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ORIGINAL PAPER

Experimental Investigation of Thermal and Mechanical Properties of Clay Reinforced with *Typha australis*: Influence of Length and Percentage of Fibers

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Abstract

This study presents the elaboration and characterization of a composite material based on *Typha australis* and clay for the use of an innovative building material in construction. For this purpose, various percentages ranging from 0 to 55% with a pitch of 15 were used. The aim is to find a better compromise between the thermal and mechanical properties of this composite material. According to this, the influence of the length of the 1 cm and 3 cm fibers was studied. As *Typha australis* is very porous, the hydric properties of the material studied in this work show that its porosity increases the rate of water absorption following a logarithmic law and the mass loss of the composite material evolves exponentially as a function of time. The mass increases when the percentage of fibers is low. The thermophysical property of *Typha australis* is 0.06 W/m K. That property allows us to state that *Typha australis* can be used for thermal insulation. The thermophysical properties of the composite material show that the thermal conductivity decreases as the percentage and length of fibers increase. In fact, the thermal conductivity of the clay is 1.03 W/m K while the mixture of clay with 55% of 1 cm fibers gave a thermal conductivity of 0.146 W/m K. The mixture of clay with the same percentage of 3 cm fibers gave a thermal conductivity of 0.113 W/m K. Nevertheless, the fibers have a negative effect on the mechanical properties and the increase in the length of the fibers improves the flexural strength.

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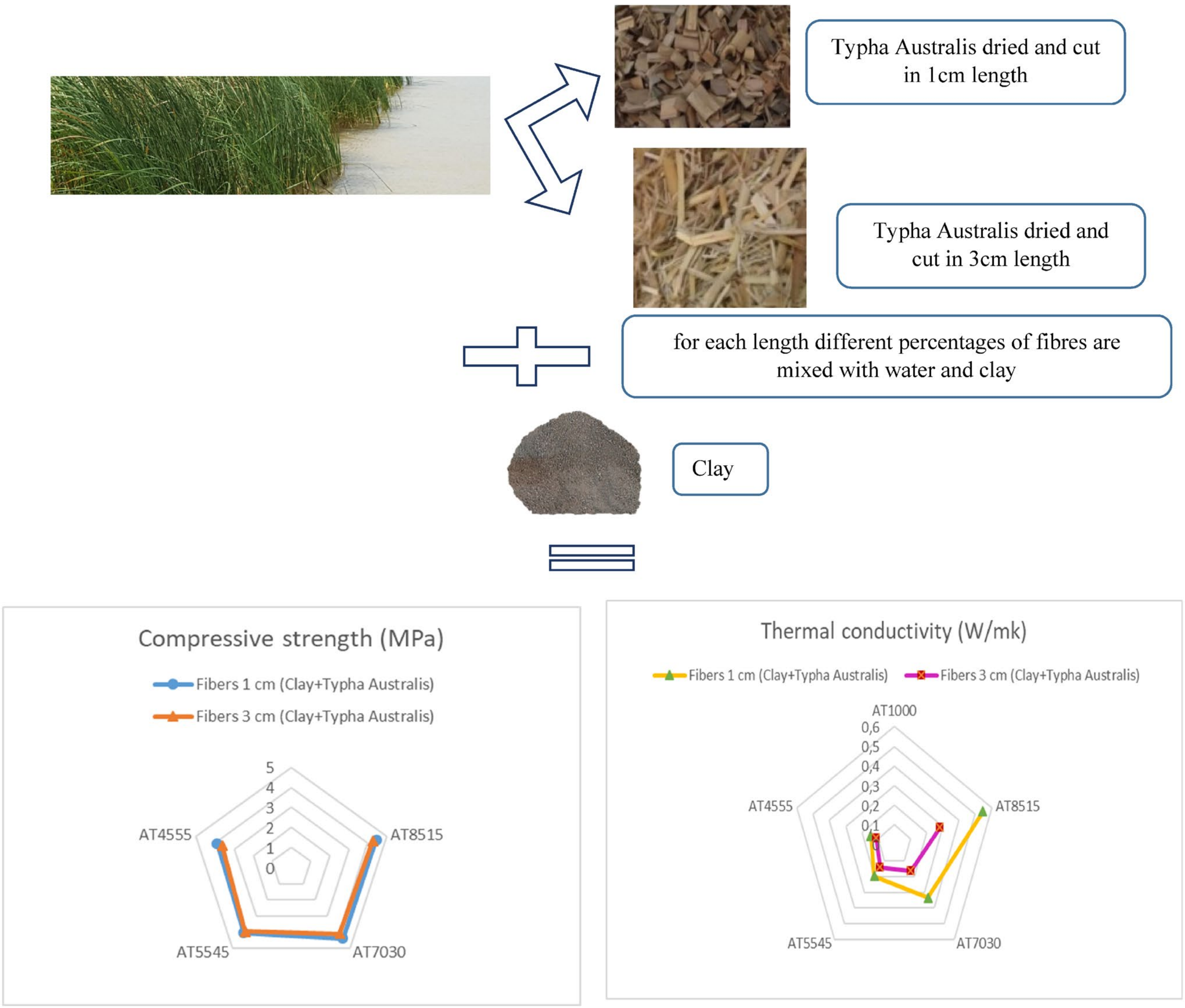
Graphi abstract



Keywords Clay · *Typha australis* · Thermal conductivity · Compressive strength · Flexural strength

Statement of Novelty

- Valorization of an invasive plant called *Typha australis* as a building material.
- Design of a new bio-based material (mixture of clay and *Typha australis*)
- Thermal and mechanical characterization of this material
- Influence of the length and percentage of these fibres on thermal and mechanical properties

Introduction

The building sector is one of the largest consumers of energy. It consumes 40% of the world's energy, and this is due to building materials and energy systems (Air Conditioning–Ventilation–Heating). In line with the "Paris Agreement", the Low Carbon Strategy, induced by the Energy Transition Law, plans to reduce GHG emissions by 50% by 2030. To achieve this objective, it's necessary to reduce the energy needs of buildings while limiting the carbon footprint of materials and equivalents [1].

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Materials of plant origin such as hemp, straw, flax, Kenaf…etc. have several advantages: Low grey energy, renewable resources, reduction of greenhouse gases.

