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Hygrothermal measurement of heavy cob materials

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Abstract. The need to reduce the energy for heating and cooling is leading to a renewal of interest in geo-sourced materials for modern building construction. These materials offer many advantages in terms of climate change adaptation, and reduction of CO_2 emissions from building materials. This study presents the characterization of clay, fiber, and hygrothermal characterization of two types of clay mixtures reinforced with natural vegetable fiber for use in modern construction. Cob is a mixture of clay, water, and vegetable fibers. It is non-load bearing and serves as a filler for the wood frame. The wall design is suited for lightly seismic zones. Cob has great potential for applications in places with high housing and cooling needs. The hygrothermal properties of 30 clay formulations containing 0%, 3%, and 6 wt% wheat fibers were evaluated. At this fiber content, the material is considered a heavy type of cob. The measured thermal and hydric properties of the clay-fiber mixture presented in this paper are thermal conductivity, thermal effusivity and diffusivity, specific heat, water absorption, water vapor permeability, moisture buffer value (MBV), and sorption/desorption isotherms. Wheat fibers used in clay material mixtures improve their hygrothermal properties for sustainable construction. These results allow the development of a model hygrothermal model of wall elements.

Keywords: Hygrothermal properties, clay, fiber, cob, geo-sourced materials, sustainable building.

1 Introduction

The population used ecomaterials such as earth and wood or earth and stone in the construction of buildings. Over the years, the ecomaterials used in construction for decades have been replaced by cement blocks with high thermal conductivity and low thermal inertia. Cement, concrete blocks, and rebar are the main consumers of energy and CO_2 emitters [1].The impact of these materials on climate change is a major issue for the construction sector, especially in Africa, where the main construction material is cement. These materials are responsible for more than 50% of greenhouse gas emissions over the entire life cycle of a building [1]. Awareness of energy resource depletion, environmental sustainability issues, and climate change has prompted architects as well as researchers to revisit clay, fiber-reinforced clay, and wood-clay building implementation techniques. Directing the building sector towards the use of these composite materials with a wood-frame structure is a major issue in the overall perspective of sustainable development [2]. The construction of wood-frame buildings using clay reinforced with plant fiber as filling materials has a particularly low energy footprint. In addition, this type of construction increases the life of the building by providing them with good seismic resilience due to its wooden structure [3]. However, the phenomena that influence the proper functioning of wood-clay walls are heat and moisture transfer phenomena. The thermal and moisture properties of clay materials reinforced with plant fiber made using the cob technique, are not precisely known and there are few studies present in scientific journals [4]. As a result, it is difficult to predict the thermal and hydric performance of buildings constructed with wood/clay reinforced plant fiber. However, before improving the energy performance of buildings, which are responsible for nearly 50% of GHG emissions, it is necessary to improve the hygrothermal performance of the elements of its envelope even before thinking about improving the mechanical systems [5]. The key factor in the energy efficiency of a building is the quality of the materials used in the design of its envelope [5]. In Africa, the housing deficit stands at about 51 million housing units and is increasing over the years due to high population growth [6]. Wood-frame construction using vegetable fiber-reinforced clay as fillers could help reduce the number of housing demands and effectively dispose of the many agricultural wastes.

In this article, we are interested in the manufacturing technique of the vegetable fiber reinforced clay material manufactured using the cob manufacturing technique and the hygrothermal properties of the materials obtained after manufacturing. The manufacture of the samples was carried out by research of quality index, cracking rate and shrinkage. This allowed us to find the most appropriate technique for the fabrication of samples for the measurement of hygro-thermal properties.

2 Materials and methods

2.1 Materials

The study focuses on the plant fibers reinforced clay material that will be used for the filling of the wood-frame building structure. The material was manufactured in the laboratory of École de technologie supérieure. Two types of clay were used, a red colored clay containing iron oxide called red clay and another beige colored clay containing more kaolinite called beige clay. The bulk density of the red clay and beige clay is 2.8 g/cm^3 and 2.7 g/cm^3 with a plasticity index of 15% and 16% respectively. Bulk density was determined according to ASTM D854 [7] guidelines and details can be found in Kabore and al. [8] and plasticity index according to Canadian standard CAN/BNQ-2501-090 [9].Both clays were sourced from the province of Alberta and the wheat fibers were sourced from the province of Quebec, Canada. Fig.1 shows the clays and fibers used to make the samples.

