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Improving the Thermal Comfort of a Building by Adding a Layer of Straw over the High Floor

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Abstract

This document deals with the thermal characterization of a building with a layer of straw above the high floor. In the current environmental context, in Senegal, buildings are the biggest consumers of energy. This is due to the construction materials used. Almost of buildings in Senegal used concrete (cement + aggregates) as based material construction. Due to this, the buildings require air conditioning or artificial ventilation to ensure minimum comfort. In face of this situation, it becomes useful to propose methods for reducing this high energy consumption. In this work, we propose to add a layer of straw above the high floor of a building in Matam city (North Senegal). In this case, we designed and modeled one building of single room in which the walls are in briks and a concrete slab. A bale of straw is layered on this slab in order to determine its influence on the energy consumption of the building. This study shows that the straw has a strong influence on the energy consumption of a building and the slab + straw building is more energy efficient than the bare slab building.

Keywords

Thermal Comfort, Energy, Building, Straw

1. Introduction

The question of the rational use of energy has been imposed in recent years, with the aim of opposing the increase in its cost and the disastrous consequences on the environment. These energy and environmental challenges have motivated industrialized countries to consider seriously the issue. Many organizations, forums and panels are working on the energy and the importance of its control. Air conditioning systems consume large amounts of energy to ensure conditions of thermal comfort inside buildings. Thus, the reduction in the consumption of energy resources from fossil sources and the reduction in the rate of pollution in the air oblige us to create buildings, which provide us more thermal comfort without resorting to air conditioning, which consumes a lot of energy. Then the researchers investigate the problem of heat exchange between the premises and the environment. Insulation is one of the main axes of bioclimatic architecture; it simultaneously increases comfort and reduces air conditioning energy consumption. However, that is not all; insulation is also beneficial for the environment because, by reducing consumption, it conserves energy resources and limits greenhouse gas emissions. Thermal insulation is therefore attractive in terms of comfort, financial savings and environmental protection [1]. However, the absence of detailed data on thermo-physical properties can lead to operational anomalies. Our study aims to carry out a scientific review of a local material for building, to deal with these anxieties which have just been listed. We propose to layer straw, which is used as a building material in rural areas in particular, above the high floor.

2. Mathematical Model

The modeling of the thermal load in a confined space aims to predict mass and heat transfers from the outside to the inside of this space during the summer. There are thus three modes of heat transmission: conduction, convection and radiation [2]. Establishing the heat balance in a space consists of determining or evaluating all of the thermal loads to be removed for a 24-hour time base. The hourly load of the building is mainly a function of the following parameters: latitude, longitude, altitude, orientation, dry and wet ambient temperatures, atmospheric pressure, wind speed and direction, sunshine, the size of the shaded external surfaces, opacity of the walls, the thickness of the walls, the conductivity of the walls, of the occupants, the lighting, the infiltrations [3]. In this work, we are only interested in the contribution of heat flow through the slab. Whatever the regime (permanent or dynamic), we obtain it by the following relation:

$$\varphi = \frac{T_e - T_i}{R_{th}} \tag{1}$$

with

$$R_{th} = \frac{1}{h_i} + \sum_{j=1}^{n} \frac{e_j}{\lambda_j S} + \frac{1}{h_e} \tag{2}$$

In our study, we have two variants (**Figure 1** and **Figure 2**): concrete slab only and concrete slab with straw layer.

By applying relation (2) on the diagrams of **Figure 1** and **Figure 2**; we obtain respectively:

$$R_{th1} = \frac{1}{h_i} + \frac{e_{cs}}{\lambda_{cs} S} + \frac{1}{h_e} \tag{3}$$

and

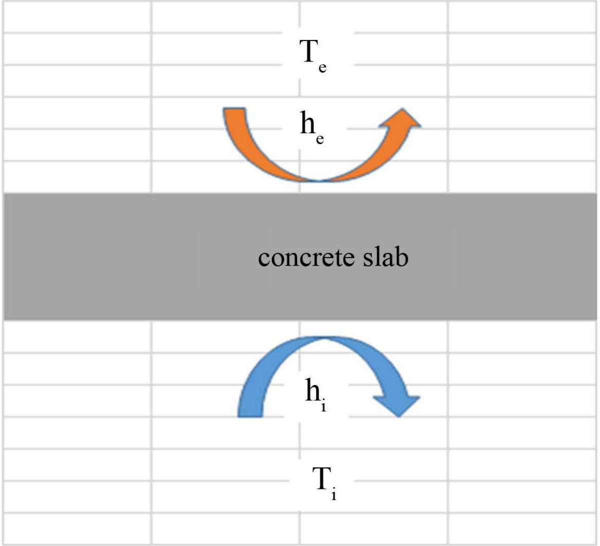

Figure 1. Concrete slab.