These materials are developing as the most successful bio-based building materials in France [1]. Several geo-source materials can be used as binders with these bio-based materials, including raw earth. Raw earth has been and remains one of the main building materials used by mankind for centuries. Today still more than 1/3 of the world's inhabitants live in earthen buildings and in developing countries; this proportion rises to 50% of the rural population and at least 20% of the urban and semi-urban population [2]. In Europe (Sweden, England, Spain and Portugal), this type of building in rural areas is part of the cultural heritage. Those buildings built by the huge (earth–fibers mixture) is a traditional earth construction technique used for thousands of years all over the world and in all climates [3]. Generally, current buildings are designed without taking into account their climatic environment, the building materials used in these buildings are polluting and there is a high emission of greenhouse gases during the manufacturing process. Unlike traditional and vernacular buildings, which were well integrated into their environment and more sustainable, thanks to local and natural materials. The advantages of sustainable buildings are resource availability, recyclability, low environmental cost, no toxicity, biodegradability and good thermo mechanical performance [4–6]. The use of those fibers are interesting from an economic and environmental point of view [7]. By using them as a bio-based material, those fibers help to stabilize the soil [8]. Daher et al. [9] have conducted an experimental study on the effect of the moisture and drying cycle on the physico-mechanical properties of rapeseed straw used as a building material. Lachheb et al. [10] have shown that the addition of alpha fibers to gypsum improves the thermal conductivity of the material. Studies have also shown that mixing clay with sunflower and rapeseed straw as well as gypsum-based bio-composites can reduce the thermal conductivity value. As the density decreases, the thermal conductivity decreases, which has a negative influence on the mechanical properties [11]. Ground coffee can also be considered as a bio-based material. Indeed, Lachheb et al. [12] have shown in their article that the mixture of plaster and ground coffee has a good energy performance. Other bio-based materials are studied in the literature. Sibiath et al. [13] studied matrices based on cement and coconut fibers and a good thermal performance was found with the addition of 4% of coconut fibers. The bio-based materials studied by Elhamdouni et al. [14] are based on straw and alpha fibers that have been mixed with clay or those studied by Palumbo et al. [15] which consist in adding maize fibers and fibers to compressed soils artificially made from Kaolinite. These materials have demonstrated their ability to decrease the value of thermal conductivity in the matrices, which confers good thermal performance. Labouda et al. [16] reviewed the issues of bio-based materials on thermal performance by conducting a comparative study of bio-based materials. This review focused in particular on *Typha australis*. Indeed, *Typha australis* is one of the aquatic plants of the family of *Typhaceae* [17, 18]. It is a plant that can be found in different continents with various applications. In India, this plant is considered a weed with a low nitrogen supply [19]. In Iran, studies on the physico-chemical properties of natural fibers extracted from *Typha australis* have been carried out [20]. In Chile, this plant is used in medicine against tumour diseases [21]. In Benin, the proliferation of this plant is a real problem for the rivers in the valley. This plant has been valorized into bioethanol produced by enzymatic hydrolysis and bio-fermentation, which can be used as a biofuel substitute for gasoline, reducing CO_2 by 90% [22]. A limited number of researchers have studied the hydric, thermal and mechanical characterization of *Typha australis* using clay or cement as a binder.

Dieye et al. [23] showed in their paper that the addition of *Typha australis* on clay decreased the value of thermal conductivity but did not improve the mechanical strength. With proportions of *Typha australis* between 15.1 and 22.9% were mixed with clay. That study showed that when the percentage of *Typha australis* increased the thermal conductivity value decreased from 0.163 to 0.127 W/m K, however the mechanical strength decreased (for compressive strength from 0.98 to 0.32 MPa and for tensile strength from 0.79 to 0.28 MPa) [23]. Niang et al. [24] studied the hygrothermal properties of *Typha australis* using earth as a binder and also studied the influence of fibers cutting on thermal performance, two cuts were made the transverse cut and the longitudinal cut and 20% (in volume concentration) of *Typha australis* was studied for each cut and 33% (in volume concentration) of *Typha australis* for the transverse cut. The result showed that the transverse cut with 20% of *Typha australis* showed a better thermal performance with a thermal conductivity of 0.115 W/m K, the longitudinal cut with 20% of *Typha australis* gave a thermal conductivity of 0.131 W/m K and the transverse cut with 33% of *Typha australis* gave a thermal conductivity of 0.164 W/m K [24]. Diatta et al. [25] studied the mixing of cement, sand and *Typha australis*. The percentage of *Typha australis* ranged from 0 to 3.5%. The addition of *Typha australis* to the mixture resulted in a decrease in thermal conductivity and also in mechanical strength. The mechanical characteristics would have been improved by the addition of *Typha domingens* natural fibers in polymer matrix composites [26]. An incorporation of *Typha* with percentages (0 to 3.5% with a 0.5% pitch) in a cement mortar was made by Abdelhakh et al. [27] in order to analyse its influence on the thermal and mechanical behaviour. The results of this experiment show that *Typha* is a very light material with a bulk density of

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Fig. 1 Typha australis

51.6 kg/m^3 and an absolute density of 144.95 kg/m^3, the density of the mixture is higher in the wet state than in the dry state and it decreases with the increase of the proportions of *Typha* which allows the value of the thermal conductivity to decrease [27].

With the aim of contributing to studies in the literature, this paper presents our experimental results concerning the valorisation of *Typha australis* in the design of bio-sourced building materials, using clay as a binder. These results should make it possible to highlight the influence of the variation in length and percentage of *Typha australis* on the hydric and thermomechanical properties of these types of materials. The percentages studied haven't been treated in the literature before.

Materials and Methods

Materials

Typha australis and clay were sampled at the same site. The sampling site is the Diawling National Park which was created in 1991 in the lower Mauritanian delta of the Senegal River. This dam was created in response to environmental and socio-economic degradation following the construction of the Diama downstream and Manantali upstream dams [28]. This site is located in the lower delta of the Senegal River on the right bank between 16° 35′ 00 and 16° 30′ 00 N [29]. *Typha australis* is taken from the site as a plant about 170 cm high, dried in the sun and cut transversely, *Typha* is shown below (Fig. 1).

The clay taken from the site was dried in the sun, then ground into powder and sieved with a 5 mm sieve, the ready clay sample is shown in the Fig. 2.

The characteristics of these materials namely: bulk and absolute density, porosity, grain size and Atterberg limit are represented in this section.

Table 1 gives the values for porosity, bulk density and absolute density. The last two are determined respectively according to the following standards NF P 94-053 and NF P 18-554.

Figure 3 gives the grain size of the clay, the percentage of passage ways as a function of the diameter of the sieve.

