood-cement	1350	450-550	0,15	0,29
"Wall" panel	761	850-1000	0,65*	0,64
Plywood	561	450-550	0,15	0,13
Agglomerated wood	647	650-750	0,17	0,14
OSB	568	550-650	0,14	0,11

*Reference case: cement boards with mass density 1400-1800kg/m.

It should be stressed that heat flux measurements were carried out by naturally exposing the wood-based panels throughout quasi-clear sky days. Limitations of the method are due to variations in the heat flux through the panels and to the non-simultaneous monitoring of the panels. Nevertheless, results are very close to reference values.

The air temperatures measured inside the test cells, as compared to concurrent results in a test cell built with the most common external wall typology in Brazil (9cm×14cm×19cm hollow ceramic bricks, plastered on both sides, white painted), give us the expected thermal behavior of wood -based building systems, relative to the conventional low-cost house with brick masonry. Indoor and outdoor air temperatures during the winter and summer monitoring periods are shown in Figures 5 and 6.

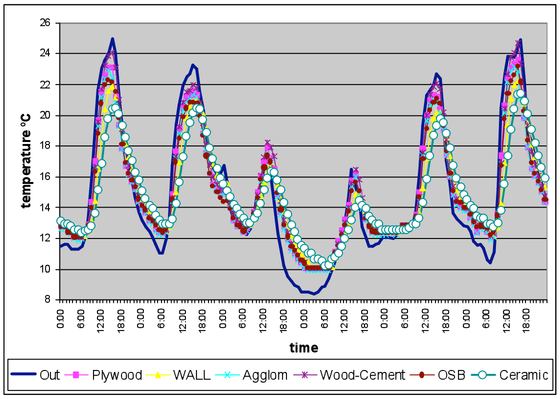

Figure 5: Indoor and outdoor temperatures with reference test cell – winter (August 9-14).

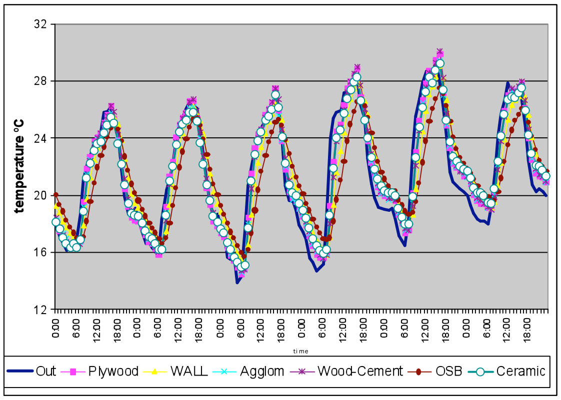

Figure 6: Indoor and outdoor temperatures with reference test cell – summer (March 3-8).

The two monitoring periods presented the typical diurnal temperature swing of the local climate, which is generally higher on clear-sky days (a slightly higher swing of nearly 12 degrees was observed during the summer monitoring period, due to mostly sunny conditions). The average daily indoor temperature swing for the two monitoring periods and for each test cell showed a relatively consistent pattern (Figure 7).

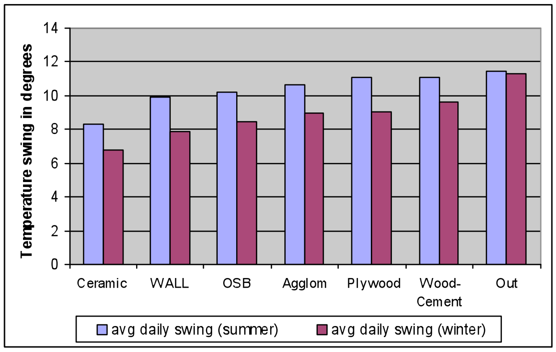

Figure 7: Average daily temperature swing in all test cells – winter and summer.

In general, the evaluated test cells showed indoor maximum temperatures very close to outdoors, especially with regard to the times of the maximum daily temperature (with almost no delay). It should be stressed that the resolution of HOBO loggers is 0.4ºC, although in this case hourly data is averaged from 12 readings. In contrast, indoor temperatures in the test cell of brick masonry have a slight time lag relative to outdoors, as a direct effect of its higher thermal mass.

