STUDY OF THE THERMOMECHANICAL PERFORMANCES OF BIO-SOURCED MATERIALS: INFLUENCE OF THE PROPORTION OF SUGAR CANE FIBER AND THE CEMENT CONTENT

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Abstract

In a context of global warming and scarcity of natural resources, this study analyzes the impact of the proportion of sugarcane fibers and the binder (cement) content on the thermal and mechanical performances of bio-based adobes. The experiments conducted include fiber proportions ranging from 2.5% to 10% and cement contents of 5% and 10%. The properties measured include thermal conductivity, effusivity, heat capacity and mechanical strength. The results indicate that the addition of 2.5% fibers and 10% cement optimizes thermal conductivity (0.4 W/m.K) and effusivity (705.065 J/m².K.$s^{1/2}$) while maintaining sufficient mechanical strength (0.59 MPa in bending and 1.15 MPa in compression at 28 days), making these materials suitable for lightweight green constructions. This research contributes to the development of sustainable building materials, offering a viable alternative to conventional materials, particularly in regions where resource management and thermal comfort are crucial.

Introduction: -

With the construction sector accounting for 35% of global energy consumption and 38% of GHG emissions [1], green materials such as sugarcane fibre reinforced and cement stabilised adobes are a crucial lever for reducing the carbon footprint [2]. In Africa, concrete, despite its high cost and poor thermal performance, remains the dominant material, contributing to 5-8% of global carbon dioxide emissions. [3], [4]. The climate emergency is pushing to explore bio-sourced materials, such as clay with plant fibers, which offer better thermal regulation and a reduction in energy consumption [5], [6]. Various studies have demonstrated the benefits of incorporating plant fiber into construction materials, paving the way for more sustainable solutions [7], [8], [9].

Different solutions have been proposed, mainly the addition of plant fibers to clay to make adobes or compressed earth blocks (CEB). Earth- kenaf composites were implemented by Laibi et al [10], by incorporating kenaf (1.2%) of variable sizes (10, 20 and 30 mm) into earth, they noted an increase in the compressive strength of 47.6% of the material with fibers of 20 mm in length. Ouédraogo et al [11] studied the impact of fonio straw on the thermo-physical and mechanical properties of adobe blocks. By varying the content (0 to 1%) of this bio-sourced aggregate with the earth matrix, they noted an improvement in mechanical properties reaching maxima of 2.9 MPa for compressive strength and 1.3 MPa in bending, respectively at 0.4% and 0.2% of fiber; i.e. respective increases of 11.5% and 18.2% compared to the initial values. To improve the insulation capacity of earth bricks, Laborel-Préneron [12] incorporated (0%, 3% and 6%) corn cob, barley straw, and hemp shiv. As expected, a decrease in the thermal conductivity of the new material following the increase in plant aggregates, from 0.57 W/mK for the material without aggregates to 0.14 W/mK when the fiber content reaches 6%. The minimum drop in conductivity is observed with barley straw, with a decrease of 75% at 6% straw content compared to 65.8% with hemp shiv and 55% with corncobs.

This work focuses on the impact of sugarcane fiber proportion and cement content on the thermal and mechanical properties of adobes, with the aim of developing alternatives adapted to current challenges.

Materials and Methods: -

Materials

To make the adobe specimens, we used Thicky clay, located in the Thiès region in western Senegal at 14°50' N, 17°06′ W. Table 1 presents the physical characteristics of this material.

Table 1:- Characteristics of Thicky clay [13]

Properties	**Plasticity index**	**Plasticity limit**	**Liquidity limit**	**Sand**	**Clay**	**Silt**	**Density (kg/m^3)**	**Water content**
Values	17.5%	24.3%	41.8%	8%	45%	47%	2381	4.78%

Sugarcane fiber residues available at the Senegal Sugar Company (CSS), located in the Richard- Toll region, are used as an additive to improve the thermomechanical properties of adobes. Sugarcane stem refers to a species of plants from the Poaceae group and the Saccharums genus, grown mainly for their stems, which allow sugarcane juice to be extracted; its height varies between 2 and 6 meters for a diameter of 2 to 7 cm. Table 2 presents the physicochemical properties of sugarcane residues.