Fig. 2 Clay

Table 1 Material characteristics

Materials	Bulk density (kg/m^3)	Absolute density (kg/m^3)	Porosity (%)
Clay	1120	2151.9	48
Typha australis	60	461.53	87

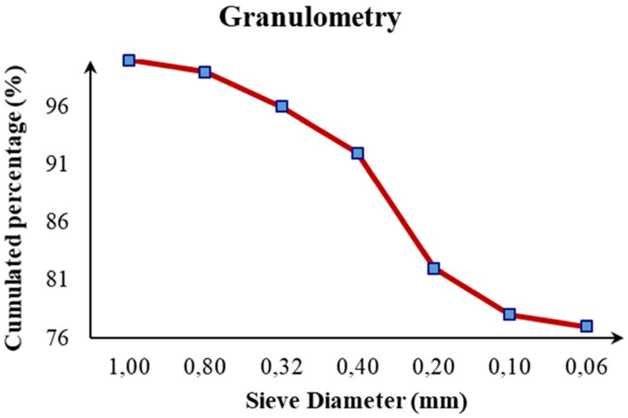

Fig. 3 Clay grain size

Table 2 Atterberg limit

Liquidity limit (LL)	43.5%
Plasticity limit (PL)	22.99%
Plasticity index (IP)	20.51%

Optimum water content = 22.55%
Dry density = 1.62 g/cm^3

Table 2 represents the Atterberg limit and the optimum water content which, at the same time, makes it possible to determine the dry density.

We had determined the geotechnical characteristics of these materials, which will be used in the formulation of the specimens. The last one will be detailed in the experimental protocol.

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Table 3 Specimen shape and size

Tests	Thermal properties	Mechanical properties	Hydricproperties
Types of specimens	Cylindrical (Diameter 11 cm, Height 5 cm)	Prismatic (4 cm*4 cm*16 cm)	Prismatic (4 cm*4 cm*16 cm)
Number of specimens	40	60	30

Table 4 Thermal and mechanical properties of some materials based on *Typha australis*

Binder	Percentage of fibers (%)	Thermal conductivity (W/m K)	Compressive strength (MPa)	Authors
Cement + sand + water	0 to 3	1 to 0.126	4 to 0.89	Diata et al. [25]
Cement + sand + aggregate	0 to 3.5	1 to 0.430	7.8 to 0.1	Abdelhakh et al. [27]

Experimental Protocol

In this part, we will show the methodology followed for the implementation of the specimens as well as the experimental protocols that have been adopted for the characterizations: hydric, thermal and mechanical.

Table 5 Specimen composition

Formulation	Water/clay (in mass)	*Typha australis* (%)	Clay (%)
AT_0^{100}	0.33	0	100
AT_{15}^{85}	0.33	15	85
AT_{30}^{70}	0.33	30	70
AT_{45}^{55}	0.33	45	55
AT^{45}_{55}	0.33	55	45

The formulations are named AT_i^j

i: percentage of *Typha australis*

j: the percentage of Clay in the matrix

Specimen's Elaboration

The specimens have been elaborated from the materials presented in the previous section. Different formulations were studied by varying the percentage and length of fibers while keeping the water/clay ratio (by mass) constant.

For each formulation, several specimens of two different size ranges were manufactured, of which 130 specimens in total (Table 3).

The percentage of fibers varies between 0 and 55% with a 15% step. This choice was made in order to distinguish it from previous work done on *typha*-based materials whose percentage ranges varied from 0 to 3.5% and 20 to 30%. Not seeing a great impact by choosing percentages between 0 and 3.5% (Table 4), we opted for percentages between 0 and 55% in order to show the real impact of these fibers on a clay matrix. For the length of fibers, being a porous material (porosity of *Typha australis* is 87%), we considered interesting to vary the length of fibers in order to evaluate its impact on the thermomechanical characteristics of the material. For this, two lengths were chosen 1 cm adapted to the one studied in the literature and increasing three times this length (3 cm). The diameter of fibers is 0.8 cm

$$\text{The aspect ratio}: \eta = \frac{1}{d} \tag{1}$$

where l: length in cm, d: diameter in cm.

The mass of the water was determined by the following formula:

$$\frac{m_e}{m_a} = \frac{(LL + LP)}{2} \tag{2}$$

where LL: liquidity limit, LP: plasticity limit, m_e : water mass, m_a : clay mass.

The masses of clay and *typha* were determined by the law of mixture according to the volumes of the specimens.

Table 5 brings together the formulations studied:

Procedure for the manufacture of specimens:

- Due to the high absorption coefficient of fibers, they were immersed in water until they were saturated (The water absorption coefficient of *Typha australis* is 350% and is reached at the 120th min.) [30].
- This pre-wetting avoids water competition during the mixture [31] gives the rapid water absorption of fibers, which allow the pulp to absorb the necessary water to improve the water-pulp interaction.
- The mixing method in the mortar mixer has been adapted to the NF ISO 18650 standard, which consists to put the mixture (binder + fibers in this case) in the bowl of the mixture and melt it in1minute in order to avoid that the fibers are crushed. We reduced the mixture to 30 s at slow speed and the quantity of water was

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Fig. 4 Manufacturing specimens

added and mixed at 30 s at slow speed was followed by mixing at 1minute at fast speed.

- Metal moulds were used with half-filled and then compacted with 60 shocks by the shaking table with the other half which was filled to the same carried out operation.

Figure 4 is an example of a specimen manufactured before demoulding and drying:

After demoulding, the specimens were placed in an oven at a temperature of 45 °C for 7 days and they were stored in a room with a temperature of 23 °C and 50% relative humidity. The tests were carried out on 30 days after demoulding.

Experimental Method for Hydric Characterization

In this study, part of the hydric characterization on these formulated materials was carried out. The hydric characterizations implemented are: the water absorption coefficient of fibers, the drying kinetics and the moisture content. The following sub-sections show the methodology followed to carry out these characterizations.

Coefficient of Water Absorption of *Typha australis*

Typha australis is immersed in water for a period t and then wrung out with absorbent paper. The mass after immersion is measured in order to calculate the absorption rate by the following relationship:

$$a(\%) = \frac{m_2 - m_1}{m_2} * 100 \tag{3}$$

m_1: dry fiber mass, m_2: mass of the fiber after immersion in water.

Drying Kinetics (Mass Loss)

The mass loss was evaluated on 4 cm*4 cm*16 cm specimens for the 5 formulations (3 specimens for each formulation). In this step, the test specimens were placed in an oven at 45 °C after remoulding and the mass of the test specimens was taken at time intervals t until a constant mass was obtained following the protocol shown in Fig. 5 and formula 4 was applied:

$$Mass\ loss(\%) = \frac{m_i - m_t}{m_i} * 100 \tag{4}$$

m_i: Initial mass in grams, m_t: Mass after drying at time t in grams.

Humidity Ratio

The humidity ratio is determined according to the NF P94-050 standard. Clay soils easily absorb water (imbibition water) at the surface of the clay minerals.

