Industrial Crops & Products 215 (2024) 118626

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

# Improved insulation with fibres in heavy cob for building walls

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A R T I C L E I N F O

*Keywords:*
Thermal properties
Wheat fibres
Clay/fibres
Cob
Clay panels
Wood structure
Sustainable buildings

A B S T R A C T

Earth construction promises to reduce the carbon dioxide impact of building materials, and more investigations are needed to define regions where the latter are suitable. This work aims to formulate clay materials reinforced with plant fibres in a traditional manner to determine their thermal properties for applications in modern wood-frame structures. The main objective is to manufacture cob using different types of clay, disregarding the clay/sand ratio, and to achieve a solid cob material characterized by an absence of cracks, low volumetric shrinkage, and thermal properties like those of a normal cob. The Atterberg limits of each clay and the absorption coefficient of the fibres were determined before the samples were made. Formulation of 93 samples was carried out with 15, 20, 25, and 30 % water and 0 %, 3 %, and 6 % wheat fibers by mass. Subsequently, 18 samples produced with 25 % water and 0 %, 3 %, and 6 % wheat fibres by mass were retained and used for testing. The thermal conductivity (λ), specific heat capacity ($C_p$), thermal diffusivity (D), and thermal effusivity (E) were measured after sample drying. The study showed an improvement in thermal properties with increasing fibers in the mixtures, leading to a significant improvement in thermal performance. The clay and cob samples showed a thermal conductivity (λ) of 1.16 W/(m K) and 0.55–0.2 W/(m K), respectively. An increase in thermal capacity was observed with the samples containing fibre, while the thermal diffusivity and thermal effusivity decreased with increasing fibres in the mixtures. Single-factor ANOVA tests were used to show no significant difference between the thermal properties of red and beige clay samples. Our observation supports the idea that beige clay can be used as a finishing coating material for cob walls formulated with red clay.

## 1. Introduction

Eco-materials are promising alternative materials for the construction sector, but additional data are needed to define how they can be reintroduced into certain regions. Earth materials present several advantages, including availability, low energy consumption during production and use (and at the end of their life), and the possibility of being recycled, in contrast with synthetic and non-biodegradable materials (Aubert et al., 2022; Laborel-Préneron et al., 2018; Sathish et al., 2022). These materials, which have been recognized in traditional construction for thousands of years, are currently experiencing a resurgence of interest due to their low environmental impact. Approximately 15 % of the architectural works appearing on the UNESCO World Heritage List are built using earth (Saidi et al., 2018; Zeghmati et al., 2016). The wood/cob construction system is an ecological and sustainable method. Compared to traditional clay structures, this type of construction increases the lifespan of the building thanks to the wood frame used as a load-bearing structure (Tomovska et al., 2017; Volhard, 2016). The wood frame provides better resistance to structural stresses, such as soil movements and seismic loads, which allows the building to remain strong and stable over a longer period. Earth material mixed with plant fibres is carbon-neutral and contributes to the fight against climate change. This mixture holds significant potential for use in regions with high demand for housing and cooling, particularly in rural Africa. With a housing deficit of approximately 51 million units and a rapidly growing population, the African continent could benefit greatly from this innovative solution (Bah et al., 2018). Using available low-carbon or carbon-neutral materials in construction could reduce the global warming potential and energy demand of buildings by providing suitable, sustainable, and environmentally friendly housing. The use of these materials could also help to address the housing deficit, especially in regions where housing is scarce or inadequate. The thermal properties of earth building materials foster the self-regulation of indoor humidity and temperature by reducing the use of air conditioning and heating systems (Meyer, 2010). Wood/clay walls are soundproof, termite-resistant, and chemical-free, and the wood frame provides good

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https://doi.org/10.1016/j.indcrop.2024.118626
Received 23 November 2023; Received in revised form 6 April 2024; Accepted 25 April 2024
Available online 7 May 2024

seismic resilience for the building structure (Meyer, 2010; Tomovska et al., 2017). However, earthen materials are criticized for their sensitivity to water and weathering, which makes them unsustainable, and explains their limited thermal performance (Lahbabi et al., 2024). Current thermal regulations require the use of efficient insulating materials to limit energy needs during the use phase of the building. The building envelope design takes advantage of the thermal inertia of these materials. All these have led to the study of several techniques, such as mechanical stabilization (where earth materials are compressed by machines to obtain earth blocks), chemical stabilization (where cement is mixed with clay earth), stabilization by firing unstabilized or chemically stabilized earth blocks, and physical stabilization (in which clay earth is mixed with plant or organic fibres). Nevertheless, it should be noted that mechanical, chemical, and baking stabilization improve mechanical properties at the expense of thermal properties (Ouedraogo et al., 2016). Physical stabilization using plant fibres is the only method that improves the thermal properties of earth materials (Ouedraogo et al., 2016). Nevertheless, it is important to consider factors such as the type of fibres, fibre size, fibre dosage, and material manufacturing technique. These factors make use of the manufacturing technique more complex for producing materials on construction sites. Nevertheless, the key concept of an optimized building envelope relies on the thermal properties and composition of the envelope materials (Bekkouche et al., 2014).

Earth composite materials reinforced with plant fibres remain a biodegradable material that can easily meet thermal performance requirements if used appropriately. As shown in the literature, the addition of plant fibres to the earth-clay mixture improves the thermal behavior (Laborel-Préneron et al., 2018; Millogo et al., 2014). Therefore, the implementation of wood/cob walls meets sustainable development objectives. These types of walls are durable, recyclable, and reusable at the end of their life. Cob materials are traditionally manufactured without industrial processing and used on-site to fill the structures of wood-frame buildings (Gomaa et al., 2021; Keefe, 2012; Quagliarini et al., 2010). However, their use in wood construction is hampered by a lack of data on their thermal properties such as thermal conductivity, thermal effusivity, thermal diffusivity, and specific heat. This data needs to be available for the thermal performance of the wood/clay mixed fibre envelope to be assessed. Existing constructions are made of rammed earth, compressed brick, and adobe, which are the materials that have been most extensively studied in the literature (Muazu et al., 2017; Patenaude, 2010; Spišáková et al., 2015; Waters et al., 2016). Cob, which is a carbon-neutral eco-material, has not been the subject of many studies, and studies on this type of construction to date have focused on existing buildings.