Table 2:- Physicochemical properties of sugarcane residues [14]

Properties	**Length**	**Cellulose**	**Lignin**	**Hemicellulose**	**Density**
Values	1-3 cm	32-44	19-24	22	105 kg/m^3

Portland cement CEM II 32.5 N produced by the Senegalese cement factory (SOCOCIM) located in Rufisque is used as a stabilizer.

Methods

Preparation of materials and preparation of test specimens

The samples were prepared manually by mixing the clay matrix with different percentages of sugarcane fibers [2.5%; 5%; 7.5%; 10%], and Portland cement CEM II 32.5 N in contents of 5% and 10% (Table 3). The sugarcane stalks were previously pressed (Figure 1.b) to extract the juice, then cut into 2 to 3 cm segments (Figure 1.c) and dried in an oven at 105 °C for 24 hours. The objective of the study is to evaluate the influence of the proportions of fibers and cement on the thermomechanical performances of the adobes, compared to a reference without fibers (0%). A water/earth ratio of 0.6% was used for the preparation of the samples. Two types of specimens were made: 40 x 40 x 160 mm³ specimens (Figure 2.b) for mechanical tests (compression and three-point bending) and 100 x 100 x 20 mm³ specimens (Figure 2.a) for thermal tests (thermal conductivity and effusivity). All samples were left in the open air in the laboratory at a constant temperature of 25 ± 2 °C to limit rapid surface shrinkage, thus minimizing the risk of cracking. The presence of water in the blocks is essential for the hydration of the cement. The samples were then sealed in bags and transported for characterization. All tests were carried out on dry samples after 28 days of drying.

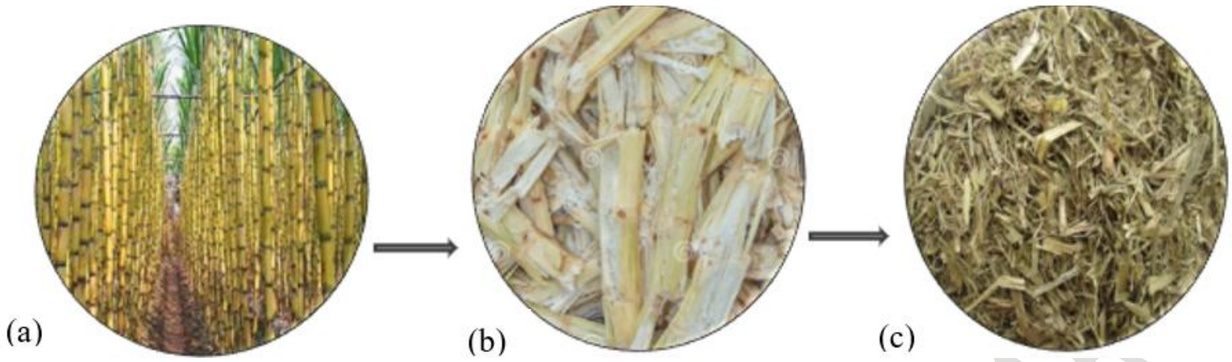

Figure 1: - Sugarcane stalk (a), Pressed cane stalk (b), Chopped fiber 2-3cm (c)