This water disappears when drying at a temperature of 105 °C. The humidity ratio makes it possible to quantify the total quantity of water contained in a material and provides information on its state of hydration. It is expressed as a percentage of the mass of dry matter. Humidity ratio is evaluated by the following relationship:

$$\omega(\%\ ) = \frac{M_1 - M_2}{M_1} * 100 \tag{5}$$

ω(%): humidity ratio, M_1: Mass of the sample before drying, M_2: Mass of the sample after drying at 105 °C.

In the following section, we will spread out the experimental method used to complete the thermophysical characteristics of the matrices.

Experimental Method for Thermophysical Characterization

This section highlights the established methodology for determining the thermophysical characteristics of composites. Thermal properties are the material-specific characteristics that will allow us to define its insulating capacity. Among the thermal properties of materials, we have: thermal

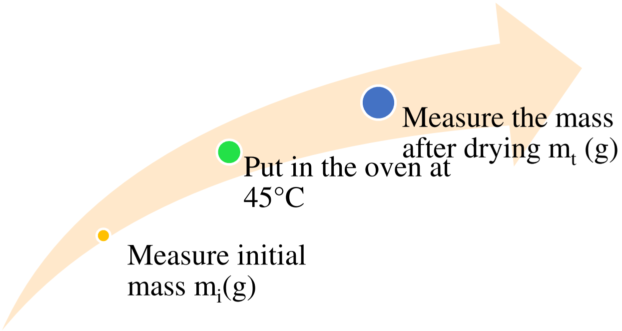

Fig. 5 Mass loss measurement protocol

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conductivity, mass heat, thermal diffusivity and thermal effusivity.

In our case, we will focus more on the thermal conductivity of the specimens.

Figures 6, 7 and 8 show the experimental devices used for thermal characterization. The transient plane source thermal characterization (TPS) technique is becoming an important tool for determining the thermal properties of a variety of materials because of its robust design, fast characterization time and ability to simultaneously measure the thermal conductivity and thermal diffusivity of complex materials, such as nanocomposites [32].

The TPS method is based on a transiently heated planar sensor procedure, and its most common adaptation is called the Hot Disk Thermal Constants Analyzer. The hot disk (the sensor) consists of a double spiral electrically conductive pattern, which has been etched into a thin sheet of metal (Nickel) (see Fig. 6). This spiral is sandwiched between two thin sheets of insulating material (Kapton, Mica, etc.) (Fig. 7). During a measurement, a flat hot disk sensor is placed between two pieces of the sample, each with a flat surface facing the sensor (Fig. 8). By passing an electric current, strong enough to raise the temperature of the sensor by a fraction of a degree to several degrees, and at the same time recording the increase in resistance (temperature) as a function of time, the hot disk sensor is used both as a heat source and as a dynamic temperature sensor [30, 31]. Using the TPS method, we measure thermal conductivity, which is defined as the property of a material to conduct heat. More precisely, it is the amount of heat per unit time and per unit area that can be conducted through a plate of unit thickness [30].

The advantages of using a TPS instrument are: non-destructive method, contact resistance between sensor and sample does not influence the measurement results, porous and transparent samples are easy to test without modification, surface roughness or color does not influence the measurement results. To obtain very good results, it is very important to fix the sample during the test and to choose an appropriate sensor, output power and measuring time [30].

Fig. 6 Hot disc with bonding wire

Fig. 7 Sample holder

Experimental Method for Mechanical Characterization

The specimens were subjected to single compression and three-point bending tests using the 3R presses shown in the Figs. 9 and 10.

The compressive strength is determined from the following formula:

$$\sigma_r = \frac{F(KN)}{S\left(\mathrm{cm}^2\right)} * 10\,(\mathrm{MPA}) \tag{6}$$

F: the maximum load, S: the section of the specimen.

The flexural strength by 3-point bending is determined from the following formula:

$$\sigma_f = \frac{3Fl}{2bh^2} * 10\,(\mathrm{MPA}) \tag{7}$$

F: the maximum load recorded by the test machine (N), l: the span length (cm), b: the mean thickness of the specimen on the plane of fracture (cm), h: the mean depth of the specimen on the plane of fracture (cm).

This part showed all the experimental protocols that have allowed the design and characterization of these materials based on *Typha australis* . In the next part we will present the results obtained.

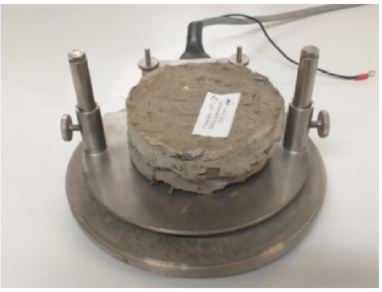

Fig. 8 Sandwich sample

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Fig. 9 3R press for compression

Fig. 10 3R press for bending

Results and Discussion

Hydric Properties

The following sub-sections represent the results of the hydric characterizations determined from the established experimental protocol.

Coefficient of Water Absorption of *Typha australis*

The initial mass was set at 3 g and formula 3 was applied at each time t. The following curve represents the evolution of water absorption coefficient of *Typha australis* as a function of time.

Two phenomena are observed on the evolution of water absorption:

The first phenomenon is the phase of surface absorption which lasts about 15 min. This phenomenon is due to the smooth epidermis of the fibres (Fig. 18) which prevents water penetration. After this time, a rapid increase of the water absorption coefficient was observed. It was characterized *Typha australis* being hydrophilic.

The second phenomenon is characterized by the slow evolution of the water absorption coefficient. This phase highlights the diffusivity of the water propagation in the plant fibres until saturation (after 120 min of immersion, the water absorption coefficient varies slightly and becomes constant from the 180th min). The coefficient of water absorption at saturation is 350%.

This absorption rate varies from one fiber to another, this could be due to the microstructure of the fibers. Just like the Kenaf studied in the thesis of Laibi Babatoundé [33], *typha* also obeys the logarithmic type law as shown in Fig. 11.Saturation is reached at 363.33% absorption from the 250th min, this high absorption is due to the porosity of the material. The speed and importance of