The current challenge is to identify an alternative cob formulation that could be easily reformulated on construction sites, as this would diversify the material supply in the construction market. Furthermore, it would contribute to mitigating housing scarcity and reducing energy consumption in the building sector (Alassaad et al., 2022; Alassaad et al., 2023; Gounni et al., 2019; Touati et al., 2023). In Africa and other regions, red clay is commonly used as filler material, while white and beige clay are applied for finishing. For example, the Winchester Hampshire Amesbury adobe building was finished in white clay, the multi-family and single-family dwellings built by Colombian architects Mauricio Sanchez and Dario Angulo were finished in beige clay, and 1200 adobe homes were finished in white clay in New-Gouma (Maniatidis et al., 2003; Paulus, 2015). In the Middle East, Latin America, China, and India, earthen constructions exist in the form of vernacular buildings (Anger, 2011; Paulus, 2015). In Europe, old earthen buildings are still used for housing (Hall et al., 2012). Further data on the thermal performance of these materials and of cob is needed to facilitate their use in other parts of the world.

Research on earth and fibre building materials has been conducted under various conditions in previous research. Moroccan researchers have produced two reinforced materials with 2 % and 4 % sisal fibre for construction (Ouakarrouch et al., 2020). For the fabrication of the test samples, the fibres were washed with water, dried, and cut to a length of 2 cm before being used. The researchers discovered that incorporating sisal fibres in the clay reduced thermal conductivity by 11.2 %, while thermal diffusivity was reduced by 8 %. The specific heat of the composite was also increased. Despite the improved thermal properties of these samples, reproducing the material in large quantities on a construction site is complex. Alfa fibres are often used in the fabrication of test samples (Ajouguim et al., 2021). The fibres are typically treated with an alkaline treatment by immersing them in a soda solution for 6 h, followed by a hydrothermal treatment in which they were immersed in boiling water for 1 h. After fabrication with a hydraulic press, the samples are stored in plastic bags for 7 days. This sample fabrication method is very challenging for large-scale reproduction in real-world construction. As the samples are manufactured by compression with a hydraulic press, using them to fill wooden building structures could be complicated due to the inconsistency of the mixture (Danso et al., 2015; Laborel-Préneron et al., 2017; Laborel-Préneron et al., 2016; Laborel-Préneron et al., 2018). Also, the sample fabrication methods available are too complex for use as filling cob materials for wood frames. However, the previous studies pretreated the fibres in the laboratory and these conditions are not realistic in the field conditions.

In our study, to ensure that the cob mixtures could be used in other countries, red and beige clays were selected as they are the two main types of clay used for earth construction in most of Africa and on other continents. This paper presents the results of experiments aimed at finding the optimal water/clay ratio for sample production using the cob manufacturing technique, along with the thermal properties of the resulting samples. In our work, the cob is manually mixed using hands, a shovel, and on foot with boots on, and a concrete mixer can be used for the mixing process in large quantities. Manual production was chosen because the fibre-reinforced clay used to fill the wooden frame is typically made by hand and foot on construction sites in Africa. The proposed fabrication method is very accessible, and no machinery or no fibre pre-treatment is needed. Additionally, reproducing this type of material in different geographical conditions is easily achievable when the data, production method, and resting time of the mixture are available. The choice of the basic components for the mixture is based on their availability on the African continent. The wheat fibres added to the mix in this study were chosen based on availability. The novelty of this article is to evaluate the thermal properties of cob material made with traditional methods with current characterization methods such as steady-state thermal transmission method and modified transient plane source method. These two characterization methods have allowed for a more precise and comprehensive evaluation of the thermal properties of cob. In addition, statistical tests have been conducted to validate these results. Cob is a material traditionally used in construction, but its thermal properties have not been fully exploited and validated until now. This study aims to fill this gap and provide accurate data on their thermal properties.

## 2. Materials and methods

### 2.1. Materials

Red (Redstone) and beige clays (Midstone) were provided by Plainsman (Alberta, Canada) with an initial water content of 1.68 % and 1.12 % respectively (Kaboreé et al., 2021). The wheat fibres used for the formulation of the samples of this project were obtained from the Institut de Recherche et de Développement en Agroenvironnement (IRDA) in Quebec, Canada (Fig. 1). They were 0.4 cm to 30 cm in length with an initial water content of 7.99 %. Before fabrication of the samples with these fibres was started, their capacity to absorb water was determined according to the ASTM D2654 standard (ASTMD2654–89a, 1989) to adjust or choose the mode of wetting of the fibres. Distilled water was used for fibre uptake testing, while potable water from the laboratory


**Fig. 1.** Photographic images of a) the red clay, b) the beige clay, c) the dry fibres, and d) the wet fibres.

was used for sample preparation. Before the absorption tests, a 123 g mass of wheat fibres was cleaned with distilled water and dried at 50 °C in an oven before sampling. After drying, the fibres were separated into three 5 g samples, and each sample was completely immersed in distilled water at a temperature of 23 °C for water absorption tests. The clays were also characterized before use, and the characterization methods and results are described in another article (Kabore et al., 2024).