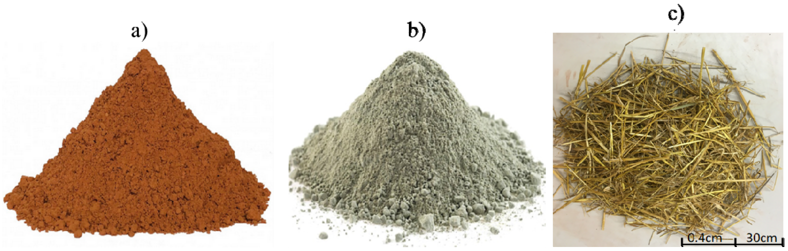

Fig. 1. a) Red clay, b) beige clay and c) fibers from 0.4 to 30 cm long

2.2 Method

2.2.1 Method of making the samples

Prior to the fabrication of the samples for the choice of the quality index as well as the mode of humidification of the fibers, the clays and fibers were previously characterized. The methods and results of the characterization of clays and fibers are presented in the work of Kaboré and Ouellet-Plamondon [10]. The manufacturing of the samples in clay without fibers was then carried out with a water/clay ratio of 15%, 20%, 25%, and 30% with 3 samples for each water/clay ratio to determine the quality index for the following. The samples have dimensions of 25 cm x 25 cm x 2.5 cm and 36 mm in diameter and 30 mm in height.

The samples were made using the adobe method, a mixture of water and clay [11]. After manufacture, they were then dried in an oven at 30°C for 10 hours - 11 hours to reduce the amount of moisture before being exposed to laboratory temperature (23°C) for 7 days. Volume shrinkage during drying being one of the most important factors for the manufacture of clay materials, especially adobe materials using a lot of water for manufacturing were therefore evaluated. The three dimensions 25 cm x 25 cm x 2.5 cm of each sample were measured using 0.01 mm precision digital calipers every 24 hours for 7 days of drying until the measured dimensions values stabilized. The volume shrinkage was therefore calculated as a function of the values obtained in each measurement of each dimension by the equation 1 [12]

$$R_v= ((V_o-V_f)/ V_o)\ ^{*}\ 100 \tag{1}$$

With R_v the volume shrinkage rate in %, V_o the initial volume in m^3 and V_f the final volume in m^3.

After obtaining the quality index with the water/clay ratio, the manufacture of samples reinforced with 3% and 6% of fibers were made with unmoistened and moistened fibers. This step consists of manufacturing clay samples reinforced with vegetable fibers with less shrinkage and without cracking. The manufacturing technique used is that of the cob and the manufacture was carried out on the spot in laboratory with the hand. Fig. 2 and 3 present the principle of choice of the quality index and the procedure of manufacture of the samples.

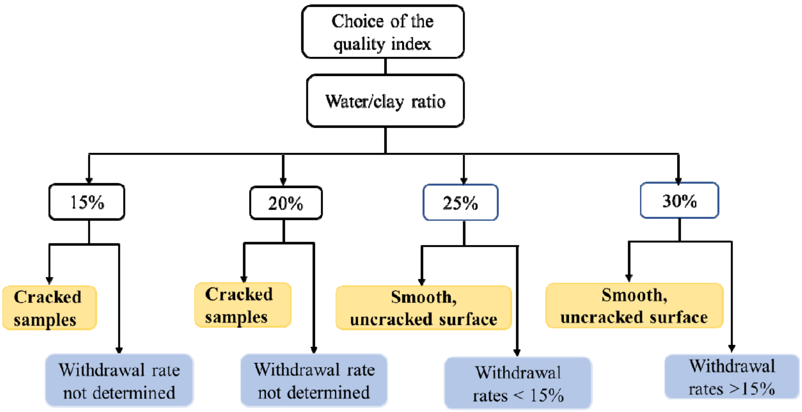

Fig 2. Choice of the quality index for the manufacture of samples without plant fibers reinforcement.

The choice of the quality index was made considering the plasticity of the mixture for the filling of the frames and for a manufacture of the material in a construction site. This manufacturing technique is very simple and is done in a traditional way (mixing by hand, feet, and shovels for large quantities). At the end of the experiment presented in figure 2, the choice of the quality index was the water/clay ratio of 25%. The samples without fibers made with 25% water gave a volume shrinkage between 12 and 13% and did not show any surface cracking. According to Laou, Lamyaa [13] volume shrinkage during of clay materials depending on their nature and clay content should be between 4% and 20%. Lertwattanaruk et al. [14] in their work, obtained volume shrinkage of 30% on adobe bricks of dimension 10 cm x 10 cm x 10 cm. And Emiroğlu et al. [15] obtained a maximum volume shrinkage rate of 23% for red clay samples and 26% for yellow clay samples of dimension 5 cm x 5 cm x 5 cm. The volume line of the samples with the water/clay ratio of 20% being less than 20%, we proceeded to manufacture samples with unmoistened and moistened fibers presented in Fig. 3.

