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CHARACTERIZATION OF THE CLAY AND FIBRES FOR HYGROTHERMAL MODELLING

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Abstract: Ecomaterials used in traditional construction are experiencing renewed interest for their low environmental impact. However, the lack of reference values for the hygrothermal behaviour of some composite ecomaterials with a low carbon footprint prevents the overall analysis of the structures of buildings designed with these materials. The wood-clay construction system is an ecological and sustainable building system. These materials have great potential for applications in places where housing needs are high, in rural areas of Africa, and have been used for hundreds of years in Europe. The plant fibres improves the hygrothermal, mechanical and weather resistance performance of clay materials. This study determines the water content absorbed by the wheat and corn stalk fibres that will allow the water/clay ratio to be adjusted. For the characterization of red and white clay, the results obtained by the pycnometer method show that the bulk density of the clay is 2.80 and 2.73 with an absolute density of 2.79 g/ml and 2.72 g/ml. The results of the characterization of wheat and corn fibres show that they have the capacity to absorb more than 200% and 120% water by weight in only 25 minutes respectively at 23℃. The water absorption of fibres increases with increasing temperature. This increase contributes to the improvement of the hygrothermal performance of the materials by the restitution of the absorbed humidity, providing a very good feeling of comfort. Samples formulated with 0% to 3% wheat fibre have shown that the addition of fibre reduces the shrinkage of clay materials by 6.35 to 1.53%.

Keywords: hygrothermal performance, wood-clay, building materials, sustainable, cob, characterization

1 INTRODUCTION

Construction activities consume 38% of the energy used worldwide each year [16]. This consumption increases more and more over the years and is linearly linked to CO_2 emissions. In addition to the CO_2 emissions produced by buildings due to heating and air conditioning systems, agricultural waste dumped at production sites poses various ecological footprint issues [1]. The challenge of the efficient disposal of agricultural waste and the growing need to reduce energy consumption in buildings has motivated researchers to examine the incorporation of this waste into clay materials. This new technique allows for the development of innovative, ecological and sustainable building materials to meet the environmental and energy challenge [10]. Regarding the alternative to the choice of materials, several local materials are available to meet the requirements imposed by the field of residential construction. The cob material is one of the materials that can be studied and improved for its integration into modern construction. Orienting the building sector towards the use of these natural composite materials with a wood frame structure is a major issue in the global perspective of sustainable development [14]. Wood-clay-frame construction has a particularly small energy footprint and could help reduce Africa's housing deficit estimated at more than 51 million housing units and will increase by 20.2% by 2050 [4]. In addition to contributing to the reduction of the housing deficit, this type of construction increases the life of the building by providing good seismic resilience to its structure [13]. In this project, the target material is wood-clay or wood-cob. The cob is a mixture of clay and vegetable fibres. It is non-load bearing and serves as a filling for the wood frame. There are few studies on its hygrothermal and mechanical behaviour, aspects which are directly related to the heating and air conditioning needs. Therefore, the study of the hygrothermal and mechanical behaviour of the building envelope is a very important factor. It is a first step to assess the impact of a material on energy consumption and interior comfort which depends on the temperature and relative humidity.

The objectives of the study are:

a. Characterization of two clays, red and white, for their use in the formulation of the study samples,

b. Characterization of plant fibres, wheat, and corn stalk, used to improve the hygrothermal performance of the clay material to determine the optimal dosage between the water/clay and clay/fibre ratio,

c. Development of a mixture of clay-fibre materials conferring satisfactory hygrothermal properties.

This project is part of the dynamics of sustainable development and has a double advantage. It aims to improve the hygrothermal performance of the wood-frame building envelope using clay as a filling material. Moreover, it is a project that will contribute to the reduction of housing deficits in Africa, which represent more than 51 million housing units, and to the creation of new jobs.