### 2.2. Methods

#### 2.2.1. Atterberg limits

The liquidity limits of the clays were measured by the Casagrande method and the plasticity limit by the roll method, following the guidelines of the CAN/BNQ-2501–090 Canadian standard (CAN/-BNQ-2501–090, 2011). After the liquidity and plasticity limits were determined, the plasticity index IP, which corresponds to the average clay plasticity range, was calculated using Eq. 1:

$$IP = wL - wp \tag{1}$$

where IP is the plasticity index in %, wL the liquidity in %, and wp the plasticity limit in %.

#### 2.2.2. Samples production: water-to-clay and water-to-fibre ratios

The samples of the tests were composed of clay materials, wheat fibres, and water. The experimental tests to assess the quality of the mixture was conducted by varying the water/clay ratio respectively by 15 %, 20 %, 25 %, and 30 % before adding 3 % and 6 % fibres by mass. Fibre-free samples, measuring 25.4 cm × 25.4 cm × 2.54 cm (10 in. × 10 in. × 1 in.), were fabricated for each water/clay ratio. This step was meant to determine the optimal water/clay ratio that yields uncracked samples with low shrinkage (fibre-free samples). The best-performing water/clay ratio would then be used to produce the samples with fibres. Fig. 2 illustrates the water/clay ratio selection experiments.

The fibre-free samples made with a 25 % water/clay ratio showed no cracking. The red and beige clay samples showed cumulative shrinkage of 13 % and 12 %, respectively (Kabore et al., 2024). This ratio was chosen to produce the fibre-free specimens for testing and to continue with the quality control tests for the fibre-reinforced samples. Samples made with 15 % and 20 % of water were difficult to press by hand. They were unsuitable for use in filling the wood frames, including those at

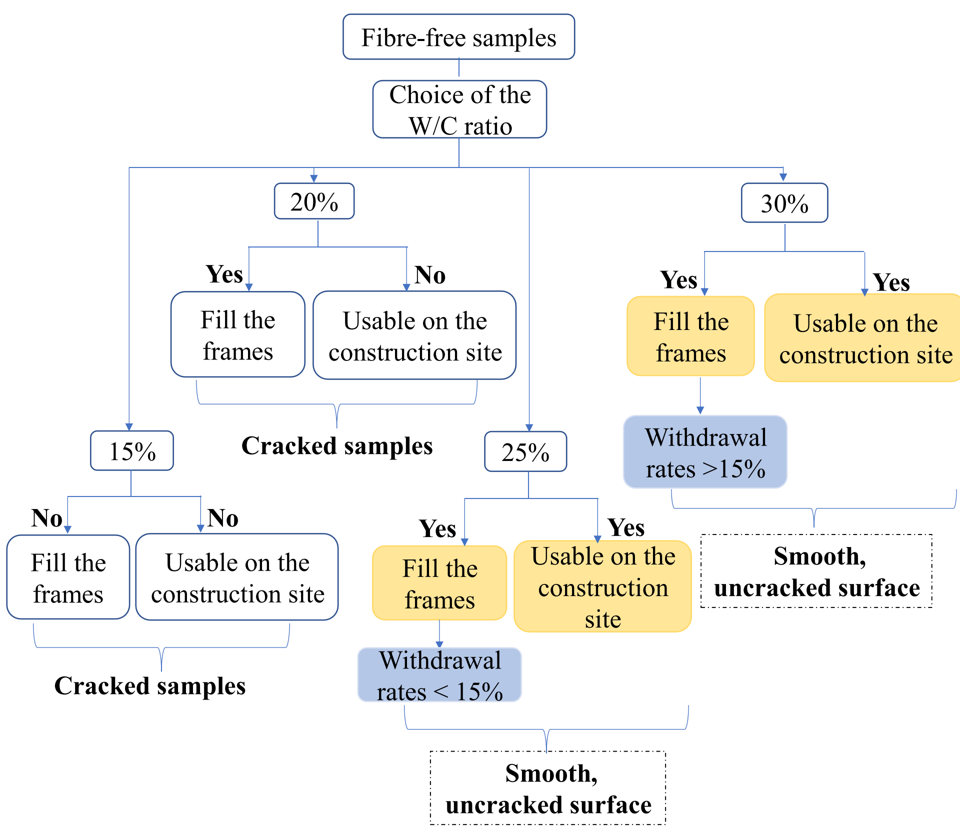


**Fig. 2.** Experiments to select the water/clay ratio.

construction sites. For the mixtures with 30 % water, the shrinkage rate exceeded 15 %, and so using this mixture to produce samples is not recommended.

To produce fibre reinforced samples, it was crucial to determine the fibre wetting method that would achieve the ideal plastic state of the mixture. Therefore, some samples were made with dry fibres, while others were made with humidified fibres. Water absorption tests of the fibres was carried out for this purpose. The fibres were immersed in distilled water and the measurement of water absorption began after 6 min. It was observed that the fibres can absorb (205 ± 15) % of their weight in water after 25 min of immersion and (439 ± 2) % of their weight in water after 60 h of immersion (saturated state). The high-water absorption of fibres is due to the presence of non-cellulosic hydrophobic materials in their structure (Dallel, 2012). This high-water absorption has also been observed for several other types of vegetable fibres (Betené et al., 2022; Dallel, 2012; Hamza et al., 2013; Surajarusarn et al., 2019). The objective of these tests was to optimize the number of sample fabrication trials with different water/fibre ratios. The water/fibre ratios used for fibre humidification are (50 ± 34) % (205 ± 15) %, and (439 ± 2) % by weight of water. These percentages represent the amount of water absorbed by the fibres during absorption tests. The immersion time for the fibres to obtain these ratios was respectively 6 min, 25 min, and 60 h for saturated state fibres.

The samples obtained with unhumidified fibres and those with 50 % humidified fibres were unusable due to cracks observed on both their surfaces. Those reinforced with fibres that had been wetted for 25 min showed no cracks, while those made with water-saturated fibres exhibited small surface cracks. In this step, the choice of technique for fabricating the samples with the fibres was also based on the quality of the mixture, the samples, and the cracking rate after drying, according to the experimental process explained in Fig. 3.