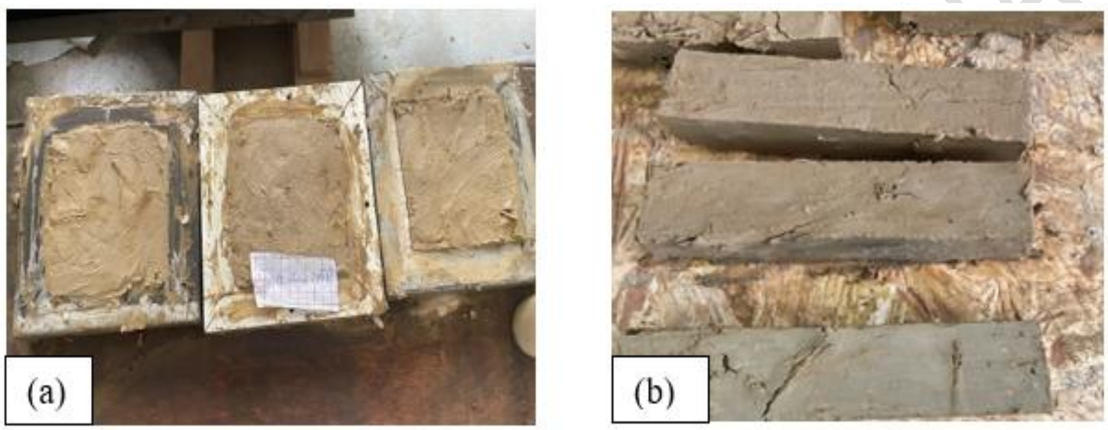

Figure 2: - Test pieces of 100 x 100 x 20 mm³ (a), Test pieces of 40 x 40 x 160 mm³ (b)

Table 3: - Mass proportion of materials used

Rating	**Clay (g)**	**Cement (g)**	**Bagasse (g)**	**MVH (kg/m^3)**	**MVS (kg/m^3)**
95% clay + 5% cement + 0% Bagasse	3800	200	0	1687.5	1512.1
92.5% clay + 5% cement + 2.5% Bagasse	3700	200	100	1789.06	1637.5
90% clay + 5% cement + 5% Bagasse	3600	200	200	1789.06	1636.7
87.5% clay + 5% cement + 7.5% Bagasse	3500	200	300	1742.19	1525
85% clay + 5% cement + 10% Bagasse	3400	200	400	1769.53	1493.75
90% clay + 10% cement + 0% Bagasse	3600	400	0	1648.43	1435.15
92.5% clay + 10% cement + 2.5% Bagasse	3500	400	100	1511.71	1245.7
90% clay + 10% cement + 5% Bagasse	3400	400	200	1656.25	1343.33
87.5% clay + 10% cement + 7.5% Bagasse	3300	400	300	1418	1047.65
85% clay + 10% cement + 10% Bagasse	3200	400	400	1613.28	1273.4

Thermal characterization method

The thermal properties of the adobes were determined using the asymmetric hot plane method. The principle of this method consists in applying a constant heat flow using a heating resistor on one face of the sample to be characterized and in recording the temperature change every 01s at the center of this same resistor using a Type K thermocouple consisting of two wires with a diameter of 0.05 mm connected to the acquisition and processing unit , having 16 channels with a resolution of 1/10 th of a degree Celsius, glued to the face of the element in contact with the insulation. In the assembly of the device (Figure 3), the heating element is of section (100 x 100 x 0.22 mm³**)** and the sample of section (100 x 100 x 20 mm³**)**, two blocks of insulating polystyrene 5 cm thick cover the plate and the sample. The whole is placed between two 4 cm thick isothermal aluminum blocks. The temperature of the external face of the sample plate is maintained by means of an isothermal plate connected to a stabilized power supply. The reading of the temperature variations as a function of time is carried out using the Picolog software.