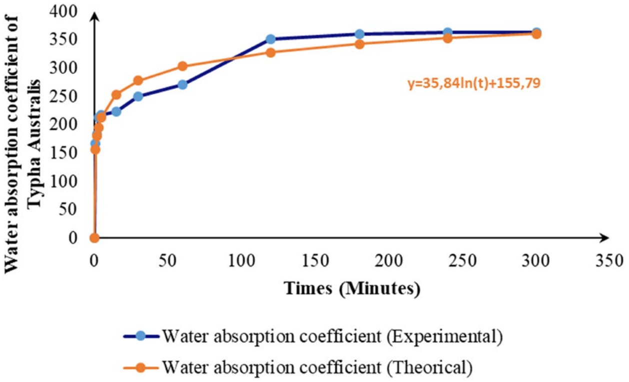

Fig. 11 Evolution of water absorption coefficient

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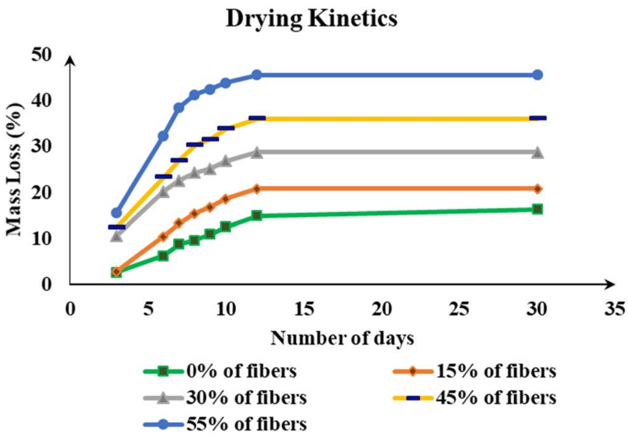

Fig. 12 Variation in mass loss with time

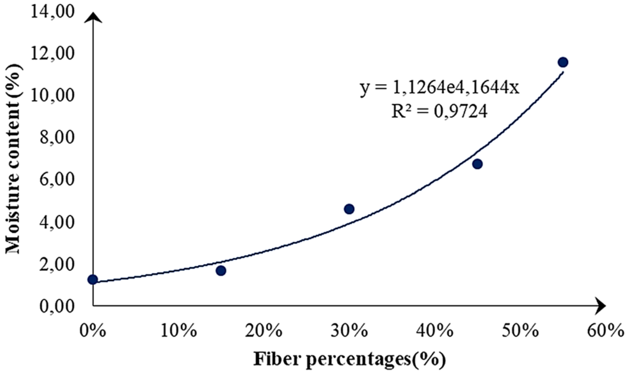

Fig. 13 Evolution of the humidity ratio according to the percentages of fibers

absorption increase with the material porosity. *Typha australis* is more porous than hemp straw, which has an absorption of 130% per minute, whereas *Typha australis* has an absorption of 166.7% under the same conditions [33]. The aggregates have a hydrophilic behaviour, especially since pore size and microstructural changes play a role in water absorption [11].

Drying Kinetics and Moisture Content

Figure 12 shows the variation in mass loss as a function of time and fibers percentage for composites composed of the 1 cm length of fibers with the different formulations. Figure 13 shows the evolution of the humidity ratio as a function of the percentages of 1 cm length of fibers.

We can observe in Fig. 12 the variation of mass loss as a function of time for the different formulations. The result shows an exponential growth of the drying kinetics as a function of time. We can see that the percentage of fibers increase causes a mass loss. This evolution could be assimilated to the water absorption rates of the fibers (Fig. 11) which also evolves rapidly. Indeed, the drying of the material consists of evaporating the water in the material, which reflects the transfer of water vapour. The addition of the fibers in the composite increases the porosity, which allows for easier moisture transport [24], resulting in rapid mass loss in the material. In accordance with the drying kinetics and water absorption rates of fibers, the humidity ratio of the material increases exponentially as a function of the fibers percentages.

Table 6 Thermal properties of *Typha australis* alone

Formulation	Bulk density (kg/m^3)	Thermal conductivity (W/m K)	Thermal diffusivity (mm^2/s)	Volume capacity (MJ/m^3 K)
Typha australis alone	60	0.061	0.931	0.0348

Thermophysical Properties

Table 6 shows the thermo-physical characteristics of *typha* alone. We observed the low apparent density as well as the low thermal conductivity. The latter is 0.061 W/m K which is less than 0.07 W/m K and which will allow the new composites to be considered as insulators [34].

Table 7 shows the thermo-physical properties of the composites for the different formulations.

Figure 14 shows the decrease in thermal conductivity with the addition of *Typha australis* fibers. This curve is exponential in shape. We can also see that the increase in the length of fibers (3 times the initial length) has a positive effect on the theoretical conductivity, which has decreased. The increase of fibers length decreases the bulk density of the composites (Table 7), and as the bulk density decreases, the thermal conductivity also decreases (Eq. 8).

$$\rho_{app} = \frac{\lambda}{D * C_p} \tag{8}$$

ρ_{app}: bulk density, λ: thermal conductivity (W/m K), D: thermal diffusivity (mm^2/s), C_p: heat capacity (J/kg K).

Figure 14 shows a slight decrease of the thermal conductivity from 30% of fibers for composites with 3 cm fibres compared to that of 1 cm fibres which decrease significantly (The decrease in thermal conductivity from 30% fibre to 55% fibre is 56.41% for 1 cm length fibres and 31.51% for 3 cm length fibres.). This variation in thermal conductivity could be due to the voids that are created when the percentages and length of fibers increase and to the poor adhesion between the binder and the 3 cm fibers. This poor adhesion is caused by the smooth outer part of fibers. Then, it should

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Table 7 Thermo-physical properties of the composites

Fiber length	Formulation	Bulk density (kg/m^3)	Thermal conductivity (W/m K)	Thermal diffusivity (mm^2/s)	Volume capacity (MJ/m^3 K)
Clay without fibers	AT_0^{100}	1300.00 ± 6.54	1.03 ± 0.020	0.671 ± 0.015	1.541 ± 0.011
Fiber 1 cm (Clay + *Typha australis*)	AT_{15}^{85}	1061.11 ± 4.51	0.546 ± 0.015	0.850 ± 0.015	0.637 ± 0.012
	AT_{30}^{70}	842.89 ± 19.66	0.335 ± 0.018	0.903 ± 0.013	0.370 ± 0.010
	AT_{45}^{55}	712.23 ± 11.93	0.199 ± 0.019	0.431 ± 0.014	0.463 ± 0.011
	AT^{45}	465.62 ± 16.26	0.146 ± 0.012	0.784 ± 0.017	0.187 ± 0.011
Fiber 3 cm (Clay + *Typha australis*)	AT_{15}^{85}	948.6 ± 24.08	0.280 ± 0.020	0.345 ± 0.012	0.812 ± 0.015
	AT_{30}^{70}	761.43 ± 10.93	0.165 ± 0.010	0.300 ± 0.013	0.55 ± 20.010
	AT_{45}^{55}	665.57 ± 17.63	0.143 ± 0.012	0.434 ± 0.012	0.328 ± 0.015
	AT_{55}^{45}	365.18 ± 20.49	0.113 ± 0.010	0.638 ± 0.011	0.178 ± 0.010

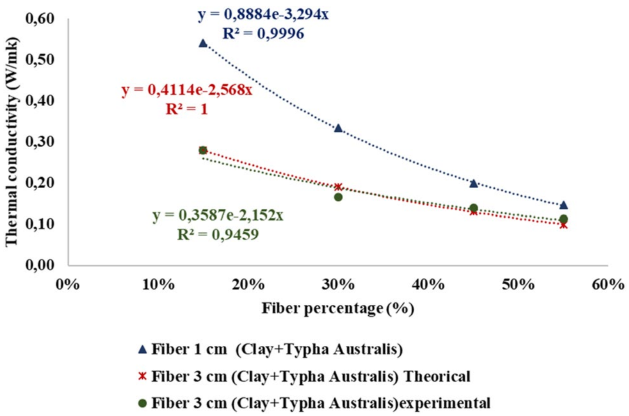

Fig. 14 Thermal conductivity of the composites

be notified that morphology plays a primordial role on heat transfer in the composite.

