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Study of the Thermal Properties of Clay-Straw Composite Material for Thermal Insulation of Buildings

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***Abstract:** Clay is an environmentally friendly material that is widely available throughout Senegal. To reduce the energy consumption of buildings and the emission of greenhouse gases, clay is often used in construction, and natural insulating materials, such as straw, are combined with it to enhance its thermal properties. An experimental transient parallel hot-wire measurement was employed to investigate the effect of straw addition on the thermal properties of the composite material. The thermal results showed that adding straw to the clay reduced its thermal conductivity by 61%. The clay-straw composite could therefore be an alternative to concrete-based materials for ensuring thermal comfort in buildings.*

***Keywords:** Clay, Straw, Thermal Conductivity, Thermal Capacity, Parallel Hot Wire, Thermal Insulation*

I. INTRODUCTION

Energy is essential to any nation's economic development. Awareness of the depletion of energy resources, rising fossil fuel prices, and climate change has led to a growing interest in controlling energy consumption in general, and building-related consumption in particular.

According to international data published in 2016 by the International Energy Outlook, the building sector accounts for approximately 25% of the world's energy consumption. According to Dieye et al [1], Senegal's building sector is the primary energy consumer at 54.7%, and accounts for 49% of CO2 emissions.

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To help reduce energy consumption and protect the environment by cutting CO2 emissions, building envelope insulation is an essential factor. It is against this backdrop that researchers have set out to study the energy efficiency of buildings using bio-sourced materials. These materials are composed of natural fibres and a binder. Their abundant availability and renewability make them a suitable choice for these materials. Given the availability of clay and its widespread use as a local building material by average households, several studies have focused on utilising clay as a building material. However, to improve the thermal properties of clay, several authors have favoured the addition of natural fibres to clay materials.

Ouakarrouch et al [2] studied the impact of adding sisal fibres on the thermal properties of clay bricks. In 2017, Dieye et al [1] studied the thermomechanical properties of a Typha-based building material. Niang et al [3] studied the thermal and hygroscopic performance of various Typha-clay composites. Lamrani et al [4] studied the effect of adding date palm fibres, straw fibres and olive waste on the thermal properties of pure clay. The thermal behaviour of hollow clay bricks made from wastepaper was studied by Sutcu et al. [5]. Mounir et al [6] studied a clay-cork composite material. They tried to improve the thermal properties of clay by combining it with cork. In 2021, Younouss et al [7] studied the thermal and mechanical properties of Typha sheet-clay panels. The modelling and measurement of the thermal properties of a moist porous medium: laterite brick with millet pod was carried out by Bal et al [8].

This article aims to enhance the thermal properties of raw clay by combining it with straw, thereby increasing its insulating capabilities and significantly reducing energy consumption in buildings. The second part of this manuscript addresses sample preparation and composition, as well as the experimental method and modelling of asymmetric hot-wire measurement. The third part is devoted to results and discussion, a conclusion and some perspectives.

II. MATERIALS AND METHODS

A. Preparation and Composition of Samples

The raw clay used in this manuscript was extracted from Thicky in the Thiès region. It is ground into a powder by hand with a hammer, but it contains a few grains. The straw used as an additive to the clay comes from the Tambacounda region. It has been dried under the sun for a week, then cut and ground into powder, but it contains fibbers.

The photos in Figure 1 show the

Cut and grind the straw and the powdered clay.

[Fig.1: Natural Appearance of Cut and Shredded Straw and Ground Clay Powder]

For the composition of the samples, we mixed a certain mass of clay with several doses of straw by weighing.

The proportions of straw incorporated into the clay material are shown in Table 1.

Table 1: Specimen Composition in %.

Designation of Specimens	E1	E2	E3	E4
Proportion of clay (%)	100	97.5	95	92.5
Proportion of straw (%)	0	2.5	5	7.5

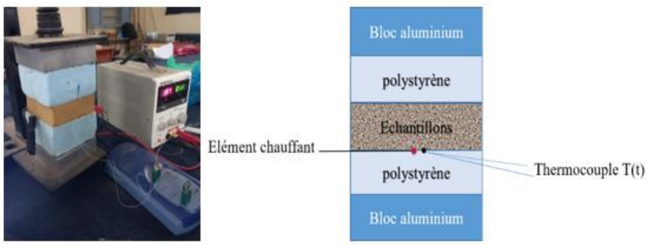
For moulding, we used a wooden mould of dimensions 10x10x4 cm³.