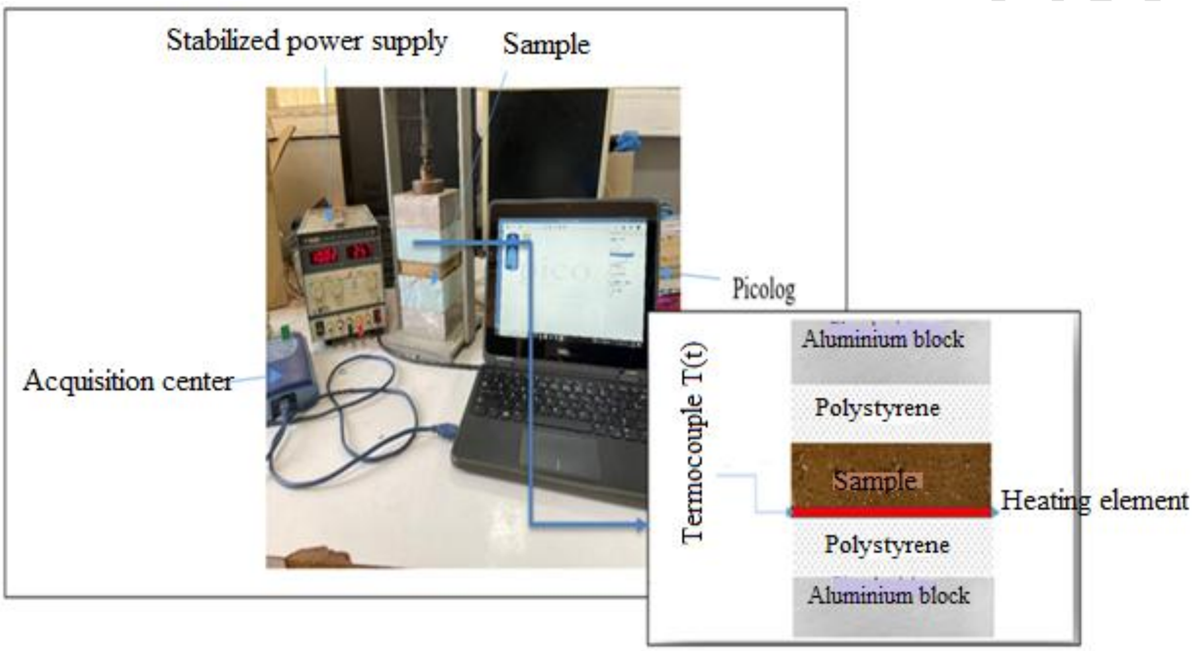

Figure 3: - Device of the asymmetric hot plane method

Asymmetric Hot Plane Data Processing Method

After measuring the temperature variations as a function of time, the data collected by the data acquisition unit are processed using a Matlab program. This program, designed specifically to analyze data from the asymmetric hot plane method, makes it possible to determine the thermal conductivity and effusivity while verifying the agreement between the experimental values obtained and the theoretical values.

Mechanical characterization method

The three-point compression and bending tests were carried out using the TESTWELL device, with a maximum capacity of 250 kPa in accordance with the standard (NF EN 196-1). The tests were carried out at a constant speed of 0.05 mm/min until the developed adobes broke. Equation (1) gives the formula for calculating the bending strength Rf in MPa. With Ff: the bending breaking force (N) of the 40 x 40 x 160 mm³ bar; b and l the dimensions of the bar in mm base of the test piece.

$$Rf = 1.5 * \frac{\mathrm{Ff*l}}{\mathrm{b}^3} \quad (1)$$

Equation (2) gives the formula for calculating the compressive strength Rc in MPa. With Fc: the maximum breaking load (N) of the half-bar of 40 x 40 x 80 mm³; b=1600 mm^2 corresponds to the surface of the test samples.

$$Rc = \frac{\mathrm{Fc}}{\mathrm{b}^2} \quad (2)$$

Results and Discussion: -

Thermal properties

Thermal conductivity

There **Figure 4** shows the results of thermal conductivity tests of the composite as a function of sugarcane fiber content and cement content.