1.1 Wood-Clay or Wood-Cob Construction

Earthen construction is a very common construction around the world due to its simplicity and low carbon footprint. This type of construction is very common in countries of the African continent, but also in Europe and North America [7]. Researchers, architects, engineers, and international organizations are looking with great passion for bioclimatic construction with research on the use of innovative clay soil building materials. To this end, several studies have shown that ecomaterials regulate heat and humidity and that cement blocks and metal sheets widely used for the envelope and roofing in urban construction are heating accumulators. Several studies have been carried out on local materials such as cob, rammed earth, adobe, compressed earth, but very few on the cob. However, cob is a building material that is arousing renewed interest in its low environmental impact. The cob is a building material based on clayey earth reinforced with vegetable fibres, which is an improvement on adobe. It is a non-load-bearing material that is used to fill the structure of the wood frame building. The cob has the role of thermal and acoustic insulation, it only needs a finish that would let the cob and the wood frame breathe to prevent mold and rotting of the frame [10]. Vernacular material, the cob reflects local techniques and know-how. The current challenge is to find an alternative formulation of cob that meets the requirements of residential building construction. This will vary the supply of materials in the construction market, contributing to the reduction of the housing shortage as well as the energy demand.

1.2 Clay-Fibre Mix

Mixing the clay with the fibres takes place in several stages. The clay soil is manually extracted at the start of the less rainy season and stored near the site of construction. It is then soaked for several days before being placed in a blender to form a homogeneous wet mass, followed by the addition of humidified or non-humidified fibres [6]. This technique is intended for the construction of wood-frame buildings. Regarding the formulation in the laboratories for the studies, the mixture is made in two parts with soaked or not soaked fibres. For the unsoaked fibre method, the clay was moistened and mixed to obtain a homogeneous mixture before adding the fibres. The mixture is then left to stand for 30 minutes or one hour by filling the framework. The same scenario is repeated for the mixture with the soaked fibres but no need to let the mixture stand. The good time to work on the cob manually in Africa is between March to October to facilitate drying and in North America between April and October to avoid freezing. The cob mixing time can vary, from one hour to 3 days [9]. The three-day duration allows the water to be distributed well in the fibres and the soil. Indeed, the role of fibres is to distribute shrinkage cracks throughout the mass of the wall, improve the cohesion and shear strength of the wall as well as resistance to weathering [9,11,15].

2 MATERIALS AND METHODS

The objective is to develop a material based on the technique of cob while considering the hygrothermal properties and economic relevance. Tests carried out in the laboratory of ETS have made it possible to determine the density of the clays, the capacity of the fibres to absorb water and the speed at which the fibres are able to return water to the environment, thus drying quickly. This shows that the fibres have the capacity to absorb rainwater when used in the formulation of earth materials but also capable of returning it when needed. Six unmoistened and moistened clay-fibre samples with a water/clay ratio of 25% and one fibre-free sample were tested to monitor shrinkage, mass loss, density and cracking during drying for seven days at room temperature (23 °C). Additional mixing will be done by varying the water/clay ratio and the clay/fibre ratio on both sides to determine the optimum water/clay and clay/fibre ratio. These optimum ratios will be used to produce a cob that is strong enough, easy to handle in the short term, and capable of being laid directly into wood walls. The samples were made with 25 cm x 25 cm x 2.5 cm frameworks and left in the open air for three days before being unmoulded. The samples are weighed daily followed by the measurement of the loss of volume, loss of mass and density. These tests will also be carried out on the 30 × 30 × 2.5 cm^3 and 30 × 30 × 7.5 cm^3 samples directly after determination of the optimal water/clay and clay/fibre ratios. The first characterizations of the clays were carried out by the pycnometer method. The dry density and dry mass volume of both clays were determined. The characterization of the fibres was carried out in accordance with [3]. Figure 1 shows the process of mixing clay with fibres.