Subsequently, the water/clay ratio of 25 % was chosen to produce the samples with and without fibres for all tests. Samples reinforced with 3 % fibres showed a shrinkage rate ranging from 2 % to 5.3 %, and those with 6 % fibres had a maximum shrinkage rate of 1 %, whether the fibers were moist or not (Kabore et al., 2024). Depending on surface cracking, samples reinforced with wheat fibres for the tests were made with humidified fibres at a 205 % water/fibre ratio (water absorption coefficient of the fibres after 25 min of testing). After humidification, the fibres were kept for 2–3 h before being used in the mixtures. The samples for hygrothermal testing were prepared with specific dimensions. Two apparatus were used to measure the thermal properties. For the TPS-3500 apparatus, the samples measured 25.4 cm × 25.4 cm × 2.54 cm (10 in. × 10 in. × 1 in.), while for the Trident apparatus, the samples were 3.8 cm (1.5 in.) in height and 3 cm (1.2 in.) in diameter.

The samples were dried after demolding in an oven at 30 °C for 10–11 h for maximum moisture removal. Once they were taken out of the oven, they were left to air dry in the ambient atmosphere in the laboratory for 7 days at 23 °C. The steps involved in sample production are shown in Fig. 4. Next, they were weighed, and Eq. 5 was used to calculate the density of each sample, using their respective mass and volume:

$$\rho = \frac{m}{V} \tag{2}$$

with ρ is the density in kg/m$^3$, m is the sample weight in kg, and V is the sample volume in m$^3$.

### 2.2.3. *Thermal conductivity from steady thermal transmission*

Thermal properties were evaluated on 18 samples measuring 25 cm × 25 cm × 2.54 cm with the TPS 3500 (Hot Disk AB, Sweden) heat flow meter apparatus, according to the ASTM C518 standard (ASTM, C518–04, 2009), based on the transient plane source technique, also known as the hot disc method. Before testing, the surfaces of all samples were smoothed with abrasive paper. The samples were conditioned at a temperature of 23 °C and relative humidity of 50 %RH in a climate chamber. After the mass of the samples had stabilized, measurements began. The test protocol was performed at room temperature (23 °C). The thermal conductivity, thermal diffusivity, and specific heat were determined simultaneously and the thermal effusivity was then calculated by using Eq. 2:

$$E = \sqrt{\lambda \rho C_P} \tag{3}$$

where E is the thermal effusivity in J/(m$^2$. K.s$^{1/2}$), λ is the thermal conductivity in W/(m.k), ρ is the sample density kg/m$^3$ and Cp is the specific heat in J/(kg. K). The experimental setup is presented in Fig. S1a, b.

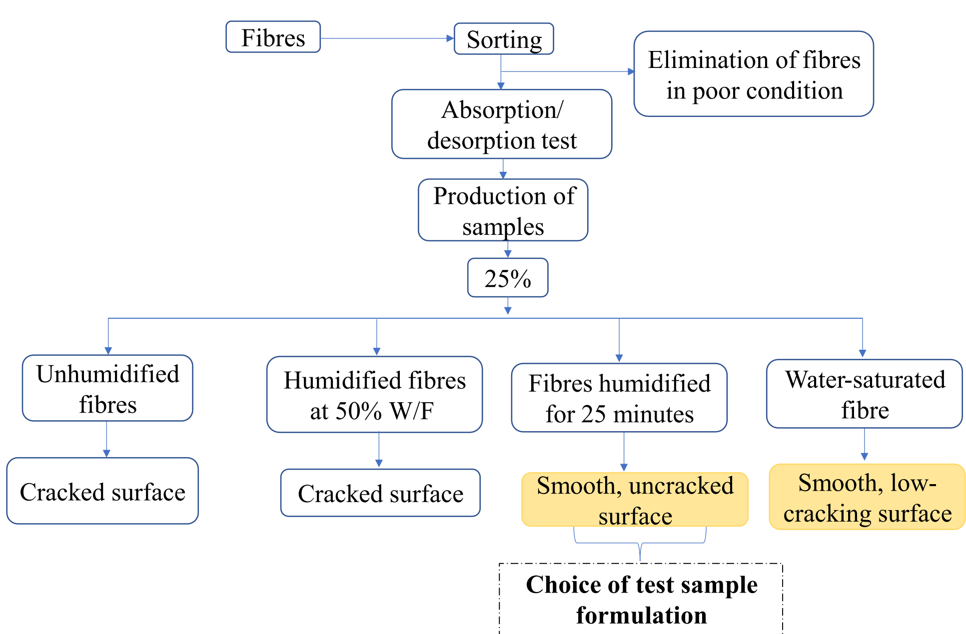


**Fig. 3.** Step to select the fibres humidification mode with water/clay to 25%.


**Fig. 4.** Steps in the production of samples.

### 2.2.4. *Thermal conductivity and effusivity from a modified transient plane source instrument*

Thermal conductivity and thermal diffusivity measurements were performed using the Trident device (C-Therm Technologies, Canada), a modified transient plane source instrument (MTPS), on 18 samples measuring 3 cm in height and 3.6 cm in diameter, in accordance with the ASTM D7984 standard at an ambient temperature of 23 °C (ASTM D7984, 2016). Tests were performed on samples conditioned at ambient laboratory temperature and humidity (23 °C and 50 %RH) and on dried samples. The moisture content of the samples after conditioning ranged from 0.53 % to 0.39 %. To obtain the dry thermal properties of the samples, they were dried at 105 °C in an oven for 24 h. The first step was to calibrate the device with the reference sample, which had similar thermal properties as earth samples. After calibration, the second step was to place the test sample on the sensor after applying a contact agent (thermal paste) to reduce the contact resistance. Pressure was applied on the sample to ensure the best possible contact. After thermal stabilization, the sample was heated with a direct electric current generated by the MTPS Trident sensors. Unlike the TPS 3500 device, the Trident instrument measures the thermal conductivity and thermal effusivity. The thermal diffusivity and specific heat were then calculated using Eqs. 3 and 4:

$$D = \frac{\lambda^2}{E^2} \tag{4}$$

$$C_P = \frac{\lambda}{D.\rho} \tag{5}$$

with D is the thermal diffusivity in $m^2/s$, E is the thermal effusivity in $J/(m^2.K.s^{1/2})$, Cp is the specific heat in J/(kg.K), λ is the thermal conductivity in W/(m.k) and ρ is the sample density $kg/m^3$. The thermal properties of six mixtures were measured with three replications for each mixture. The experimental setup is presented in Fig. S1c, d.

### 2.2.5. *Statistical test*

The data are presented as the means ± standard deviation (SD) of three independent replicates or more. All results presented in the tables were subjected to ANOVA or a t-test. Individual means were compared for the identification of significant differences at $p < 0.05$. Errors bars on the graph were generated using 2 SD.

## 3. Results and discussion

### 3.1. *Atterberg boundary: liquidity and plasticity limits of clay*

The average liquidity value limits observed after the tests vary between 33 % and 36 % for the red clay, and between 31 % and 35 % for the beige clay, while the number of strokes of the Casagrande apparatus varies between 18 and 32 and 17 and 34 for the red and the beige clay, respectively. The plasticity limits determined after the tests were (15.3 ± 0.3) % for the red clay and (16.4 ± 0.4) % for the white clay. The liquidity limits obtained during the tests were (32.5 ± 0.6) % for the red clay and (34.0 ± 0.8) % for the beige clay. The Atterberg limits of different clays obtained in the literature vary greatly. The liquidity limit values are between 20 % and 45 %, while the plasticity limits are between 15 % and 29 %. In some cases, the liquidity limits range between 39 % and 70 %, while the plasticity limits go from 24 % to 35 % (Aubert et al., 2015; Chakchouk et al., 2006). The Atterberg limit values obtained for the two clays are in line with the range of compared values.

For the plasticity index, the usual values for clay soils used to manufacture compressed earth brick samples range from 10 % to 39 %; for adobes, 20–39 % (Fabbri et al., 2022). Table 1 presents a summary of the liquidity limits, plasticity limits, and plasticity index results. The tested clay samples present a lower plasticity index as compared to some data in the literature.

### 3.2. Thermal properties of clay fibres and earthen samples

#### 3.2.1. Thermal conductivity and specific heat

Table 2 shows the thermal conductivity and specific heat mean values and standard deviations obtained for samples conditioned at 50 % RH and 23 °C from measurements of the steady thermal transmission method according to the ASTM D518 standard and the modified transient planar source method according to the ASTM D7984 standard. Statistical tests showed that the thermal conductivity values (λ) measured with the steady thermal transmission method (TPS-3500) are slightly higher than those measured with the modified transient planar source method (Trident) for the two clays with 3 % and 6 % fibre samples (Table S1-S3). The difference between the two methods can be explained by the difference in the acquisition environment. The TPS-3500 is a sensitive method performed under a controlled environment. Consequently, slight variations in conditions affect measurement results. In contrast, the Trident method is used to measure thermal conductivity in unstable conditions, which means that small changes in temperature and relative humidity will not affect the measured results. As widely reported in the literature, the use of plant fibres to produce clay-based composite materials offers significant advantages, particularly in terms of improving thermal insulation. Additionally, this practice also facilitates the efficient removal process of plant fibres on agricultural sites. The test results showed an improvement in thermal conductivity of the samples with a fibre content of 3 % from 40 % to 51 % and from 56 % to 63 % for the samples with a fibre content of 6 % (Table S3).

This improvement in insulation can be explained by the decrease in density due to the increase in porosity of the material thanks to the fibres in reinforced clay samples. Air-filled pores significantly reduce the materials' thermal conductivity. The thermal conductivity of the air is 0.026 W/(m. K). Due to the low thermal conductivity of these materials, they are more insulating and thermally efficient. For the specific heat, a 2–10 % improvement is observed for the samples reinforced with 3 % fibres and from 3 % to 10 % for the 6 % fibres (depending on the type of test). The thermal conductivity values of the clay fibre-free materials conditioned at 50 %RH and 23 °C presented in the literature vary between 1.25 and 1.66 W/(m. K) with specific heat between 817 and 1129 J/(kg. K) (Bal et al., 2013; Laou, 2017; Medjelekh, 2015; Millogo et al., 2014). Other authors have presented thermal conductivity values between 0.50 and 1.10 W/(m. K) with specific heat between 678 and 1030 J/(kg. K) obtained for dried clay fibre-free materials (Cagnon et al., 2014; El Azhary et al., 2017; Laborel-Préneron et al., 2018; Maillard et al., 2014). The thermal conductivity and thermal capacity values obtained with the two tests align with the thermal conductivity values in the literature. With the samples conditioned at 50 %RH and 23 °C, the thermal conductivity increases significantly (Ouellet-Plamondon et Kabore, 2023).