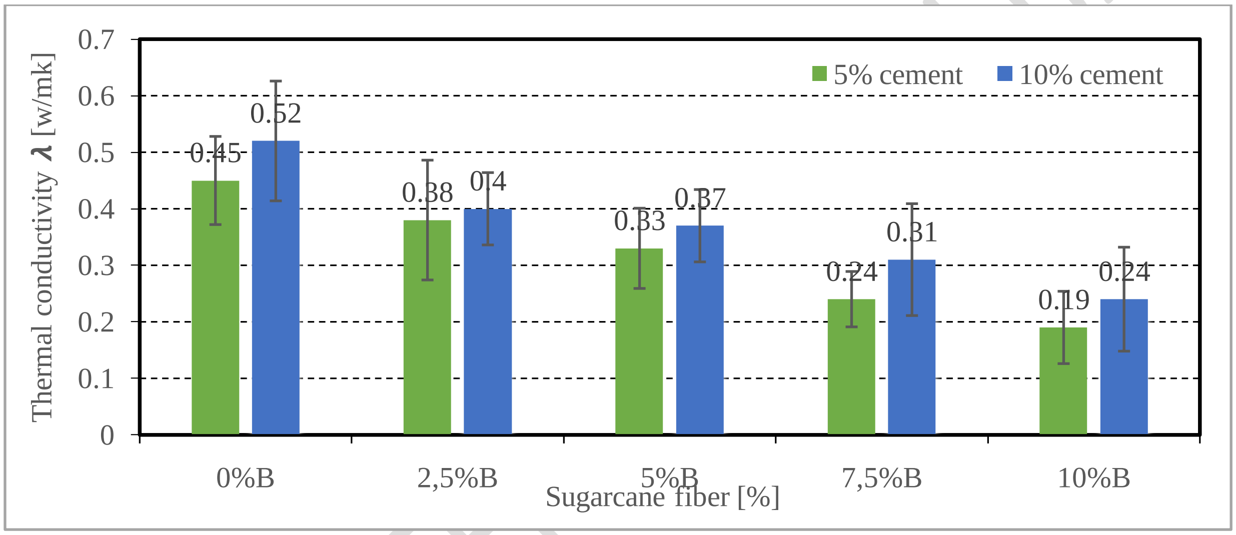

Figure 4: - Variation of thermal conductivity as a function of sugarcane fiber content and cement content

The absence of fibers leads to a high thermal conductivity (0.45 W/mK with 5% cement and 0.52 W/mK with 10%). The addition of fibers up to 10% significantly reduces the conductivity (up to 57.78%), reaching 0.19 W/mK with 10% fibers and 5% cement (Figure 4). This underlines the insulating effect of the fibers, which limit the increase in conductivity due to the increased density with more cement.

Thermal effusivity

Figure 5 below shows the variation of thermal effusivity of the composite as a function of sugarcane fiber and cement content.