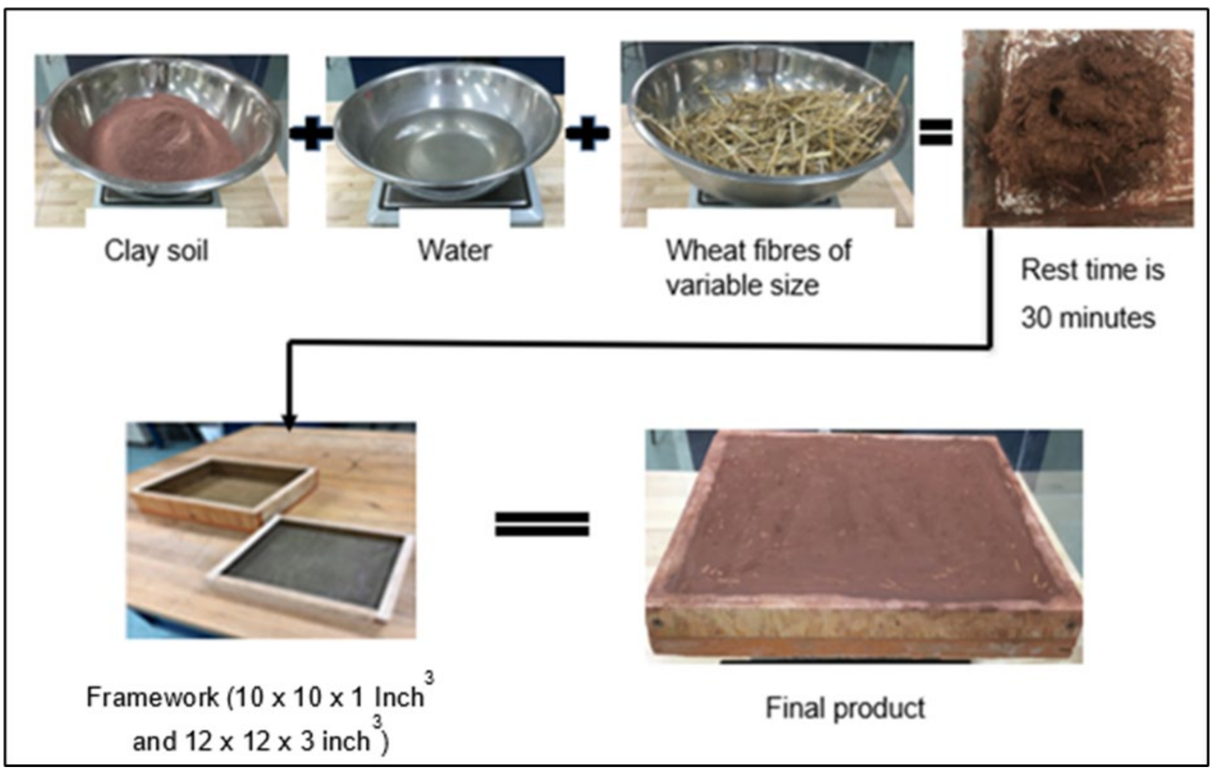

Figure 1: Process of making the cob

2.1 Characterization of the clay

For the characterization of the white and red clay, approximately 200 g of each clay was taken directly from the bags following the guidelines of [2] and weighed using a balance before putting them in the oven for 24 hours at approximately 110℃, then separated into four 50 g parts of each clay. Three 50 g samples were used for each clay for the test. Figure 2 shows the clays prepared for drying and the prototype of the pycnometer method and Figure 3 shows the three samples of the red clay introduced into the pycnometers filled with distilled water (a) and placed in the air bubble eliminator apparatus (b).

a) b)

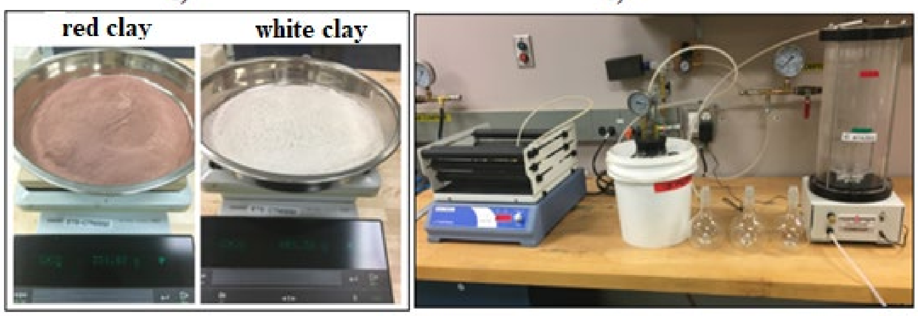

Figure 2: Clay sampling (a) and prototype of the pycnometer method (b)

a) b)

Figure 3: Samples of red clay for tests (a) and removal air bubbles (b)

2.2 Fibre's characterization

The wheat and corn stalk fibres come from the Institut de recherche et de développement agroenvironnement (IRDA) in Quebec City, Canada. Before starting the trials, initial moisture content was determined. The fibres were taken directly from the bags, 10.26 g for the wheat fibres and 10.11 g for the corn stalk fibres and dried in an oven at the temperature of 30℃ for 2 hours for a first calculation. A second calculation was performed by putting these fibres back quickly in the oven at the same temperature for 1 hour. The two drying cycles confirmed that the 2 hours were sufficient for drying. The initial moisture content was determined for this purpose. The characterization was done according to [3] and to evaluate the average length of the fibres, measurements were made on several wheat and corn fibres with a caliper and a measuring roller. Figure 4 illustrates the samples used to determine the initial moisture content (in an anhydrous state) in the fibres.