**Table 1**
Summary of test results.

| Clay | Liquidity limit $W_L$ % | Plasticity limit $W_p$ % | Plasticity index IP % |
|---|---|---|---|
| Red | 32.5 ± 0.6 | 15.3 ± 0.3 | 17.2 ± 0.3 |
| Beige | 34.0 ± 0.8 | 16.4 ± 0.4 | 17.6 ± 0.4 |

**Table 2**
Density, thermal conductivity, and average specific heat of the samples conditioned at 50 % RH and 23 °C.

| | | Steady thermal transmission | | | Modified transient planar source method | | |
|---|---|---|---|---|---|---|---|
| Clay | Fibre % | ρ kg/m³ | λ W/(m.K) | Cp J/(kg.K) | ρ kg/m³ | λ W/(m.K) | Cp J/(kg.K) |
| Red | 0 | 2016 ± 17 | 1.16 ± 0.25 | 786 ± 52 | 1954 ± 21 | 1.10 ± 0.05 | 901 ± 7 |
| | 3 | 1654 ± 80 | 0.70 ± 0.07 | 865 ± 60 | 1538 ± 17 | 0.55 ± 0.03 | 917 ± 5 |
| | 6 | 1412 ± 80 | 0.51 ± 0.02 | 870 ± 69 | 1370 ± 80 | 0.42 ± 0.04 | 927 ± 20 |
| Beige | 0 | 1956 ± 16 | 1.28 ± 0.06 | 738 ± 33 | 1914 ± 51 | 1.13 ± 0.01 | 930 ± 18 |
| | 3 | 1588 ± 39 | 0.56 ± 0.01 | 962 ± 12 | 1650 ± 55 | 0.60 ±0.03 | 903 ± 34 |
| | 6 | 1367 ± 80 | 0.44 ± 0.07 | 1133 ± 14 | 1400 ± 63 | 0.42 ± 0.05 | 988 ± 22 |

The clay samples with 3 % and 6 % fibres have thermal conductivity values ranging from 0.20 W/(m. K) to 0.52 W/(m. K) for dry red clay and from 0.40 W/(m. K) to 0.58 W/(m. K) for dry beige clay. The increase in the quantity of fibres to 6 % improves the thermal performance by 75 % for red clay samples (Table S4) and by 54 % for beige clay samples (Table S5). In comparison, it has been demonstrated that the most effective vegetable fibres for improving the thermal performance of clay materials is straw (Laborel-Préneron et al., 2018). Indeed, the addition of 6 % fibres in the mixture leads to a 75 % reduction in thermal conductivity compared to the fibre-free mixture. These results are consistent with our findings.

The thermal conductivity values appearing in the literature vary between 0.26 W/(m. K) and 0.7 W/(m. K) with a specific heat between 596 J/(kg. K) and 897 J/(kg. K) (Bachar et al., 2015; El Azhary et al., 2017; Laborel-Préneron et al., 2018; Medjelekh, 2015). The specific heat values obtained with the Trident apparatus are slightly higher than those obtained in the literature. The specific heat values increase with the volume of fibres contained in the mixtures due to the presence of more voids (pores) in the material. The same observation has been made in the work of other authors (Charai et al., 2022; Laborel-Préneron et al., 2018; Limami et al., 2023; Sayouba et al., 2023). However, this increase could be attributed to the type of fibers and the method used for the production of the test samples (Sayouba et al., 2023; Tchiotsop et al., 2022). These results show that the addition of wheat fibres in the clay matrix positively affects the thermal properties of clay-based materials.

This combination simultaneously improves thermal conductivity and specific heat. The incorporation of more fibres in clay mixtures is very useful for the development of insulating materials for the construction of thermally efficient wood-frame residential buildings. The advantage of adding fibres in clay mixtures is also observed in the works of several authors, regardless of the fabrication method (Charai et al., 2020; Laborel-Préneron et al., 2018; Mellaikhafi et al., 2021). The effect of the fibre content on the thermal conductivity and specific heat of the samples dried and conditioned at 50 %RH and 23 °C is shown in Fig.5 and Fig.6.

#### 3.2.2. Thermal effusivity and diffusivity averages of clay fibres and earthen materials

Table 3 shows the thermal diffusivity and thermal effusivity values obtained from measurements made with the steady thermal transmission (according to ASTM D518) and modified transient planar source methods (according to ASTM D7984) (mean values and standard deviations). The thermal diffusivity and thermal effusivity are more affected by the addition of wheat fibres, decreasing when the fibre content increases (Table S6). The thermal effusivity (E) and thermal diffusivity (D) of the red and fibre-free beige samples and of the samples