The thermal conductivity at 30% of *Typha australis* is almost identical to the one that Niang et al. [24] found which is about 0.16 W/m K and also the one from Dieye et al. [23] for a percentage of the *typha* between 15.1 and 22.87%. The thermal conductivity varies between 0.155 and 0.115 W/m K; therefore, Dieye et al. has adopted the hot plate method induce small errors due to the presence of air when the specimen is in contact with hot plate. Indeed, the greater quantity of fibers, the more porosity is generated in the matrix, which reduces the thermal conductivity.

These results are confirmed by several studies, Omrani et al. [35] showed that the addition of 20% *Juncus acutus* fibers decreased the thermal conductivity from 0.902 W/m K for the reference sample (without fibers) to a value of 0.327 W/m K. The incorporation of biomass fibers (cork) into an earthen material resulted in a thermal conductivity varying around 0.35 to 0.55 W/m K [34]. Brzyski et al. [36] incorporated hemp shives and flax straw in a mixture that also included lime and cement, reaching values of about 0.112 W/m K.

Table 8 Mechanical properties

Fibers length	Formulation	Compressive strength (MPa)	Flexural strength (MPa)
Clay without fibers	AT^{100}_0	4.63 ± 0.047	1.51 ± 0.020
Fibers 1 cm (Clay + *Typha australis*)	AT^{85}_{15}	4.45 ± 0.041	1.32 ± 0.030
	AT^{70}_{30}	4.36 ± 0.026	1.02 ± 0.030
	AT^{55}_{45}	4.03 ± 0.032	0.81 ± 0.035
	AT^{45}_{55}	3.89 ± 0.052	0.75 ± 0.020
Fibers 3 cm (Clay + *Typha australis*)	AT^{85}_{15}	4.27 ± 0.025	1.40 ± 0.020
	AT^{70}_{30}	4.09 ± 0.040	1.21 ± 0.026
	AT^{55}_{45}	3.93 ± 0.032	1.05 ± 0.015
	AT^{45}_{55}	3.62 ± 0.032	1.00 ± 0.020

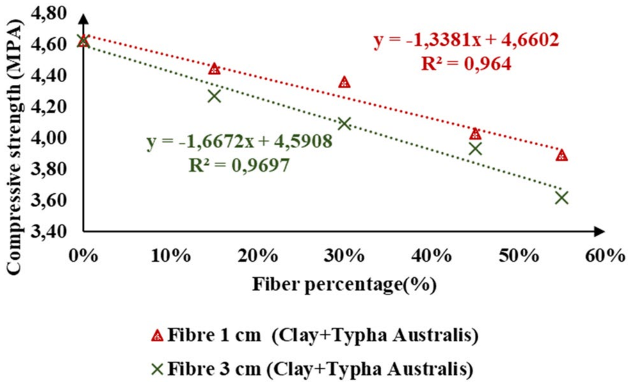

Fig. 15 Compressive strength as a function of fibers percentage

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Mechanical Properties

Table 8 shows the mechanical properties of the following composites of different formulations.

The curves in Fig. 15 represents the variation of compressive strength as a function of the percentage of fibers.

We can observe that the increase of fibers in the materials by substitution decreases of the compressive strength. This case confirms our previous observations that the addition of fibers by substitution in the composite increases the porosity of the materials which decreases the density. Therefore, the compressive strength decreases. In fact, in Fig. 15 the matrix composed of 3 cm fibers has a lower strength than the matrix composed of 1 cm fibers, Hence the correlation between the matrix composition, the thermal conductivity and the compressive strength (Fig. 20). The compressive strength values show that the fibers are well coated with the binder (this will be confirmed by the microscopic pictures). It should be noted that poor adhesion could lead to degradation of *Typha australis* over time in the composite.

The following curve represents the variation in flexural strength as a function of the percentage of fibers in each formulation.

The curves in Fig. 16 show the flexural strengths of the matrices. We can see that the flexural strength of the matrix composed of 3 cm fibers is higher than that composed of 1 cm fibers. This is explained by the fact that the flexural strength of fibers governs the flexural strength of the matrix. Indeed, the increase in the length of the fibers increases the flexural strength of the matrix, hence the higher flexural strength. Composites have ductile properties due to the presence of the fibers. The tensile strength of *Typha* alone can be up to 21 MPa at a density of 1 g/cm^3 [37]. Marques et al. [38] have shown that composites with a higher percentage of rice husk are less rigid and have a lower internal bond strength [38]. However, some studies such as Wang et al. [39] have shown that the addition of jutes fibres in expansive soil increases the tensile strength, since the addition of fibres with a density of the same order as the binder with good tensile strength strengthens the composite and improves the mechanical properties [39].

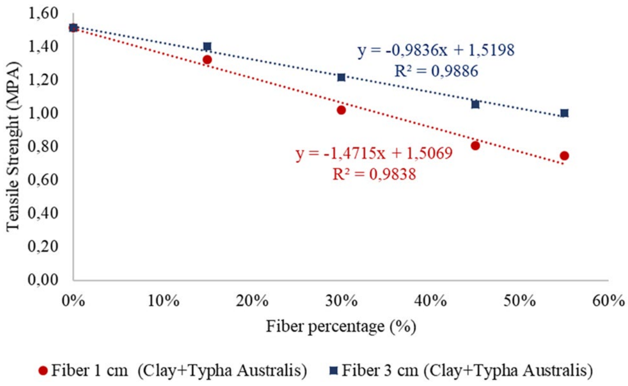

Fig. 16 Flexural strength as a function of fibers percentage

Fig. 17 Clay without fibers

Microscopic Images

The following images represent the optical microscope images of the specimens after compression. Optical microscope images have a resolution of 2560*1920 with an enlargement factor × 5.

- Clay and fibre
- with a length of 1 cm fibers
- with a length of 3 cm fibers

On Fig. 17, the presence of elements other than clay was observed. On Fig. 18 we can observe that *Typha australis* has a smooth external part.