Figure 4: Samples of wheat fibre (a) and corn stalk fibre (b) before placing in the oven.

For the determination of the water absorption coefficient, 123 g and 62 g of wheat and cob stalk fibre respectively were cleaned with distilled water and dried in the oven at 50 °C for 4 hours (Figure 5). Afterwards, they could cool down before being weighed again. After washing and drying, 120 g of wheat fibre and 61 g of corn stalk fibre were obtained. After cooling for both drying steps (1st drying last 4 hours and 2nd drying 1 hour), the moisture content of the fibres was 0%.

Figure 5: Drying the fibres at 50 °C.

At the end of the washing and drying step, the fibres were separated into three samples of 5 g each for temperature testing. Each sample was completely immersed in distilled water at a temperature of 23°C to perform the water absorption tests. The same procedure is used for the corn stalk fibre absorption test at 23°C. For the 40°C and 50°C tests, each sample is completely immersed in distilled water heated to 40°C and 50°C and placed in the oven set at 40°C and 50°C for 48 hours (3 samples of 5 g per temperature).

3 ANALYSIS OF RESULTS

3.1 Characterization results

3.1.1 Red and white clay

The results of these tests gave density of 2.80 and 2.73 for the red and white clay respectively, density of 2.79 g/cm^3 and 2.72 g/cm^3, with initial water contents of 1.68 % and 1.12 % for the red and white clay, respectively. The results are summarized in Table 1. Red clay is denser than white clay. After these tests, the formulation two first test samples were made with a water/clay ratio of 25% and a fibre variation of 0%, 2% and 3%.

Table 1: Test results of clays with the pycnometer according to the ASTM D854-14 standard.

Type of clay	Density	Density by mass g/cm^3	Initial moisture content % (taken from the bags)	Margin of error %
Red clay	2.80	2.79	1.68	0.016
White clay	2.73	2.72	1.12	0.017

3.1.2 Wheat and Corn Stalk Fibre

The physical characterizations of the fibres on water content, length, water absorption and desorption rate were determined. Corn fibres are very long, they were cut prior to the measurements. The corn stalks in the laboratory are about 110 cm long. The use of corn stalk fibres for mixing requires the milling process. Table 2 presents the results of the physical characterization of the fibres.

Table 2: Physical characteristics of the fibres

Type of fibre	Length of the fibres	Initial water content % (from the bags)
Wheat	30 ± 0.4 cm	7.99
Corn stack	21.31 ± 2.35 cm	6.65

The water absorption rate for each sample is obtained by calculation after each weighing of the fibres removed from the water as a function of time. Equation 1 is used to calculate the water content at time t.

$$m_t = \frac{(m_w - m_d)}{m_d} * 100\ (\%) \qquad \text{Equation 1}$$

m_t	Moisture content for each weighing at each t (time) in %
m_w	Mass of the sample after immersion in water g
m_d	Initial sample mass (anhydrous) g

within 25 minutes of being placed in water, wheat fibres absorb more than 200% of water relative to their initial mass, and water absorption continues until saturation. Whereas corn stalk fibres absorb only about 120% water based on their initial mass for the same number of minutes at room temperature (23°C). The amount of water absorbed increases with increasing temperature and the fibres saturate more rapidly when the temperature is above 23°C. Figures 6 and 7 shows the evolution of the water absorbed by wheat and corn fibres over 48 hours.