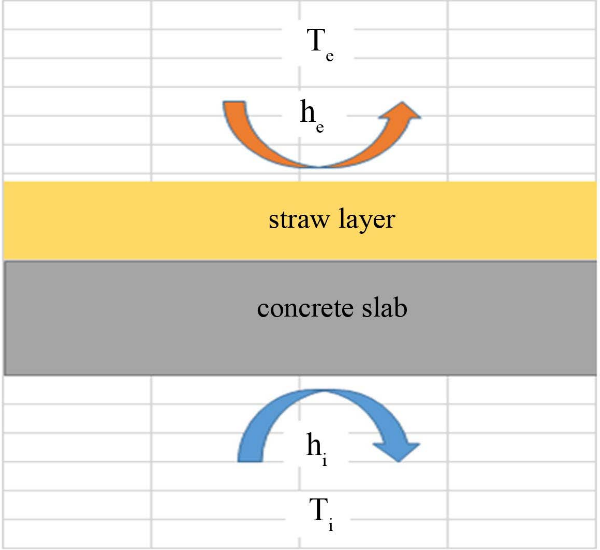

Figure 2. Concrete slab + straw layer.

$$R_{th2} = \frac{1}{h_i} + \frac{e_{cs}}{\lambda_{cs} S} + \frac{e_{sl}}{\lambda_{sl} S} + \frac{1}{h_e} \tag{4}$$

3. Parameters Estimation

The straw used in this study is part of the family of proaceae and the genus pennisetum found in abundance in this study area. This straw is generally used in Senegal for the construction of thatched roofs in rural areas. The photos in **Figure 3** show the appearance of this straw in fibbers (a) and after preparation (b).

The technique for measuring thermal conductivity of the straw used in this work is called the "box method" (**Figure 4**). It is installed at the Applied Energy


(a) (b)

Figure 3. Physical appearance of straw.

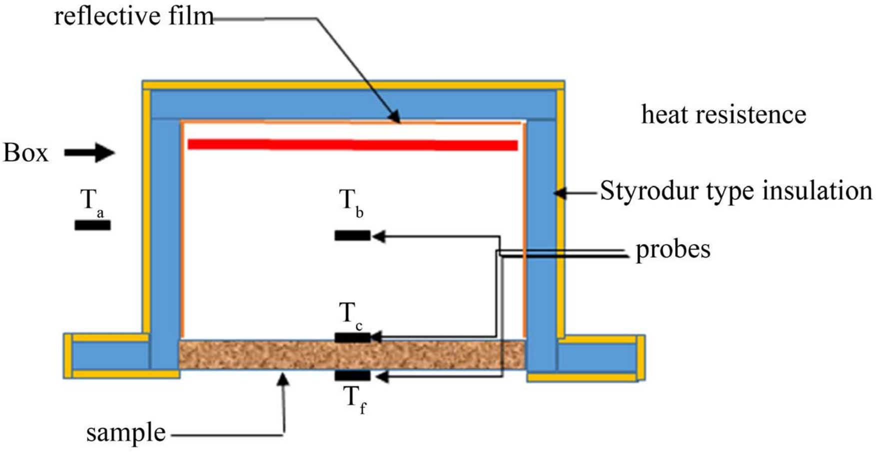

Figure 4. Box for measurement of thermal conductivity and position of probes.

Laboratory (LEA) of the École Supérieure Polytechnique (ESP) in Dakar. Furthermore, the measurements are made more or less under the actual conditions of use of the material. It has been used successfully by various authors including [4] [5] [6].

According to the principle of energy conservation, the heat flux given off by the heating film will on the one hand be transmitted by conduction through the sample, and on the other hand lost through the side walls, this leads us to the following equality:

$$\lambda = \frac{e}{S\left(T_c - T_f\right)}\left[\frac{V^2}{R} - C\left(T_b - T_c\right)\right] \tag{5}$$

The loss coefficient (C) characterizes the heat losses through the side walls of the boxes due to the presence of a temperature gradient between the inside of the boxes and the outside atmosphere. Theoretically, it is determined using the formulas of Carslaw and Jager [7] which make it possible to determine the thermal flows through a dihedral in steady state, and those of Langmuir [8], giving the values of the form coefficient for a corner. For boxes with Styrodur as insulation and plywood as external cover, the numerical application of these formulas [9], gives us $C = 0.19$.