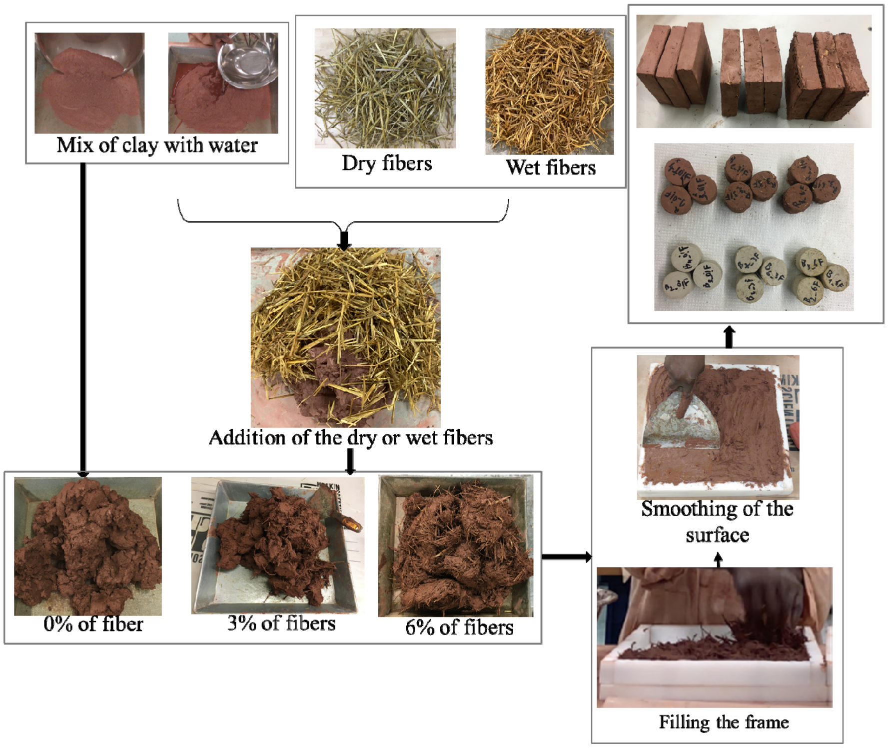

Fig 3**.** Procedure for making samples

The procedure of fabricating samples with both wetted and unwetted fibers resulted in the selection of samples that did not show cracks. The samples selected for testing were the samples made with wetted and unsaturated fibers (see Fig. 3). After these two steps, the samples with dimensions of 25 cm x 25 cm x 2.5 cm and 36 mm diameter and 30 mm height were again fabricated for thermal property measurements. For measurements of hydric properties, the beige clay samples tested were samples without fibers and samples with 6%fibers. This clay will be used as a fiberless coating. However, it is necessary to observe the influence of the fibers on the hydric properties of the samples made with this clay, so measurements of the hydric properties were made on samples of beige clay alone and reinforced with 6% fibers. Three samples per mix were used for the tests and the results are presented in Section 3.

2.2.2 Method for measuring hygrothermal properties

Thermal conductivity (λ) and thermal effusivity (E) were measured by the transient plane source method modified using the C-THERM apparatus (see Fig. 4a), thermal diffusivity (D) and specific heat [16] were obtained by calculation using Equations 2 and 3. The C-THERM method uses a one-sided sensor to directly measure the thermal conductivity and effusivity of materials. The samples used for testing were dried in room air (23°C).

$$D = \lambda^2 / E^2 \tag{2}$$

$$Cp = \lambda / \rho.D \tag{3}$$

The water absorption coefficient was determined by the partial immersion capillary absorption method (Fig. 4b) and the water vapor permeability was determined according to ASTME96 [17]. As for the moisture buffer values (MBV), they were measured following the NORDtest protocol [18]. All samples were first sealed and stabilized at 50% relative humidity before testing. Fig.4c shows the principle of sealing the samples according to the Nordtest protocol. The dynamic vapor sorption (DVS) method was used for the sorption tests.

