Experimental and numerical investigation of roof insulation on cooling loads of a typical southern clay and straw house

David Y.K. Toguyeni[a], Ousmane Coulibaly[a], Abdoulaye Ouedraogo[b], Jean Koulidiati[a], Yvan Dutil[c]*, Daniel R. Rousse[c]

[a] UO-UFR/SEA –Lab.phys.chimie de l'environnement (LPCE) , 03 BP 7021 Ouagadougou 03, Burkina Faso
[b] UO-UFR/SEA –Lab.énergie thermique et renouvelable (LETRE), 03 BP 7021 Ouagadougou 03, Burkina Faso
[c] Chaire de recherche industrielle en technologie de l'énergie et efficacité énergétique (t3e).
École de Technologie Supérieure, Université du Québec, 1100, rue Notre-Dame, ouest, Montréal, Canada

Abstract

This paper presents an investigation of the influence of local insulated roofing materials used in Burkina Faso on air conditioning loads of typical individual houses located in dry tropical climates. The walls are made of a composite clay-straw mixture whereas the insulated materials are made of red wood, white wood, and two assembled insulated panels. The thermophysical properties of the insulating materials as well as the clay-straw composite have been investigated, with a genuinely designed experimental apparatus based on the hot plate method. The values of the thermophysical properties obtained are in the same range as those published in the literature. Afterward, the house has been modeled using TRNSYS together with the climatic data of Ouagadougou. This simulation shows that the clay-straw mixture reduces the air conditioning load by about 8% compared to clay walled houses. As for the roof, the study indicates the influence of the insulated materials on the air conditioning load. Hence, a 1.5 cm thick insulator made of red wood induces a saving of energy about 6.2% and 12.1% for an insulation panel made of natural fiber and a lime-cement mixture on the air conditioning load.

Keywords: hot plate method, roof influence, clay-straw mixture, TRNSYS model, air conditioning load, dry tropical climate

1. Introduction

In Burkina Faso, the buildings were designed until today without any consideration for their energy efficiency. This results in high cooling loads for owners unacquainted with the proper use of energy. Thus, the energy consumption of public buildings, including the operation of air conditioning units, is estimated at 30 GWh/yr. This corresponds to a financial cost estimated at 3.4 billion francs CFA/yr or 5.2 million euros (DGE, 2003) [1]. These financial charges are very important for a country such as Burkina Faso for which the GNG/cap is low. With the expected larger air conditioning market penetration combined with the increase in temperature due to climate change [2], this financial burden will grow further if nothing is done to mitigate it. To further illustrate the importance of this issue, cooling loads in Bukina Faso are of the same order of magnitude as the heating loads in Canada (~4500 heating degree-day in Canada vs ~3900 cooling degree-day in Burkina Faso [3]) Thus, promotion of building insulation materials to improve energy efficiency in housing is essential.

As part of its Programme International de Soutien à la Maîtrise de l'Énergie (PRISME), l'Institut de l'énergie et de l'environnement de la Francophonie (IEPF), a subsidiary body of the Agence Intergouvernementale de la Francophonie, provided recommendations for improving energy efficiency in buildings in tropical regions. These studies [4,5] have identified potential savings on energy costs that varies from country to country from 30 to 45%. According to these studies, most of the potential energy savings can be found in air conditioning installations that represent more than 60% of exploitable negawatt sources. In [4], the Institute reported that, in tropical climates, the roof is responsible for approximately 30% of heat gain inside the building. Recently, work by Ouédrago et al. [6] have focused on the design of a bioclimatic roof to provide passive cooling optimal habitat in Ouagadougou, the capital of Burkina Faso that has a hot and dry tropical climate.

Given the fact that clay is the most available and widely used building material by the average household in Burkina Faso, this research was conducted on the influence of straw on the insulating properties of clay based construction materials. To alleviate the issue of the weak mechanical strength of clay, the traditional

[*] Corresponding author. Tel.: +14186532910 E-mail: yvan@t3e.info

technique is to make a concrete base and add slender mortar surface coatings to the wall. In addition, it should be noted that the addition of fibers, in this case straw, improves the overall mechanical properties of the clay [7-9]. It is also recognized that the clay has a high thermal inertia. It is this property that imposes the use of dynamic building simulation codes as the response time in storage lags the heat load from the environment.