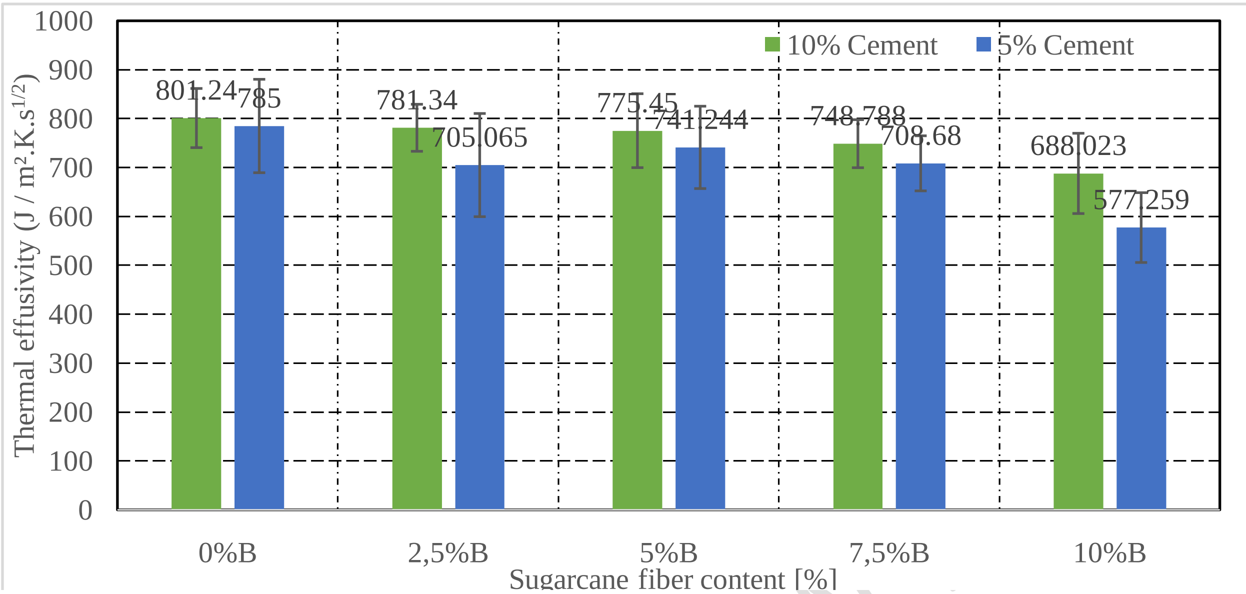

Figure 5: - Variation of thermal effusivity of the composite as a function of sugarcane fiber and cement content.

The thermal effusivity decreases with the addition of fiber, with 10% cement it decreases from 801.24 J/m²·K·s$^{1/2}$ without fibers to 688.02 J/m²·K·s$^{1/2}$ at 10% fibers (Figure 5). This indicates a reduced thermal reactivity, reinforcing the insulating properties of adobes. The material becomes less reactive to thermal variations thanks to the sugar cane fibers.

Mechanical properties

Flexural Strength

There **Figure 6** shows the results of the three-point bending tests carried out on the specimens of (16x4x4 cm^3).

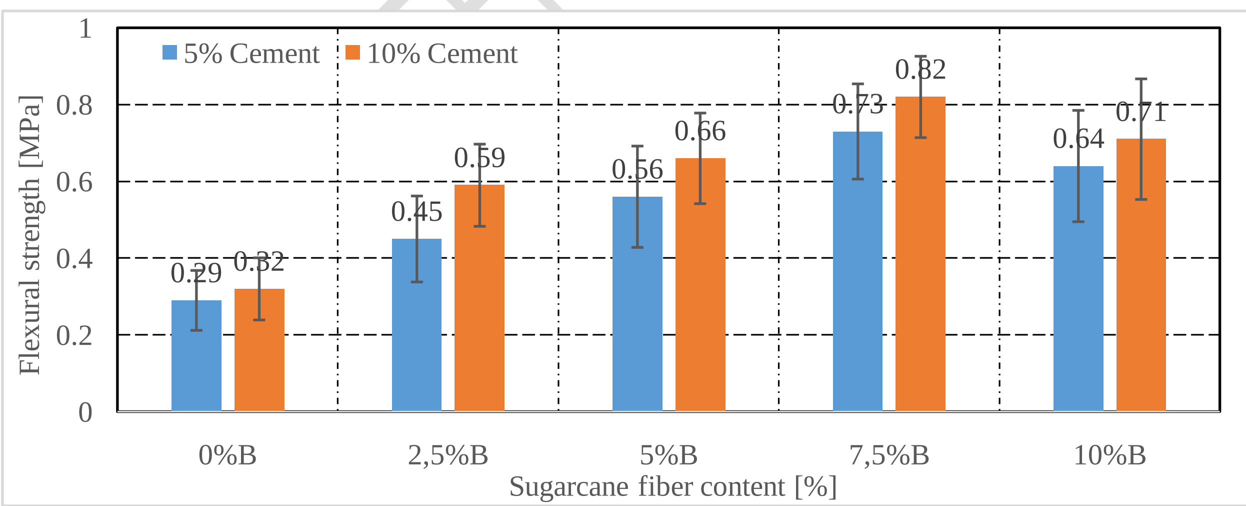

Figure 6: - Flexural strength of the specimens.