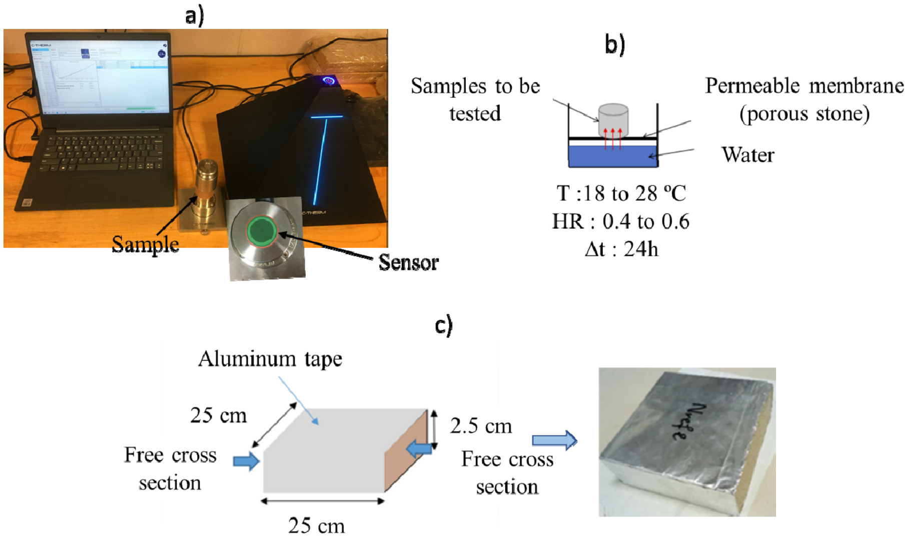

Fig. 4. a) C-THERM device, b) Principle of water absorption test of cob and earthen samples, and c) Principle of sample sealing for the Nordtest protocol

3 Results and discussion

3.1 Thermal properties

The average dry densities of the samples used for thermal properties measurements range from 2016 to 1997 kg/m^3 for samples without fibers, 1626 kg/m^3 to 1588 kg/m^3 for samples with 3% fibers, and 1412 to 1370 kg/m^3 for the 6% fibers. As expected, the dry density decreases with increasing fiber content in the mixtures. The results of thermal conductivity, specific capacitance, thermal diffusivity and thermal effusivity of the samples are presented in Fig. 4 and 5. The addition of fibers in the clay mixtures positively affects all the coefficients of thermal properties of the samples.

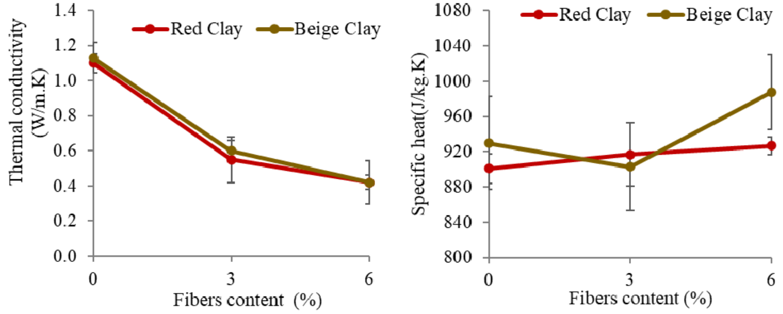

Fig 5. Thermal conductivity and specific capacity with increasing fiber content (dried samples at 23°C)

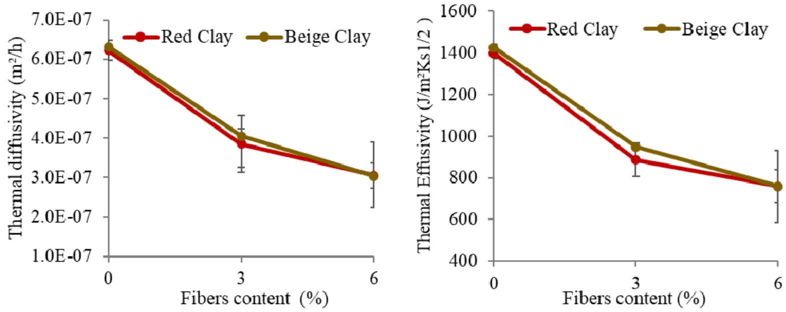

Fig 6**.** Thermal diffusivity and Thermal diffusivity with increasing fiber content (dried samples at 23°C)

The results indicate that increasing the wheat straw fiber content from 0 to 3, or 6% results in a significant increase in the thermal insulation of the material. The increase in specific capacity improves the ability of the material to store absorbed heat. The remarks on the decrease in thermal conductivity have been observed in the work of several authors including Ashour and al. and Ramakrishnan and al. [19, 20] although the technique of fabricating the samples for his work is different from the one used for this work. As for the thermal inertia properties, they decrease with fiber content, which was observed in the work of [21]. Ideal building materials for application in construction in hot regions should have the lowest thermal effusivity, i.e., the lowest capacity to absorb heat from the environment, and/or the highest specific heat capacity, i.e., the highest capacity to store the absorbed heat [22]. This translates into low thermal conductivity and diffusivity and consequently, high thermal inertia. Materials with 3% and 6% fibers would be better materials to use for wood framing in hot regions, however materials with 6% fibers have the best properties because materials made with 6% fibers have high thermal inertia than those with 3% fibers and no fibers.