In this measurement study, we carried out two tests and the values of the temperatures and voltages recorded when the steady state is reached are indicated in **Table 1**.

The injection of the values of these two arrays into the relation (5) allows us to obtain: $\lambda_1 = 0.076$ et $\lambda_2 = 0.050$. The average of the two values of the conductivity: $\lambda_{mean} = 0.063\ \text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$. Even if the difference between the two experimental values is quite large, we note that the average value is fairly close to an indication in the literature [10].

For the measurement of the thermal conductivity of the concrete slab, it was envisaged to use the asymmetric hot plane method. However, the sample representing the slab is problematic because the slab is generally made up of hollow bricks and other aggregates. Some literature data indicate that for a solid concrete whose density value is between 1700 and 1900 kg/m^3, the thermal conductivity value varies from 0.8 to 1.75 W·m^{-1}·K^{-1} [11]. For calculation purposes, we have set the upper limit value.

4. Calculation of Energy Consumption

4.1. Methodology

The energy consumption linked to the search for comfort in the home currently poses many financing problems in households and in particular in rural areas. In these areas, especially in the Matam region (northern Senegal), the temperature is very hot during certain periods (May, June), as shown by the temperature data diagram in the area in **Table 2**.

The problem is much more difficult for the latter because most of them live abroad and build so-called modern habitats, the envelope of which is made of concrete and therefore unsuitable for periods of heat. To estimate the energy consumption, it is sufficient for each case to determine the heat flow transferred through the slab (bare or with straw layer). The capacity of the refrigerating machine to extract this transferred heat per unit of operating time corresponds

Table 1. Experimental values recorded at the first and second steady state test.

Parameters	T_f	T_c	T_a	T_b	$V\,(Volt)$	$R\,(Ohms)$	$T_c - T_f$	$T_b - T_a$
Test 1	18.44	25.76	30.14	30.23	14.89	266.00	7.32	0.09
Test 2	17.53	24.18	27.76	28.30	12.53	266.00	6.65	0.54

Table 2. Average monthly temperatures in the Matam region.

TEMP (˚C)	JAN	FEB	MAR	APR	MAI	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
Mean-Min	15.5	17.3	20.1	23.5	26.1	27.2	25.6	24.5	24.4	23.8	19.7	17
Mean-Max	33.5	36.4	38.7	41.1	42.5	40.9	36.7	34.6	35.4	38.4	37	33.8
Mean	24.5	26.8	29.4	34.3	34.3	34	31.1	29.5	29.9	31.1	28.3	25.4

in absolute value to its refrigerating capacity. The power absorbed by this machine can be obtained if we know the coefficient of performance. Thus, the electrical power is calculated by estimating the coefficient of performance of the compressor and we deduce the following:

$$COP = \frac{\varphi}{Pa} \quad \text{ou} \quad Pa = \frac{\varphi}{COP} \tag{6}$$

The annual energy consumption is equal to the product absorbed by the compressor operating time according to:

$$C_{e-a} = Pat_o \tag{7}$$

By replacing with the above, we obtain for any type of wall:

$$C_{e-a} = \frac{T_{ext} - T_{int}}{\frac{1}{h_i} + \sum_{j=1}^{n} \frac{e_j}{\lambda_j S} + \frac{1}{h_e}} \cdot \frac{t_o}{COP} \tag{8}$$

4.2. Steady State

In our case, we are studying in particular the contribution to the energy consumption of the upper slab. Matam has a desert climate (BWh) according to the KÖPPEN-GEIGER classification and over the year. The average temperature in the studied area is 30.6˚C with a relative humidity (RH) which can reach 65% during the rainy season. The internal thermo-hygrometric conditions are fixed as follows: 24˚C and 50% RH. The room studied is an administrative building which is open from 8 a.m. to 6 p.m. and Monday to Friday, *i.e.* 50 hours/week, which corresponds to 2600 hours annually. The heat exchange resistance of the internal surface r_{si} and that of the external surface r_{se} are taken from the literature equal to 0.17 and 0.05 $m^2 \cdot K \cdot W^{-1}$ respectively for a horizontal wall [12]. The value of this surface heat exchange resistance depends on the inclination of the wall and the internal one is always greater than the external value because the air movements are greater outside than inside, which influences convective heat transfer.