Table 2 presents some characteristics of indoor and outdoor temperatures for all test cells, also showing the relation between the indoor and the outdoor daily temperature swing. Such 'daily swing relation' can be meaningful for evaluating the thermal performance of buildings in climates with high daily fluctuations. Once indoor temperature conditions can be stabilized around a given range, it is matter of adjusting it (by mechanical means or passively, with solar gains or shading devices) to a comfortable temperature range. A low daily swing relation means that the building is capable of narrowing this range, relative to outdoors.

Table 2: Indoor and outdoor temperatures (summary).

WINTER RESULTS

	Daily minimum (average in ºC)	Daily maximum (average in ºC)	Average daily temperature swing	**Daily swing relation (DT in/DT out)**
Outdoors	*10.3*	*21.5*	*11.3*	**-**
Wood-cement	*11.6*	*21.3*	*9.6*	***0.85***
Wall	*11.7*	*19.5*	*7.8*	***0.69***
Plywood	*11.6*	*20.6*	*9.0*	***0.80***
Agglomerated	*11.4*	*20.4*	*8.9*	***0.79***
OSB	*11.6*	*20.1*	*8.4*	***0.75***
Ceramic	*12.0*	*18.8*	*6.8*	***0.60***

SUMMER RESULTS

	Daily minimum (average in ºC)	Daily maximum (average in ºC)	Average daily temperature swing	**Daily swing relation (DT in/DT out)**
Outdoors	*16.1*	*27.6*	*11.5*	**-**
Wood-cement	*16.9*	*28.0*	*11.1*	***0.96***
Wall	*17.3*	*27.2*	*9.9*	***0.87***
Plywood	*16.8*	*27.9*	*11.1*	***0.97***
Agglomerated	*16.9*	*27.5*	*10.6*	***0.92***
OSB	*17.2*	*27.3*	*10.2*	***0.88***
Ceramic	*17.7*	*26.0*	*8.3*	***0.72***

It can be noticed that among the wood-based test cells especially the test cell composed of “Wall” panels present the lowest daily swing relation. This relation is in winter relatively close to that of the ceramic bricks test cell. In all cases, daily minimum temperatures are higher than outdoors, but lower than the reference test cell. This factor is strongly related to the thermal resistances of the evaluated panels, which are ranging between 0.06 to 0.14 $m^2.K.W^{-1}$ corresponding to about a quarter to one half of that of walls with hollow ceramic bricks, with plaster (around 0.2-0.3 $m^2.K.W^{-1}$). Regarding the fully wood-based panels (except the “Wall” panel, which is a composite with reinforced cement sheets), Figure 8 shows the high correlation between the temperature swing relation and the thermal resistance.

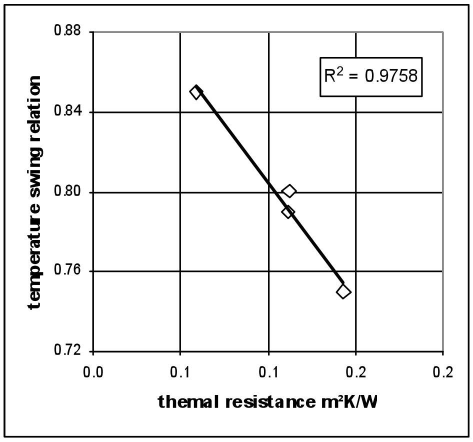

Figure 8: Correlation between temperature swing relation and thermal resistance for the wood-based panels.

7. Conclusions

This paper presented thermophysical properties and a thermal analysis of wood-based panels, which were assembled together as a 1m³ test cell for comparative analysis. The results of the thermal analysis suggest that in all situations a single panel configuration yields a rather poor thermal performance, relative to the most common wall material employed in low-cost houses in Brazil (hollow ceramic bricks, plastered on both sides). Nevertheless, a double panel configuration could achieve a thermal performance comparable to that of the reference case.

A follow-up of the present study has the purpose of evaluating thermal comfort in a typical low-cost house (full scale), by means of computer simulations, using single and double wood-based panel configurations.

8. Acknowledgements

We wish to thank the wood panel manufacturers Eternit, Berneck, ABIMCI and Masisa for the donation of panels for analysis and the staff and team of researchers of the Programa de Pós-graduação em Engenharia Florestal of the Federal University of Paraná in Curitiba.

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