In the present study, the local materials that can be used as roof insulation were also examined. These are the red wood and white wood, which are two tropical species known also respectively as Wa wa Samba (*Triplochiton scleroxylon*) and African mahogany (*Khaya ivorensis*). Two insulating panels 1 and 2 made from natural fibers of Burkina Faso (*Hibiscus sabdariffa*) and lime-cement mixtures were also considered as potential alternatives.

2. Characterization of samples by the method of hot plate

Insulation material thermophysical properties were determined using the hot plate method [10]. In this method, a uniform heat flux is imposed at the interface of two samples of this symmetrical arrangement and along the extension in the direction perpendicular to the interface makes the problem one-dimensional at mid-height. The samples are then treated as an infinite medium in the y-direction (height) when the ratio of length to the thickness of the heating element is greater than 20. Moreover, the side faces of the two samples are isolated such that the transfer can be considered unidirectional. The temperature response over time is measured with J-type thermocouples. The method is reviewed in details in prior work [11].

In total six materials were tested: two wood types (white and red), two insulating panels, the clay and the straw-clay composite wall material. Note that the white wood and red are two tropical species available locally. As for the insulating panels 1 and 2, they were made by Jean Hugues Thomassin from l'École Supérieure des Ingénieurs de Poitiers from natural fibers of Burkina Faso (Hibiscus sabdariffa) and lime-cement mixtures. These materials were sent to the Laboratoire de physique et de chimie de l'environnement for their thermal characterization. It should be noted that parallel research conducted in the same laboratory allowed comparison of the thermophysical properties of the panels from alternate experimental methods and that use herein. The relative differences are in the order of 8% [12].

Table 1, reports the thermophysical properties of materials that were extracted from the measurements and determined by the method described above. These results can be compared with those of Izard [13]. However, the adopted properties of mortar coating, concrete and asphalt are taken from the literature [5].

It should be noted that the heat capacity of the clay walls has been greatly enhanced by the presence of straw. This reflects the fact that straw is strongly hydrophilic. Tests were carried out in summer when moisture levels in air are very high (RH ≈ 95%). In consequence, water content (with a high heat capacity) of the straw-clay composite is increased. Given the particular composition of the mixture, it is not really possible to make a direct comparison with previous studies [7-9,14]. However, the observed properties, especially thermal conductivity, are of the same order of magnitude.

Table 1. Materials properties

Material	Thermal Conductivity $[Wm^{-1} K^{-1}]$	Mass volumic $[kg/m^3]$	Thermal capacity $[Jkg^{-1}K^{-1}]$
Clay	2.12	2026	658
Straw Clay	0.53	1796	2202
White wood	0.22	359	772
Red wood	0.31	595	830
Panel 1	0.20	386	455
Panel 2	0.13	349	450

3. Modelling with TRNSYS 16.1

To illustrate the impact of the inclusion of local materials in the building envelope on the cooling loads, a typical clay-straw house has been modeled in TRNSYS, based on the works of Al-Ajmi et al. [15], Annabi et al. [16], and Diez-Webster et al. [17].

3.1 Building description

The model implemented in TRNSYS 16.1 [18] is that of a standard house for residential use with a floor area of 50.02 m² with a south facing facade of 9.30 m wide by 3 m high. It is a standard one story building involving two bedrooms, a living room, and a bathroom. It was built under the project 10 000 housing units by CEntre de GEstion des CItés (CEGECI) in Ouagadougou, Burkina Faso. The building configuration is schematically depicted in Figure 1.

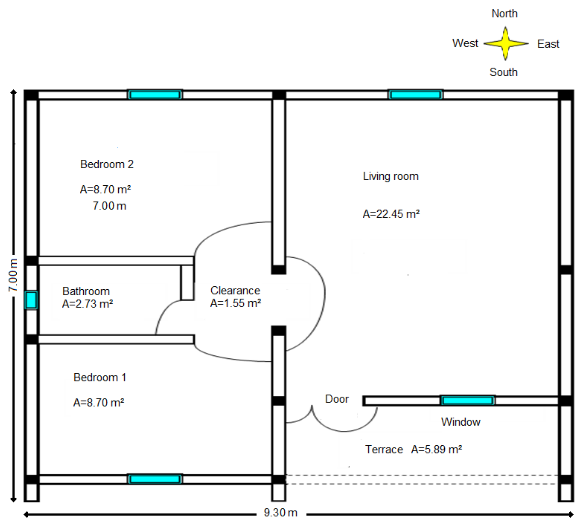

Fig.1: Floor plan of the investigated building with orientation, dimensions, and surface areas.