- Concrete slab alone

By numerical application of the previous Equation (3), we obtain with **Table 3**, the value of the contribution of the concrete slab on the annual energy consumption which is 30.2 kWh.

- Concrete slab and straw

For the concrete Slab combined to straw layer, we obtain in **Table 4**, the annual energy consumption which is 14.4 kWh.

By distributing the annual operating time over the 12 months, we draw the curve of electrical power consumed in steady state as well for the bare slab as for the slab covered with a layer of straw, **Figure 5**.

These results show that the energy consumption which was 12 kW for concrete slab only is reduced to approximately 6 kW for concrete slab with straw. Layering the straw one the concrete slab contributes to reduction of energy

Table 3. Energy consumption due to the concrete slab in steady stage.

e_1 (m)	λ_1 ($\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$)	$S\,(\mathrm{m^2})$	$e_1/(\lambda_1 S)$		$r_{si} = 1/h_i$	$r_{si} = 1/h_i$	R_{th}
0.2	1.75	16	0.007		0.17	0.05	0.2271
$T_{m\text{-ext}}$	$T_{m\text{-}ixt}$	ΔT	ϕ_1 (W)	COP	P_a (W)	t_f(h)	$C_{e\text{-}a}$ (kW·h)
30.6	24	6.6	29.06	2.5	11.6	2600	30.2

Table 4. Energy consumption due to the concrete slab + straw layer in steady stage.

e_1 (m)	λ_1 ($\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$)	$S\,(\mathrm{m^2})$	$e_1/(\lambda_1 S)$		$r_{si} = 1/h_i$	$r_{si} = 1/h_i$	R'_{th}
0.20	1.75	16	0.007		0.17	0.05	0.4752
e_2 (m)	λ_2 ($\mathrm{W{\cdot}m^{-1}{\cdot}K^{-1}}$)	$S\,(\mathrm{m^2})$	$e_2/(\lambda_2 S)$				
0.25	0.06	16	0.248				
$T_{m\text{-}ext}$	$T_{m\text{-}ixt}$	ΔT	ϕ_2 (W)	COP	P_a (W)	t_f(h)	$C_{e\text{-a}}$ (kW·h)
30.6	24.0	6.6	13.89	2.5	5.6	2600	14.4

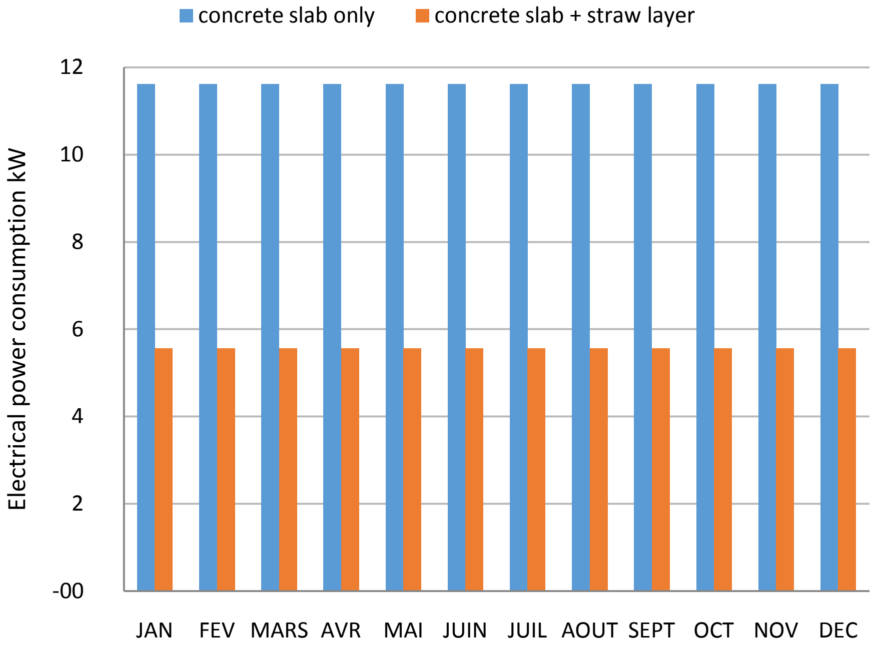

Figure 5. Electrical Power consumption in steady stage.

charges. This is benefits for the customers and the national energy distribution because it will participate to reduce the load shedding.