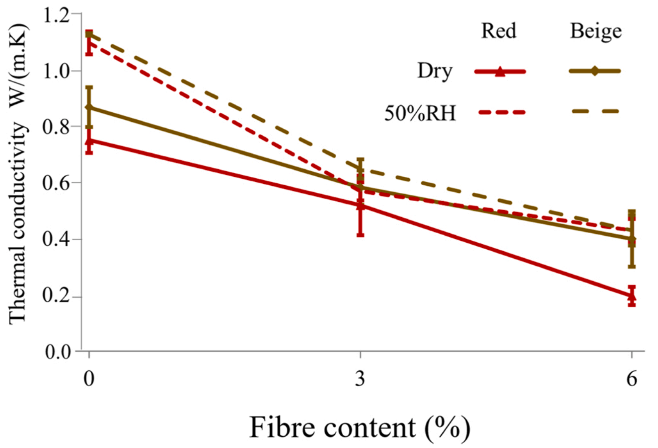


**Fig. 5.** Influence of fibre content on thermal conductivity: Modified transient planar source method.

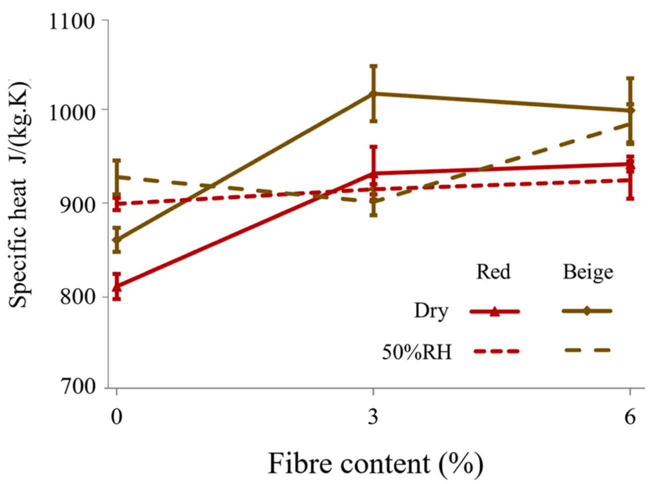


**Fig. 6.** Influence of fibre content on the specific heat of samples: Modified transient planar source method.

**Table 3**
Thermal effusivity and diffusivity averages of clay fibres and clay samples conditioned at 50 %RH and 23 °C.

| Clay | Fibre % | Steady thermal transmission E J/(m$^2$.K. s$^{1/2}$) | D m$^2$/s | Modified transient planar source method E J/(m$^2$.K. s$^{1/2}$) | D m$^2$/s |
|---|---|---|---|---|---|
| Red | 0 | 1353 ± 54 | 6.22E-07 ± 7.00E-08 | 1398 ± 34 | 6.23E-07 ± 1.62E-08 |
| | 3 | 1359 ± 44 | 8.89E-07 ± 6.14E-08 | 1426 ± 5 | 6.31E-07 ± 3.34E-09 |
| | 6 | 956 ± 51 | 6.29E-07 ± 1.06E-07 | 886 ± 25 | 3.85E-07 ± 2.48E-08 |
| Beige | 0 | 924 ± 13 | 3.66E-07 ± 1.02E-8 | 948 ± 36 | 4.05E-7 ± 1.51E-8 |
| | 3 | 790 ± 15 | 4.16E-07 ± 4.65E-08 | 759 ± 46 | 3.05E-07 ± 2.27E-08 |
| | 6 | 828 ± 58 | 3.59E-07 ± 7.17E-09 | 759 ± 43 | 3.10E-7 ± 4.43E-08 |

with fibre conditioned at 50 %RH and 23 °C are approximately the same for the values obtained with the modified transient planar source method. With the regular heat transfer method, the thermal effusivity of the samples of both clays is the same and the thermal diffusivity of the red clay samples is 30 % lower than that of the beige clay. The thermal effusivity of the clay samples containing 3 % and 6 % wheat fibres is reduced by 37 % and 46 % for the red clay mixture, respectively, and by 34 % and 47 % for the beige clay mixture, respectively. For the thermal diffusivity, it is reduced by 38 % and 51 % for the red clay cob, respectively, and by 36 % and 52 % for the beige clay mixture, respectively for the same samples. This damping of the thermal diffusivity is due to the fibre structure of the samples, which opposes heat flow with the creation of pores within the composite materials (Mellaikhafi et al., 2021). This also leads to a decrease in the thermal conductivity of the materials containing fibres, as presented in Section 3.2.1 of this paper.

The effect of fibre content on the thermal diffusivity and thermal effusivity of the dry samples and those conditioned at 50 %RH and 23 °C is shown in Fig. 7 and Fig. 8. The addition of 3 % and 6 % fibres in clay mixtures leads to better thermal properties in terms of thermal conductivity, specific heat, thermal diffusivity, and thermal effusivity (Table S2). This trend was also reported in other studies (Laborel-Préneron et al., 2018) (Mellaikhafi et al., 2021). Comparing the two clays, it is found that both clays have interesting thermal inertia for a wood/clay-fibre construction. However, red clay is more commonly used and has better thermal inertia than beige clay (Table S7).

For completely dry samples, a decrease in thermal diffusivity of 24 % and 70 % is observed for red clay mixtures with 3 % and 6 % fibres, respectively, and of 32 % and 46 % for beige clay mixtures with 3 % and 6 % fibres, respectively (Table S8). This decrease improves the thermal insulation performance of the sample by increasing the thermal phase shift time between the inside and outside temperatures. The thermal effusivity decreases by 52 % (red clay mixes with 6 % fibres compared to the fibre-free mix) and by 38 % (beige clay with 6 % fibres compared to the fibre-free mixture) (Table S8). These results illustrate that fibre-reinforced samples can retain heat for a very long time because the heat absorbed at the surface will slowly dissipate when the temperature of its surroundings decreases (Laborel-Préneron et al., 2018). These two distinct coefficients are referred to as the transmission inertia and the storage inertia; the incorporation of fibres into the clay improves both coefficients simultaneously. Based on the results obtained in the present study, fibre-reinforced clay materials are more suitable for building walls than are fibre-free earth materials.

Other materials can be used in combination with cob and earth materials to enhance the overall thermal performance of a building. Tannin-based foam offers a promising alternative to petroleum-based foams in the field of building insulation due to their advantageous characteristics such as low thermal conductivity, high fire resistance, and self-extinguishing properties (Abu-Jdayil et al., 2019; Delgado-Sanchez et al., 2018). While commercial petroleum-based foam