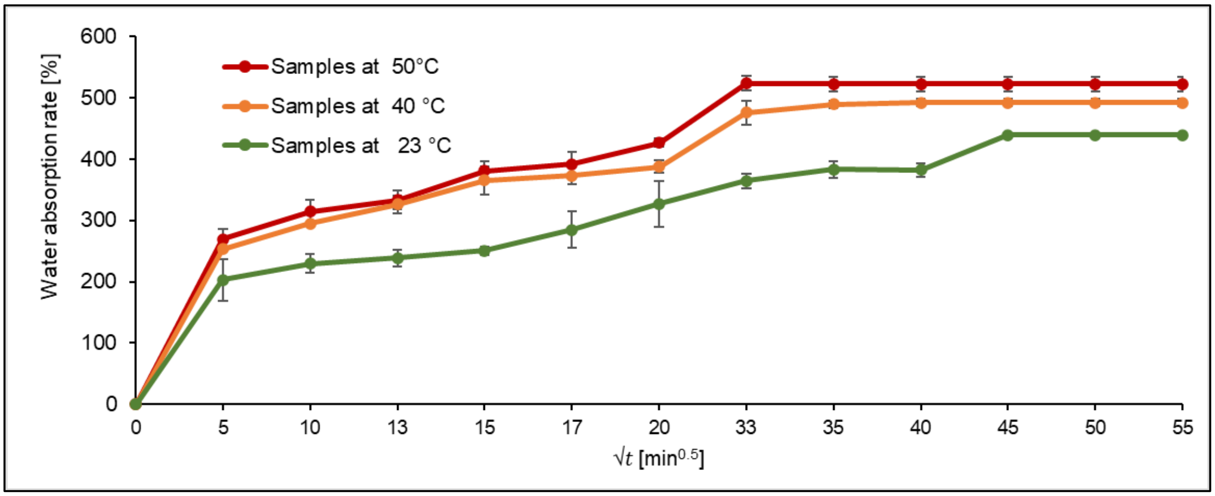

Figure 6: Evolution of the water absorption rate of wheat fibres function of the immersion time

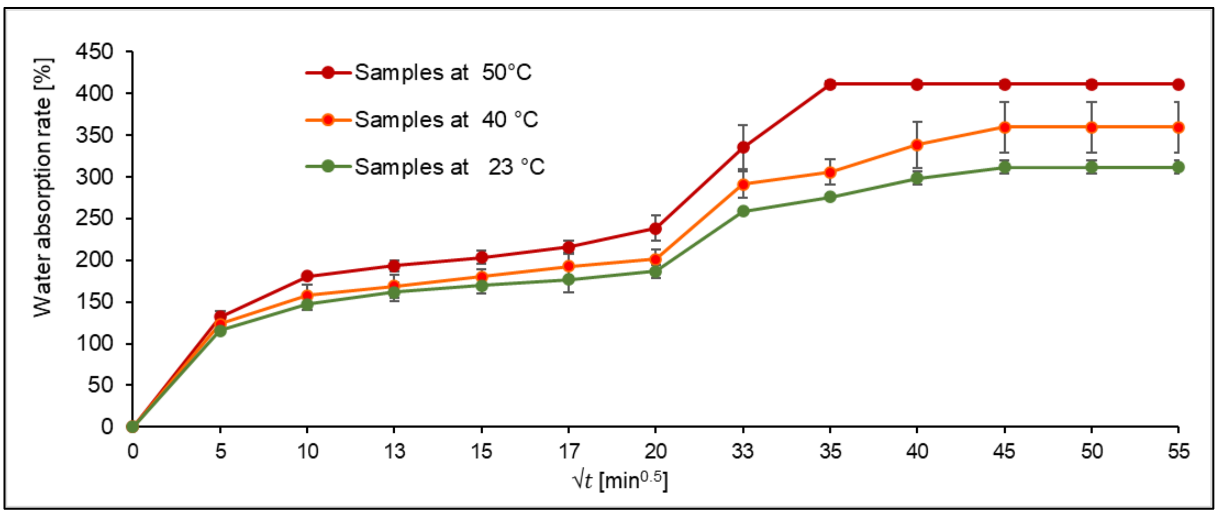

Figure 7: Evolution of the water absorption rate of the corn stalk fibres as function of the immersion time