Since the materials will be used in a dry state, we did not consider the quantity of water used for formulation. After demoulding, we obtained the following specimens:

[Fig.2: Mould and Clay Specimens Made]

B. Thermiques Thermal Properties Measurement Method

As it may be difficult in some cases to obtain two samples of the same composition and water content, a hot-wire setup parallel to a single sample was chosen. The aim is to measure the thermal conductivity and volumetric heat capacity of the material. The principle consists of inserting a thin heating wire between the sample to be characterised and the five-centimetre-thick polyurethane. A K-type thermocouple composed of two thin wires is placed at a small distance d from the heating element and bonded to the face of the polyurethane in contact with the component. The device is completed by another block of polyurethane placed on top of the sample. The whole is placed between two aluminium blocks of known thickness.



[Fig.3: Experimental Set-up]

As the thermocouple is in contact with a deformable material, its presence does not generate any additional contact resistance. Moreover, since polyurethane is an insulator, the contact resistance between the heating element and the polyurethane can be neglected.

When a constant flux step is applied to the heating element, the temperature change is recorded by the thermocouple [9].

i. Complete Estimation Method

The following assumptions are made

- Heat transfer is 1D radial at the centre of the device,
- The medium is semi-infinite,
- Heat transfer is purely conductive,
- The temperature is uniform and constant in the system at the initial instant. It has been shown that the Laplace transform $\theta(p)$ of the thermocouple temperature rise is written:

$$T(t) = \mathcal{L}^{-1}\left\{\frac{\frac{\varphi\omega}{pL}K_o(qd)}{\rho_w C_w \pi r_w{}^2 p K_o(qr_w) + 2\pi o \lambda q r_w [1 + \rho_w C_w \pi r_w{}^2 p R_c L] K_1(qr_w)}\right\}$$

With:

$$q = \sqrt{\frac{p}{a}}$$

Where:

I_o,I_o, K_o, K_1 They are modified Bessel functions of the first and second kind.

$\rho_w C_w$ Heating wire volumetric heat capacity

L Heating wire length

r_w Heating wire radius

d Distance between heating wire and thermocouple

λ Sample thermal conductivity

A sample thermal diffusivity

R_c Contact thermal resistance

p Laplace parameter

φ_w Heat flow in the heating wire

The inverse Laplace transformation is performed using the MATLAB program "invlap" based on De Hoog's algorithm. The Matlab program "leasqr", based on the Levenberg-Marquart algorithm, is used to estimate the parameter values λ and ρc that minimize the sum: S = $\sum_{i=1}^{N}[T_{ext}(t_i) - T_{mod}(t_i)]^2$ [10]

III. RESULTS AND DISCUSSIONS

Our various-shaped materials were characterised using the parallel hot-wire method. The results obtained enabled us to estimate the values of conductivity and volumetric heat capacity. This estimation was carried out using a complete model derived from a MATLAB program. The parameter estimation results are shown in Table 2.

Table 2: Measurement Estimation Results

Straw Content (%)	0	2.5	5	7.5
oneonehermal conductivity (W.m^{-1}.K^{-1})	0.75	0.62	0.41	0.29
Volumetric heat capacity 10^6(J.m^{-3}.K^{-1})	2.954	1.949	0.250	0.05

A. Analysis of Residues

The model, experimental and residual curves obtained

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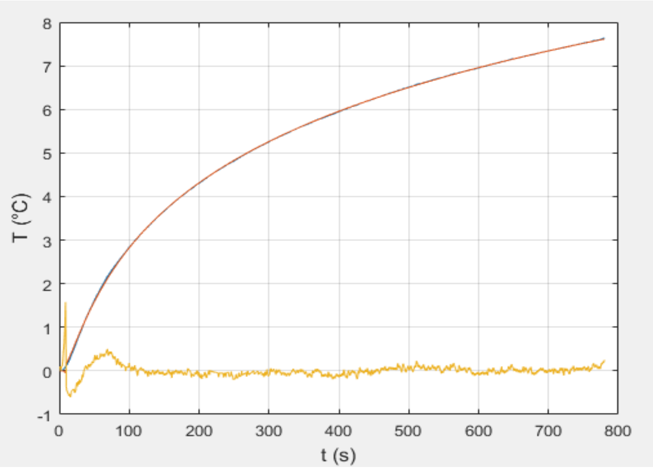
by estimating the parameters of the pure clay sample using the complete model from a Matlab The program is shown in Fig. 4, providing information on measurement accuracy and model validation.