The walls of the building are assumed to be made of clay or clay-coated straw with a mortar coating inside and outside. The core of the wall is made of 20 cm thick clay, two mortar coatings 2.5 cm thick are added on each side of the core. A white paint is used on the inside and dark yellow paint on the outside. For aesthetics purposes, a clay coating is often used inside this type of habitat instead of concrete. That is why simulations with this type of inner coating were conducted for comparison with the interior coating made of mortar.

The floor is a 15 cm thick concrete slab. The doors are made of wood within a double steel frame. The windows are made of a single 4 mm thick glazing within a steel frame. Window conductance without the boundary layer resistance is equal to 5.7 $Wm^{-2}K^{-1}$ and solar heat gain coefficient is equal to 0.85. The roof concrete slab is 22 cm thick and covered with an asphalt sealing. Effects of red wood, white wood and insulation panels 1 and 2 on the cooling loads are analyzed.

This building has a considerable thermal mass which will lead to a damping of the amplitudes of internal temperature fluctuations with a phase shift of the latter compared to those from outside. This situation tends to increase the thermal comfort for the occupant, which in turn reduces the cooling needs. This situation imposes the use of a dynamic model to correctly describe the thermal behavior.

The simulations are performed over a complete year with a time step of 1 hour (0 to 8760 h) using a typical multizone building (here a Type 56 building, characteristic of buildings found in the area). To get a more refined modeling of the habitat with respect to its real use, the entire space has been divided it into six areas described in TRNSYS (that is Living room, Terrace; Clearance; Bedroom 1 and 2; Bathroom). The meteorological data METEONORM for Ouagadougou proposed in version 16.1 of TRNSYS have been used for this simulation.

3.2 Internal charges and air conditioning system

According to the bioclimatic diagram of Givoni [19], the comfort zone lies between temperatures ranging from 20 to 27 °C, but the upper limit decreases, when the relative humidity exceeds 50% down to 24 °C. Another study conducted in the Ivory Coast showed that in dry tropical climates, interior comfort conditions are obtained for a dry bulb temperature of 26.5 °C and a relative humidity of 50% [16]. Hence, here, the thermal comfort zone is consequently defined by a dry bulb temperature between 26 and 27°C and a relative humidity between 50 and 55%. This condition is then consistent with the study of Givoni [19].

For the purpose of simulations, the air conditioner is assumed to be turned on when the indoor temperature rises above 26°C with a relative humidity of 50%. Ventilation and infiltration are set at one volume per hour. Due to their compact nature, the walls are naturally airtight. Scenarios for weekdays and weekend uses for the bedrooms and living room have been created. The number of occupants is four in the living room and two in each bedroom. For lighting, a fluorescent lamp whose power is 8 W is used in each room [5]. The living room holds a television (60 W) and a refrigerator (70 W) with a duty cycle of 100% and a DVD player (150 W) with load factor of 40% [5]. Cooking does not bring additional charges as it is normally done outdoors. These are standard figures for such a unit in Ouagadougou.

4.Simulation results and discussion

Figure 2 compares the monthly thermal load of the clay wall to a wall made with a clay-straw composite both involving a non insulated roof. It presents the total heat load on the building in kWh with respect to the time of the year (here in months). As expected, the wall of clay-straw induces less energy consumption than the wall made entirely of clay; the relative difference being 7% over the year. Moreover, this difference is larger for the warmer months, March to June (see Fig. 5), which will impact the peak power consumption. This might allow using a smaller cooling system, bringing additional savings.

Since the simulation results demonstrate that a building envelope made of a 3% clay-straw mix is more efficient than one involving pure clay, the former was investigated to obtain the values of global heat gain for the whole year for various wall and roof configurations. In addition, interior coating of mortar improves only slightly the performance of the building envelope compared to a coating of clay. Since this is the most efficient configuration, we will use it for our subsequent analyses.

Figures 3 shows the monthly thermal loads in the building for a clay-straw wall while the external surface is coated with a thin concrete layer and the interior involves an extra thin clay layer. The best roof insulation is obtained with insulation panel 2. For roof insulation 1.5 cm thick, changing from red wood to insulation panel 2 lowers expenses from 6.2% to 12.1%. Overall, energy consumption is reduced by 18.4% with inclusion of straw combined with a roof insulation made of panel 2 compared with the reference house with walls made of pure clay.