By comparing the results of wheat and corn stalk fibres obtained in this study with those of hemp and coconut fibres [8], flax[12], alfaıfa [5], the fibre water uptake rates are very high in the first minute of their release or in a controlled environment. The amount of moisture absorbed increases with the temperature of the environment. Wheat fibres can absorb up to 439%, 492%, 523% water by mass for complete immersion in distilled water at temperatures of 23°C, 40°C, 50°C, respectively. Corn stalk fibres absorb 316%, 350% and 410% for complete immersion in distilled water for the same temperatures. Temperature has a significant influence on the water absorption of plant fibres. The higher the temperature, the process of water diffusion into the fibres is accelerated. For all samples used for the tests, the quantities of water absorbed by the wheat fibres are always higher than those of the corn stalk fibres. This can be explained by the fact that wheat fibres have very large capillary pores compared to corn stalk fibres. The high-water absorption of the fibres may also be due to the presence of non-cellulosic hydrophobic materials [5]. For the alfaıfa fibres studied by [5], these fibres can absorb between 156% to 640% of water relative to their initial mass and this is due to the presence of hydrophobic non-cellulosic materials. The high absorption rate values of the vegetable fibres prove that a product made from these fibres will offer a good feeling of comfort since it will absorb more moisture from the ambient air and, if necessary, release it again. To evaluate the ability of the fibres to release the moisture absorbed during the test, all samples were exposed to ambient air for 48 hours at the end of the water absorption test (after saturation). It takes 20 hours for all fibres to become saturated while it takes just 48 hours to return the fibres to their original mass (dry state). The complete loss of water in the fibre structure of corn stalks and wheat fibres is a rapid process. This shows that the use of these fibres in the formulation of clay materials will not cause mold in case rainwater infiltration occurs on the wall surface. However, this infiltration could lead to the modification of the hygrothermal properties of the material. For the formulation of clay/fibre samples, it is necessary to adjust the water/clay ratio to avoid rapidly drying of the final material which can lead to desiccation cracking.

3.2 Mixing Results

The following Figures 8 and 9 compare the mass and density of wheat fibre-reinforced and fibre-free samples in the wet state and after a 7-day drying period. Samples reinforced with moistened fibres have higher masses than samples reinforced with unmoistened fibres and on day 7, the opposite is observed.