Dynamic State

Calculating steady state energy consumption does not reflect reality well. Indeed, there are very important variations of the temperature during the year. By setting the value of this average temperature under certain conditions, there is a risk of oversizing or doing the opposite. So, instead of starting on an annual average, we will use the monthly averages, Table 5.

Starting from the heat flow for each month where the average temperature is

Table 5. Monthly consumption in kW·h for concrete slab comparing to concrete slab with straw layer.

Month	JAN	FEV	MARS	AVR	MAI	JUIN	JUIL	AOUT	SEPT	OCT	NOV	DEC
Conc Slab	0.19	1.07	2.05	3.16	3.92	3.80	2.70	2.09	2.24	2.70	1.64	0.53
Conc Slab + Straw	0.42	2.36	4.55	6.99	8.67	8.42	5.98	4.63	4.97	5.98	3.62	1.18

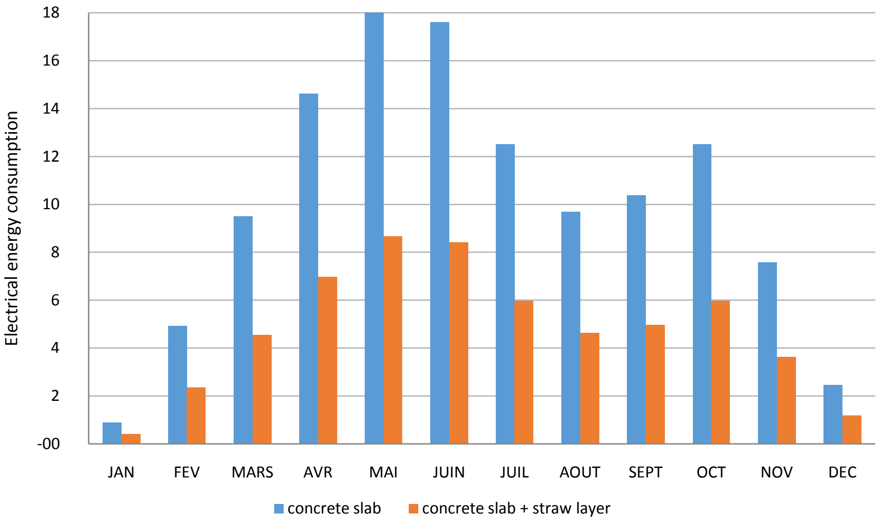

Figure 6. Electrical power consumption in dynamic stage.

assumed to be constant, we draw the curve representing electrical power as a function of time, Figure 6.

The study in dynamic mode shows that the electric power required to maintain the room at 24˚C varies according to the seasons. This is due to the fact that the losses are less important when the temperature difference is small.

5. Conclusions

In the work, we have studied the thermal properties of the straw in order to use it in construction in northern Senegal. This straw is added over the high floor. We designed a one-piece building made of a reinforced concrete slab made of cellular bricks.

In this work:

- The thermal load was first modelled in order to determine the contribution of the slab relative to this load.
- We have made a bibliographic review of the various measurements of thermal properties in order to choose those which make it possible to determine the parameters necessary for calculating the heat flux.
- Knowledge of the modelling of these methods made it possible to prepare the methodology and the measures to be taken to arrive at a correct estimate of the parameters.
- We have shown through this document that whatever the regime (permanent

or dynamic) that the addition of a layer of straw on a concrete slab reduces very significantly (50% in our case) heat transfer.

In further work:

- We wish to make a study by ENERGYPLUS or TRANSYS to better refine the calculation of energy consumption in dynamic stage.
- We also want to make an optimization study on the thicknesses of straw to be superimposed on the concrete slab for fixed thickness.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

Symbols:	
S	surface of element, m^2
T	temperature, ˚C
e	thikness, m
V	Voltage, V
R	Electrical resistance, Ω
R'	Resistance, K·W^{-1}
P	Electrical Power, W
h	isothermal convection coef., W·m^{-2}·K^{-1}
C	Loss coef. of boxes
t	Time, h
COP	Coef. of performance
W	Energy consumption, kW·h
Greek Letters:	
λ	thermal conductivity, W·m^{-1}·K^{-1}
φ	heat flux, W
Indices/Exponents:	
i	internal
e	external
th	thermal
j	layer number
n	number of layer
B	box
A	ambient
C	hot contact
F	cold contact
a	absorbed
o	operating
an	annual