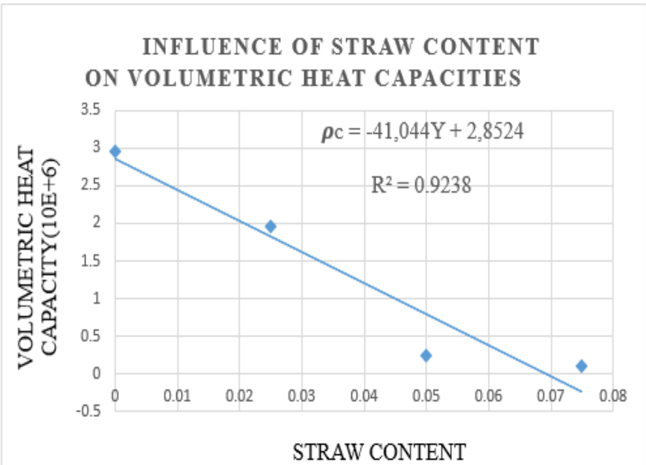
[Fig.5: Model and Experimental Curve and Residuals of a Hot Wire]

We can see that the model and experimental curves overlap. These results indicate that the simulated theoretical model is in excellent agreement with the experimental curve up to 800 seconds. The orange curve represents the residual. In this curve, we initially note the influence of probe inertia and contact resistance. It then remains centred at zero, demonstrating the validity of the 1D model at the centre of the sample. The results obtained satisfy the criterion of minimizing the squared deviation between the experimental curve and the theoretical curve. The sensitivity and residual curves indicate that the thermophysical properties ρc and λ can be accurately estimated using the comprehensive model employed.

B. Analysis of Experimental Results

i. Volumetric Heat Capacity

The data in Table 2 can be used to plot the heat capacity curve as a function of different straw contents.

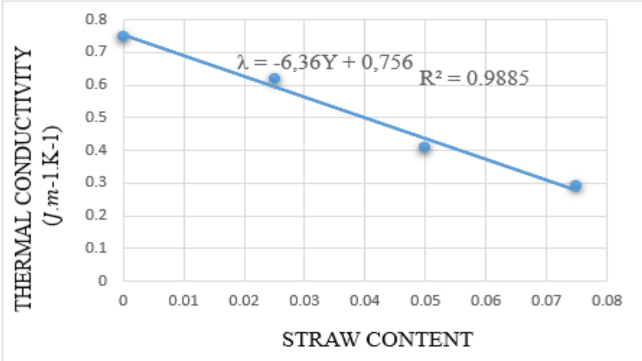


[Fig.6: Evolution of the Volumetric Heat Capacity as a Function of Straw Content]

This curve shows that the volumetric thermal capacity of our clay-straw composite materials decreases with increasing straw content.

ii. Thermal Conductivity

The data in Table 2 can also be used to monitor changes in conductivity as a function of straw content.



[Fig.7: Experimental Results of Measurements of Thermal Conductivity λ as a Function of Straw Content]

Analysis of the curve shows that thermal conductivity decreases with increasing straw content. This decrease is 61% for the 7.5% straw content.

Straw, being a light material, reduces the density of the final composite when added to clay. As a result, the composite becomes more insulating. It therefore serves to improve the insulation of the building envelope by minimizing heat loss in the building.

IV. CONCLUSION

The present manuscript aims to contribute to reducing energy consumption in the building industry. Thermal characterization of clay-straw composites yielded good thermal insulation properties. The composites can be used as thermal insulation materials for the building envelope, offering improved energy efficiency. This would result in significant savings for low-income populations.

However, the material's thermal properties are not the only criterion for choosing a construction material; its mechanical properties are also an essential parameter for ensuring building stability.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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