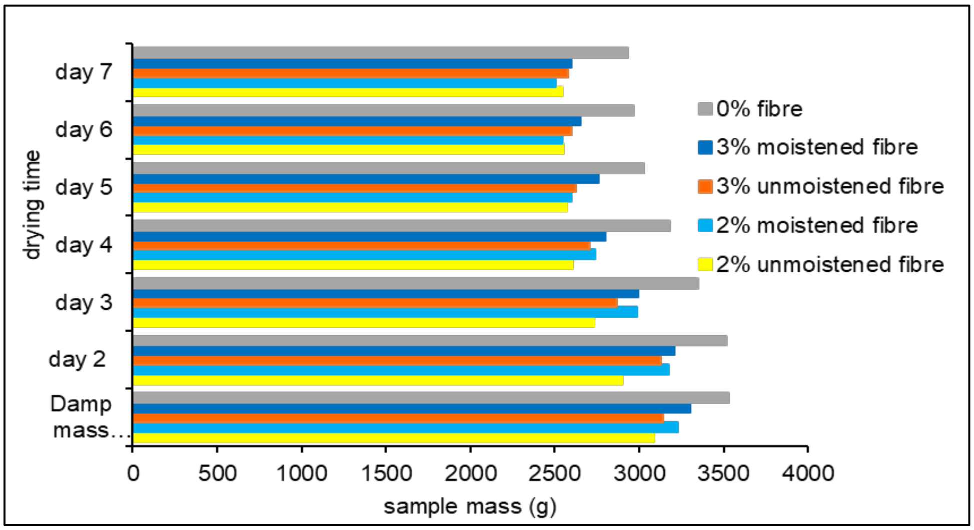

Figure 8: Variations of the mass of the samples as a function of the drying time

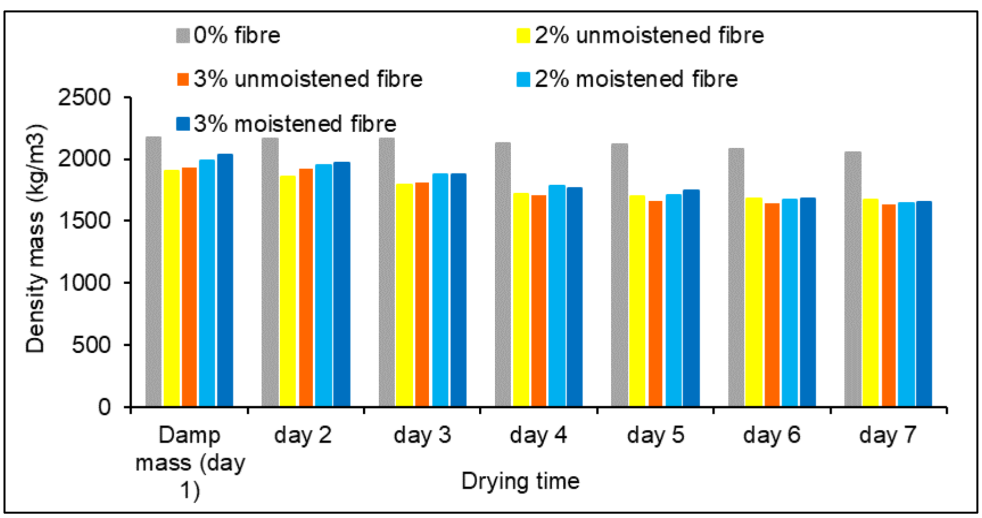

Figure 9: Variation of a sample of the density mass as a function of drying time

The results illustrated in Figure 10 show that in each formulation a withdrawal takes place. This shrinkage is due to the evaporation of water which causes the particles to move closer to the sample matrix. However, it should be noted that the presence of fibres reduces the rate of shrinkage (Figure 10). The time required for stable sample shrinkage is estimated to be after 7 days of drying for the fibre-free formulation, about 6 days for mixtures of 2% and 3% fibres, whether soaked or not. The shrinkage of the 3% fibre-reinforced mixture is 1.53% compared to 6.35% for the fibre-free mixture.

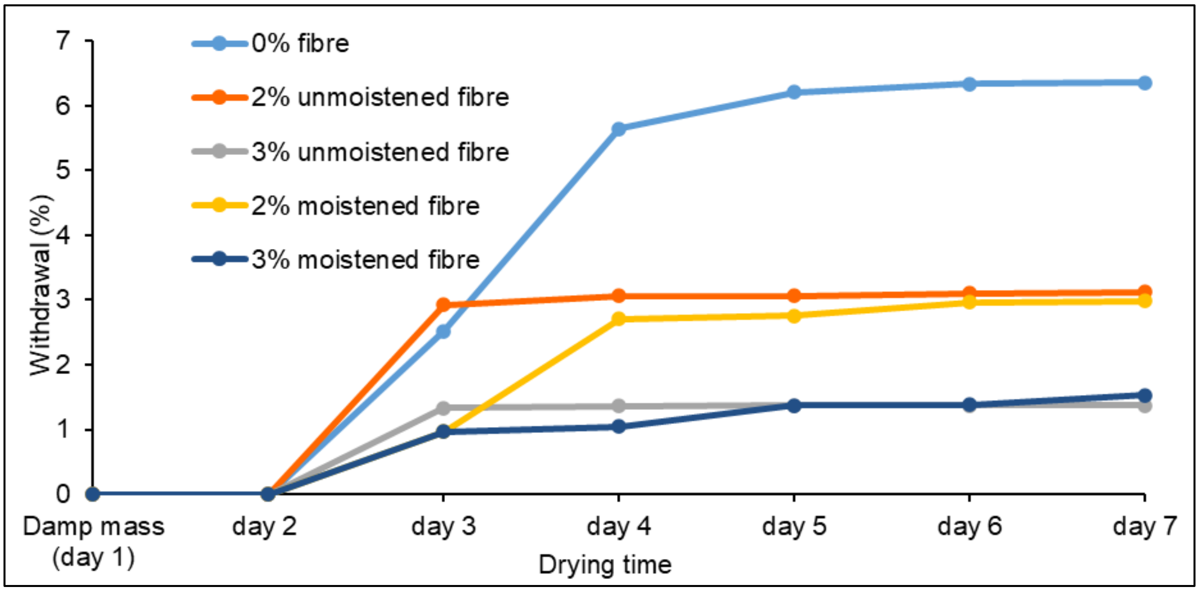

Figure 10: Time dependent water withdrawal

4 CONCLUSION

The knowledge of cob needs to be deepened to be used in modern construction and to promote the understanding of this construction technique for both rural and urban populations. Clay materials are particularly sensitive to water. Adding fibres to clay will increase its sensitivity to water. All the work presented in this article was carried out in the research laboratory of the École de Technologie Supérieure. The objective of this work is to study the hygrothermal and mechanical behaviour of cob for a wood-clay construction. In the first part of the work presented in this article are the test results for water absorption of the fibres and five clay formulations reinforced with wheat fibres with a proportion of fibres that varies between 0% and 3%.