On Fig. 19, the fibres are covered with clay and they are arranged in several directions. A low adherence is observed in the figure with the increase of the percentages of the fibres as well as the creation of voids.

These results are consistent with the literature. Olacia et al. [40] studied the thermomechanical characterization

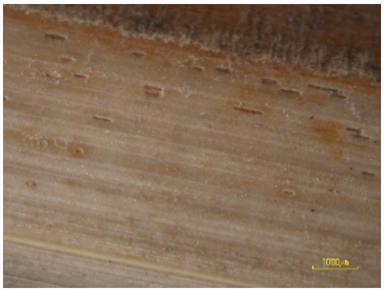

Fig. 18 External part of the *Typha australis*

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- with a length of 1 cm fibers

15% of fibers

30% of fibers

45% of fibers

55% of fibers

- with a length of 3 cm fibers

15% of fibers

30% of fibers

45% of fibers

55% of fibers

Fig. 19 Clay with fiber

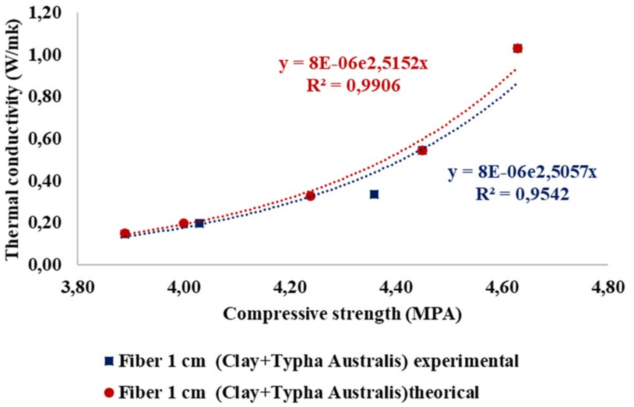

Fig. 20 Thermal conductivity as a function of compressive strength with fiber 1 cm

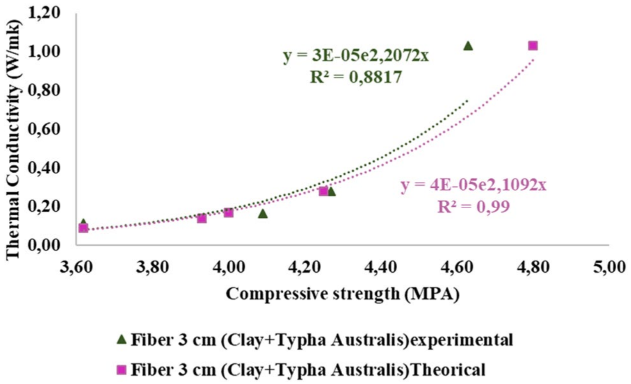

Fig. 21 Thermal conductivity as a function of compressive strength with fiber 3 cm

of adobes reinforced with marine fibers at two different lengths 1 cm and 3 cm and a comparison with straw fibers, the results showed that from a given percentage (from 1.5 to 3%) the 1 cm length had a better compressive strength than the 3 cm length for straw and the opposite for marine fibers. Flexural strength showed a decrease when more fibers are included in the adobes [40]. Marques et al. [38] claim that composites with a higher percentage of rice husk are less rigid and have a lower internal bond strength [38].

Variation of Thermal Conductivity as a Function of Compressive Strength

The following curves represent the thermal conductivity as a function of compressive strength:

Figures 20 and 21 show the variation of thermal conductivity as a function of compressive strength. We see from the curve that there is a relationship between them, because both (thermal conductivity and compressive strength) depend simultaneously on the same parameters such as: porosity, apparent density, adhesion between the matrix and the fibers…etc. When the thermal conductivity increases, the

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Table 9 Classification of RILEM

	Concrete of lightweight aggregates		Autoclaved aerated concretes	
	Class II (structural and insulating)	Class III (insulating)	Class II (structural and insulating)	Class III (insulating)
Rc (MPA)	>3.5	>0.5	>2.5	>0.5
λ (W/m K)	<0.75	<0.3	<0.75	<0.3

compressive strength also increases, this is due to the adhesion between the matrix and the fibers (and intragranular) which decreases the porosity, hence the increase in density. It's a good compromise between thermal conductivity and compressive strength for fibrous matrices. Indeed, based on the RILEM classification (Table 9), the studied fibrous composites can all be classified in class II. They can be used as structural and insulating.

Conclusion

This work aimed a design and characterization of a clay material reinforced with *Typha australis* and to evaluate the influence of the percentages and length of this fibre on the thermal and mechanical properties. Some conclusions can be drawn from the results:

- The hydric properties studied showed that *Typha australis* plays a role in the evacuation of water in clay composites and that the smooth epidermis of *Typha austarlis* partly influences the water absorption coefficient of fibres.
- Thermal properties showed that the thermal conductivity of *Typha australis* alone is 0.06 W/m K. This fibre can be considered as an insulator. As the percentages, the length of the fibres increase in the composite, the values of the thermal conductivity of these composites decrease. For a fibre length of 1 cm with percentages varying from 0 to 55% the thermal conductivity decreases from 1.03 to 0.146 W/m K. For a length of 3 cm with percentages also varying from 0 to 55% the thermal conductivity decreases from 1.03 to 0.113 W/m K.
- As thermophysical properties, the percentage of fibres and the length of the fibres play a role in the mechanical properties. As the percentage of fibres increases, the compressive and flexural strengths decrease. The same effects were observed on the influence of fibers length on compressive strength. Nevertheless, flexural strength was improved as the length of the fibres increases. This is due to the flexural strength of the fibres, which governs the flexural strength of the matrix, and to a ductility effect that has been observed with the fibres.

According to these results and RILEM's classification, the mixture of clay and *Typha australis* is a promising composite, especially in terms of thermal insulation in buildings. It would be available to take into consideration the length and percentage of fibers.

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Compliance with Ethical Standards

Conflict of interest The authors declare that there is no conflict of interest.