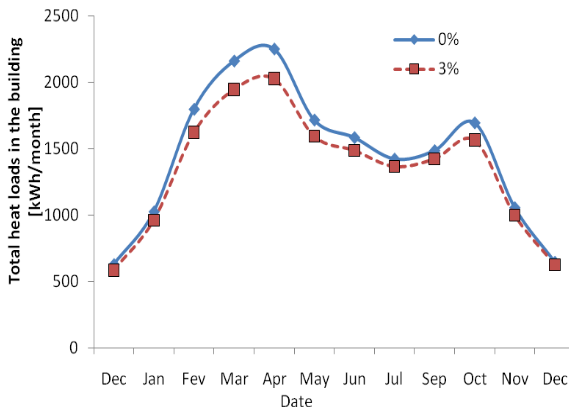

Fig 2: Impact of the addition of straw in wall on the thermal load.

In this case, the relative differences between the reference case (straw-clay and non-insulated roof) with clay internal coating and other cases vary between 6.8% and 13.1% for April and between 6.3% and 12.1% for the month of May. These values change to between 6.9% and 11.4% for April and between 5.4% and 10.4% for the month of May for the reference clay wall and non-insulated roof.

As expected, the months of April and May, the hottest of the year, (average maximum temperature of 41.8 °C and 41.6 °C, respectively) are those for which the overall heat gains are the largest and, consequently, the cooling loads are the greatest. It is also important to note that the solar flux is at its maximum in Ouagadougou during these two months.

A preliminary economic analysis indicates that the period of return on investment for adding insulation panel 2 is about 3 years while it turns out to be 5 years for the red wood roof. Under these circumstances, it would be advantageous to increase the thickness of the insulation to increase the net energy savings over the lifetime of the building.

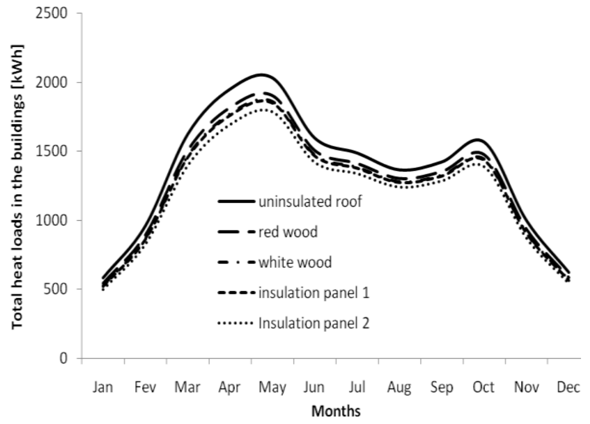

Fig.3 : Clay-straw wall , mortar external coating, clay internal coating

5. Conclusion

This paper presents a study aimed at estimating the influence of local materials used for roof insulation on cooling loads of a typical clay-straw house. At first, the thermophysical properties (conductivity, thermal effusivity, density) of these materials were determined using a hot plate method with an analysis of thermograms in steady and unsteady regimes. The results obtained, while not directly comparable, are in the same range as those reported in the literature.

In the second part of this work, TRNSYS simulations indicated that the clay-straw wall consumes an average 7% less energy than the standard clay wall on an annual basis. Then, the study highlights the influence of roof insulation on cooling loads. It has been shown that insulation only 1.5 cm thick can provide savings of up to 6.2% (red wood) to 12.1% (panel 2) on cooling loads. Finally, it indicates that differences in cooling loads due to the use of an interior clay coating in comparison with the concrete coating is negligible (0.24% on average). It has also been noted that the economic efficiency of insulation made from local materials is good, while further optimization should be explored. Researches are ongoing to determine the ideal clay-straw mix to minimize the cooling loads as an additional method to improve the overall insulation.

6. Future work

This research did not attempt to optimize the insulation thickness as other studies did [20-24]. This will now be considered as a natural extension of this work.

However, other avenues, potentially more promising, for reducing thermal loads need to be explored before. For example, using a white coating on the roof [25-26], or adding an air gap in walls and roof [23], using night ventilation [27] as well as improving thermal insulation of windows could be more cost effective.

In addition, in hot climates, there is the possibility of over-insulating a building, which traps the internal heat and accordingly, increases the cooling loads [28].

As a consequence, the optimization of the roof insulation will have to await the results of future studies on these approaches, since it must be part of an integrated analysis.

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