The literature review highlighted the interest of the addition of fibres for earth construction and its capacity to reduce the shrinkage of earth materials. The incorporation of fibres accelerates drying thanks to the rapid removal of moisture from the fibres to the outside environment. In this article, the study was conducted with Canadian red clay and wheat fibres from the research Institut de Recherche et de Développement Agroenvironnement (IRDA) in Quebec City, Canada in Quebec City. The density of the clay used for these tests is 2.79 with a water content of 1.68%. The wheat fibres have a very high sensitivity to water with a very high-water absorption of 200% for an immersion time of 25 minutes. The formulated samples showed that the addition of 3% fibre decreases the shrinkage rate from 6.35% to 1.53%. As cob is a very porous material, the continuity of this study on the analysis of the hygrothermal, mechanical and fire resistance behaviour will be successively carried out. Several samples will be prepared for the continuation of the work with fibres of stems of corn, fibres of wheat, red and white clay. The results presented in this paper and which will be obtained in future work will be used for the hygrothermal simulation model.

5 References

1. Adazabra, A., Viruthagiri, G., & Shanmugam, N. (2017). Management of spent shea waste: An instrumental characterization and valorization in clay bricks construction. Waste Management, 64, 286-304.

2. ASTMD854-14. (2014). Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. ASTM international, 100Barr Harbor Orive,PO Box C700, West Conshohocken.

3. ASTMD2654-89a. (1989). Standard Test Method for Moisture in Textile. ASTM D2654–89a, ASTM; West Conshohocken, PA, USA. 10. Repéré à https://global.ihs.com/doc_detail.cfm?document_name=ASTM%20D2654&item_s_key=00016807

4. Bah, E.-H. M., Faye, I., & Geh, Z. (2018). Housing market dynamics in Africa. Springer Nature.

5. Dallel, M. (2012). Evaluation du potentiel textile des fibres d'Alfa (Stipa Tenacissima L.): Caractérisation physico-chimique de la fibre au fil (Université de Haute Alsace-Mulhouse).

6. Fodde, E. (2009). Traditional earthen building techniques in Central Asia. International Journal of Architectural Heritage, 3(2), 145-168.

8. Ho Thi, T. N. (2008). Étude de l'influence de la température et de l'humidité sur les propriétés mécaniques en traction des fibres de chanvre et de coco (École de technologie supérieure). Repéré à http://espace.etsmtl.ca

9. Keefe, L. (2012). Earth building: methods and materials, repair and conservation. Routledge.

10. Muntean, R., GrÄa, dinaru, C. M., È, tild, erbÄa, . . . Sârbu, G. C. (2020). Improved concrete blocks with dispersed fibers as contribution for environmental protection. Environmental Engineering and Management Journal, 19(1), 85-94. Repéré à https://www.scopus.com/inward/record.uri?eid=2-s2.0-85090927892&partnerID=40&md5=27d0eb98c6fe2fcf8247b7d177e243b9

11. Phung, T. A. (2018). Formulation et caractérisation d'un composite terre-fibres végétales: la bauge.

12. Roudier, A., Charlet, K., Moreno, F., Toussaint, E., Géneau-Sbartaï, C., Commereuc, S., . . . Béakou, A. (2012). Caractérisation des propriétés biochimiques et hygroscopiques d’une fibre de lin. Matériaux & Techniques, 100(5), 525-535.

13. Tomovska, R., & Radivojević, A. (2017). Tracing sustainable design strategies in the example of the traditional Ohrid house. Journal of cleaner production, 147, 10-24. Repéré à www.elsevier.com/locate/jclepro

14. Umurigirwa, B. S. (2014). Élaboration et caractérisation d'un agromatériau chanvre-amidon pour le Bâtiment (Reims).

15. Watson, L., & McCabe, K. (2011). The cob building technique. Past, present and future. Informes de la Construccion-Revista, 63(523), 59.

16. Yüksek, Í. (2015). The evaluation of building materials in terms of energy efficiency. Periodica Polytechnica Civil Engineering, 59(1), 45-58.