The addition of cement (5% or 10%) improves the flexural strength of adobes due to its stabilizing properties, with an improvement of up to 31%. The incorporation of sugarcane fibers also strengthens adobes, especially up to 7.5%, where the flexural strength increases significantly (Figure 6). The fibers delay crack formation and improve the ductility of the material, but beyond 7.5%, saturation of the mixture can lead to a decrease in strength.

Compressive Strength

There **Figure 7** shows the results of the three-point bending tests carried out on the specimens of (16x4x4 $cm^{3)}$.

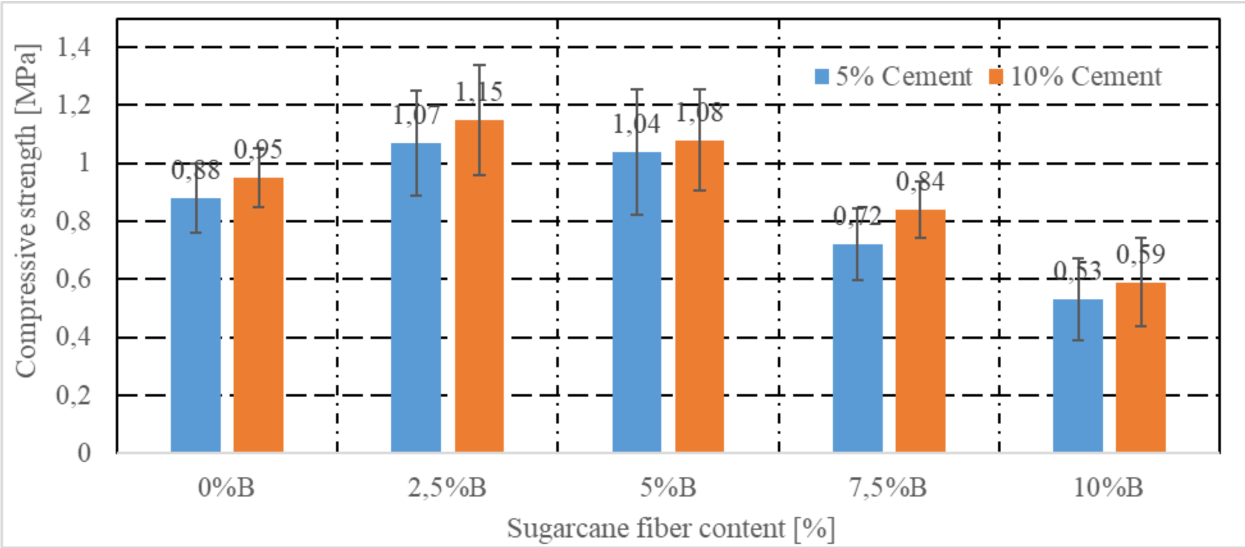

Figure 7: - Compressive strength of specimens

For compressive strength, increasing the cement content slightly improves the performance, with higher results for samples with 10% cement (Figure 7). The addition of sugarcane fibers in small proportions (up to 5%) increases the compressive strength, but at high percentages (7.5% and 10%), the strength decreases due to the loss of compactness and cohesion of the material. This shows the importance of an optimal dosage of cement and fibers to maximize the mechanical performance of adobes.

Conclusion: -

This study values cement-stabilized clay adobes reinforced with sugarcane fibers for sustainable construction. The objective was to evaluate the impact of the proportions of fibers (2.5% to 10%) and cement (5% and 10%) on thermal and mechanical performances. The results show that:
The addition of 2.5% fibers and 10% cement optimizes the thermal and mechanical properties, with a three-point bending strength of 0.59 MPa, a compressive strength of 1.15 MPa, a thermal conductivity of 0.4 W/m.K, and an effusivity of 781.34 $J/m^2.K.s^{1/2}$.
Dosages of more than 5% further improve thermal performance but at the expense of mechanical resistance.
These adobes, with promising performances, are suitable for ecological constructions, particularly in regions sensitive to thermal efficiency and natural resource management, and can be used as blocks for filling, as oudis or even thermal insulation.

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