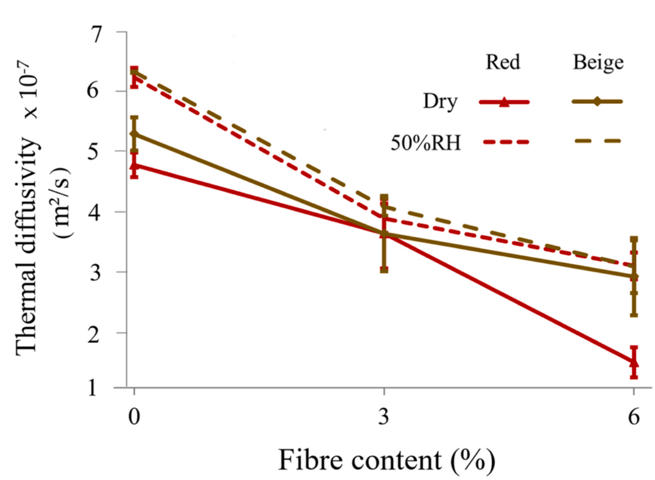


**Fig. 7.** Influence of fibre content on thermal diffusivity of samples: Modified transient planar source method.

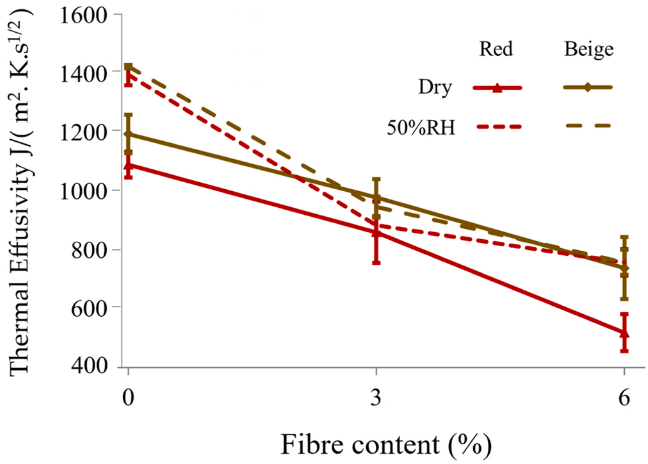


**Fig. 8.** Influence of fibre content on thermal effusivity of samples: Modified transient planar source method.

provides superior thermal insulation (Arafat et al., 2023; Yang et al., 2023), they have drawbacks including high flammability, high moisture absorption capacity, and low biodegradability, leading to environmental concerns (Chen et al., 2023; Siracusa et al., 2020; Stachowiak et al., 2021; Yang et al., 2023). A model of a fully hybrid bio-based biocomposite has been developed and compared to a fully petroleum-based composite in terms of volatile organic compound emissions and impact on human health (Al-Mudhaffer et al., 2022; Khoshnava et al., 2020). The results indicated that a combination of 27 % heavy materials, 13 % clay, 40 % petroleum-based materials, and 20 % sandwich panels reduced the indoor temperature of buildings without the need for a cooling system. However, the works of (Balo, 2015) and (Srinivasan et al., 2023) explore solutions to reduce the use of petroleum-derived chemicals in the development of composite materials in a more sustainable and environmentally friendly manner.

## 4. Conclusion

This article describes a method for producing fibre-reinforced samples using the cob manufacturing technique and presents experimental results of the thermal properties of these samples, as well as samples of raw clay intended for use in filling the wooden frame structure of the building. The main objective of this study was to investigate the possibility of manufacturing cob material that can be used for wooden frame buildings to reduce the energy demand associated with air conditioning or heating. The sample fabrication method presented is very easy to extrapolate to large-scale production without the use of mechanical or electrical mixers. The experimental results indicate that increasing the fibre content in the clay mixture lightens the clay samples by reducing their density while increasing their insulation capacity.

Measurements of the thermal properties of the samples with and without fibres were performed using two methods: 1) steady thermal transmission based on the transient plane source method and 2) the modified transient plane source method. The experimental tests showed that the clay samples had a higher conductivity, ranging from 1.10 to 1.28 W/(m.K). The addition of fibres to the clay matrix improved the thermal insulating behaviour of the material by reducing its thermal conductivity, thermal diffusivity, and thermal effusivity. The thermal capacity increased with the increase in fibre content. The positive influence of loose vegetable fibres on the thermal properties of the samples increased their insulating capacity, providing better thermal comfort. The thermal conductivity of the samples decreased by 40–63 %, and the thermal capacity increased by 2–10 % with the addition of 3 % and 6 % fibres. Thermal conductivity values of 0.2 and 0.4 W/(m K)c were obtained for the dry samples made with 6 % fibres of red clay and beige clay, respectively. The thermal properties of the composite materials obtained in this study are promising for the enrichment of clay/fibre materials produced using the cob manufacturing technique. Their use in construction would contribute to reducing the environmental impact due to the availability of raw materials, ease of material production, and low carbon footprint. The statistical analysis (Anova, t-test) validated the thermal property data while highlighting the key role of fibres in enhancing the thermal properties of samples made with cob and adobe fabrication techniques. Statistical test results showed differences between the constant heat transmission method (TPS 3500) and the modified transient plane source method (Trident-C-Therm). TPS 3500 method measure the thermal conductivity in a controlled environment (temperature and relative humidity), while the Trident C-Therm method is performed in a non-controlled environment, which explains the disparity.

These types of materials present the advantage of being mouldable into any shape and size according to needs, which makes them effective as filling material for constructions with wood frame structures. The results of this study can be scaled up in the field because the experiments were carried out in a traditional way, considering their implementation on construction sites. Fibre-reinforced earth materials (3 % or 6 %) in construction reduce the cost of handling materials for housing due to the abundance of clay earth and limit the incineration of plant fibres after harvesting. In addition, the integration of these materials into the construction process would contribute to a reduction of carbon dioxide emissions related to building materials and the use of cooling and heating systems in buildings. The thermal property results indicate that fibre-reinforced clay materials are more suitable for building walls than fibre-free earth materials.

## Funding

This research was funded by the Pôle de Recherche et d'Innovation en Matériaux avancés du Québec (PRIMA), the Natural Sciences and Engineering Research Council of Canada (NSERC) Alliance program, Quebec Wood Export Bureau (QWEB), American Structures, and Boralife. (Funding number: ALLRP 560404-20).

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgments

The authors thank SEREX for its participation in the hygrothermal properties measurements of the studied materials for this project. The authors also thank Patrick Brisebois, Mathieu Bendouma, Jana Vander Goot and Sinead Crotty for reviewing previous versions of the manuscript.

## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2024.118626.

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