3.2 Hydric properties

Table 1 shows the results on the average values of water vapor permeability, water absorption and moisture buffer value. The water absorption coefficient increases with the increase of the fiber rate used for the fabrication of the samples. These results were validated with the sorption isotherm curves presented in Fig. 6. The moisture buffer value decreases with the fiber rate. However, all the values of the moisture buffer value remain above 2 (g/ (m^2. %H), thus excellent according to Rode and al. [18].

Table 1 Average values of water vapor permeability, water absorption coefficient and moisture buffer value of the samples

Sample code	Water vapor permeability (kg/(s·m·Pa))	Water absorption ceofficient (%)	Moisture buffer value (MBV) (g/ (m^2. %H)
Red clay without fiber	$1.5.10^{-11}\pm5.1.10^{-13}$	7	6.1 ±0.01
Red clay with 3% fibers	$1.4.10^{-11}\pm5.2.10^{-13}$	10	5.5 ± 0.1
Red clay with 6% fibers	$1.6.10^{-11}\pm5.4.10^{-13}$	22	3.2 ± 0.1
Beige clay without fiber	$1.2.10^{-11}\pm7.8.10^{-13}$	7	4.2 ±0.1
Beige clay with 6% fibers	$1.3.10^{-11}\pm1.2.10^{-12}$	24	4.0 ± 0.1

The hygrothermal properties of the materials such as water vapor permeability, water absorption coefficient and moisture buffer value (MBV) of the plant fiber reinforced clay materials manufactured by the cob manufacturing technique are little studied and few results can be found in the literature, so it is difficult to comment on the hygrothermal properties obtained in this paper with those in the literature.

Following the understanding of the hygrothermal performance of wheat fiber reinforced materials, Fig. 6 presents the sorption behavior of samples manufactured with 0%, 3% and 6% fibers. The time evolution of all samples subjected to increasing relative humidity shows that the response of the plant fiber reinforced and non-fiber reinforced samples to a change in relative humidity is somewhat rapid and the water balance is reached in less than 10 days for some humidity intervals. It can be seen from the sorption curve that the equilibrium moisture content increases with increasing relative humidity for all samples but also with increasing fiber content.

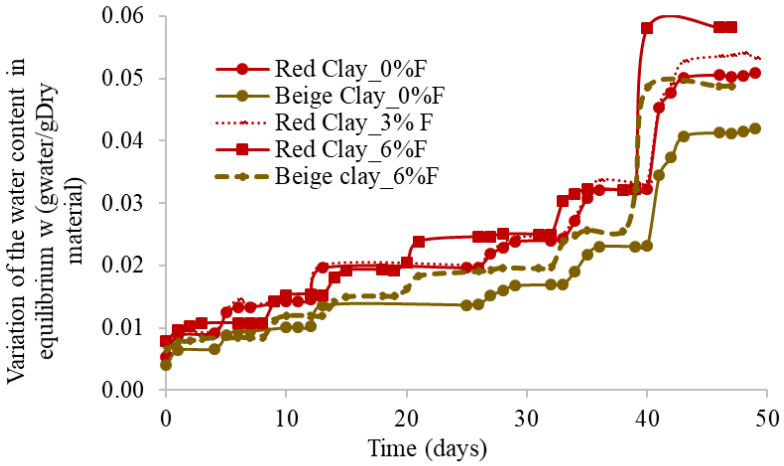

Fig 7. Sample mass variation during sorption-desorption tests.

4 Conclusion

This article aims to valorize clay materials in the cob technique by studying their hygrothermal properties. The samples in the study were made with 0%, 3%, and 6% of traditional fibers. The role of the addition of fibers is to improve the hygrothermal properties of the clay materials. This work has shown that the addition of fibers in the matrix of clays have improved all the hygrothermal properties of the studied samples. The thermal conductivity, thermal diffusivity and thermal effusivity of the samples decreased with the increase of the fiber content in the mixtures. Except the heat capacity which increased with the increase of fiber content in the mixtures. The water absorption coefficient increased with increasing fiber content while the moisture buffer values decreased with increasing fiber content. However, all MBV values are above 2 (g/ (m². %H) so these samples have excellent moisture capacity. The sorption test also showed that the samples reinforced with the fibers have a capacity to absorb moisture from its environment for more than 10 days without showing mold on their surface.

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