References

1. Mazhoud, B.: Elaboration et caractérisation mécanique hydrique et thermique de composites biosourcés. Thèses de doctorat Spécialité Génie Civil, INSA RENNES, France (2017).
2. Houben, H. H. Centre de recherche et d'application pour la construction en terre. Grenoble villefontaine, France (2006).
3. Rohlen, U.: Construction en terre crue: construction, rénovation, finitions. Le moniteur, Paris (2013)
4. Panyakaew, S., Fotios, S.: New thermal insulation boards made from coconut husk and bagasse. Energy Build **43**, 1732–1739 (2011). https://doi.org/10.1016/j.enbuild.2011.03.015
5. Chikhni, M., Agoudjil, B., Boudenne, A., Gherabli, A.: Experimental investigation of new biocomposite with low cost for thermal insulation. Energy Build **6**, 267–273 (2013). https://doi.org/10.1016/j.enbuild.2013.07.019
6. Benmansour, N., Agoudjil, B., Gherabli, A., Kareche, A., Boudenne, A.: Thermal and mechanical performance of natural motarrenforced with date palm fibers for use as insulating materials in building. Energy Build **81**, 98–104 (2014). https://doi.org/10.1016/j.enbuild.2014.05.032
7. Iiczyszyn, F.: Caractérisation expérimentale et numérique du comportement mécanique des agro-composites renforcés par des fibres de chanvres, Thèse de doctorat Spécialité Systèmes Mécaniques et Matériaux, Université de Technologie de Troyes, France (2013).
8. Galán-Marín, C., Rivera-Gómez, C., Petric, J.: Clay-based composite stabilized with natural polymer and fibers. Constr. Build. Mater. **24**, 1462–1468 (2002). https://doi.org/10.1016/j.conbuildmat.2010.01.008
9. Daher, S., Benazzouk, A., Zerrouki, R., Chargui, S., Langlet, T., Beji, H.: Durability of construction materials based-vegetable

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particles (rapeseed straw) subjected to wetting and drying cycles. In: International conference on materials and energy ICOME 18, 30 April–04 May 2018, San Sebastian, Spain (2018).

10. Lachheb, M., Elmarhoune, R., Saadani, R., Agounoun, M., Rahmoune, K.: An experimental investigation on the thermophysical properties of a composite basis of natural fibers of Alfa. Int. J. Mech. Mechatr. Eng. **17**, 27–32 (2017)
11. Brouard, Y., Belayach, N., Hoxha, D., Ranganathan, N., Méo, S.: Mechanical and hygrothermalbehavior of clay – Sunflower (*Helianthus annuus*) and rape straw (*Brassica napus*) plaster bio-composites for building insulation. Constr. Build. Mater. **10**, 196–207 (2018). https://doi.org/10.1016/j.conbuildmat.2017.11.140
12. Lachheb, A., Allouhi, A., ElMarhoune, M., Saadani, R., Kousksou, T., Jamil, A., Rahmoune, M., Oussouaddi, O.: Thermal insulation improvement in construction materials by adding spent coffee grounds: an experimental and simulation study. J. Cleaner Prod. **209**, 1411–1419209 (2019). https://doi.org/10.1016/j.jclepro.2018.11.140
13. Osseni, S.O.G., Apovo, B.D., Ahouannou, C., Sanya, E.A., Jannot, Y.: Caractérisation thermique des mortiers de ciment dopés en fibres de coco par la méthode du plan chaud asymétrique à une mesure de température. Afrique Sci. **12**, 119–129 (2016)
14. Elhamdouni, Y., Khabbazi, A., Benayad, C., Mounir, S., Dadi, A.: Thermophysical and mechanical characterization of clay bricks reinforced by alfa or straw fibers. IOP Conf. Series **186**, 12035 (2017). https://doi.org/10.1088/1757-899X/186/1/012035
15. Palumbo, M., McGregor, F., Heath, A., Walker, P.: The influence of two crop by-products on the hygrothermal properties of earth plasters. Build. Environ. **105**, 245–252 (2016). https://doi.org/10.1016/j.buildenv.2016.06.004
16. Bagrg, L., ElAbbassi, I., Kane, C.S.E., Darcherif, A.M., Ndongo, M.: The challenges of local and biosourced materials on thermal performance: Reviex, classification and opportunity. Int J. Eng. Res. Afr. **47**, 85–101 (2020). https://doi.org/10.4028/www.scientific.net/JERA.47.85
17. Caleshenne, A.: Valorisation fouragéne de typha australis en elevage extensif de zebres maures laitiers dans la region du trarza. Dess, Montpellier (2002)
18. Ozenda, P.: Flora and vegetation of sahara. CNRS, Troisième (2004)
19. Jha, P.N., Kumar, A.: Endophytic colonization of typhaaustralis by a plant growth promoting bacterium klebsiellaoxytoca strain GR-3. J. Appl. Microbiol. **103**, 1311–1320 (2007). https://doi.org/10.1111/j.1365-2672.2007.03383.x
20. Moghaddem, S.M.K., Mortazavi, S.M.: Physical and chimical proprieties of natural fibers extracted from typhaaustralis leaves. J. Nat Fibers **13**, 353–361 (2016). https://doi.org/10.1080/15440478.2015.1029199
21. Duko, J.A.: Handbook of Energy Crops. Purdue University, West Lafayette (1983)
22. Kouwanou, C.S., Dossa, C.P.A., Adjou, E.S., Issiakou, M., Wotto, V.D., Sohounhloué, D.C.K.: Valorization of typhaaustralis stems in bioethanol production using enzymatic hydrolysis and biofermentation. Acad. J. Chem. **4**, 90–95 (2019). https://doi.org/10.32861/ajc.410.90.95
23. Dieye, Y., Sambou, V., Faye, M., Thiam, A., Adj, M., Azilinon, D.: Thermo-mechanical characterization of a building material based on Typha. J. Build. Eng. **9**, 142–146 (2017). https://doi.org/10.1016/j.jobe.2016.12.007
24. Niang, I., Maalouf, C., Moussa, T., Bliard, C., Samin, E., Thomachot-Schneider, C., Lachi, M., Pron, H., Mai, T.H., Gaye, S.: Hygrothermal performance of various Typha–clay composite. J. Build. Phys. **42**, 1–20 (2018). https://doi.org/10.1177/1744259118759677
25. Diatta, M.T., Gaye, S., Thiam, A., Azilinon, D.: Détermination des propriétés thermo-physique et mécanique du Typha Australis. Cong. SFT, Perpignan (2011)
26. Ponnukrishnan, P., Ponnukrishnan, P., Thanu, M.C., Richard, S.: Mechanical characterisation of *Typha* domingensis natural fiber reinforced polyester composites. Am. Int. J. Res. Sci. Technol. Eng. Math. **3**, 241–244 (2014)
27. Abdelhakh, A. O., Saleh, A. M. Soultan, Sow, D., Menguy, G., Gaye, S.: Improving energy efficiency of buildings by using a light concrete based on the typhaaustralis. In: 3rd International Conference on Renewable Energies for Developing Countries (REDEC), pp. 13–15 juillet (2016). https://doi.org/10.1109/REDEC.2016.7577512.
28. Barry, M.E., Taïbi, A.N.: Du Parc National du Diawling à la Réserve de Biosphère Transfrontalière: jeux d'échelles à l'épreuve du développement durable dans le bas delta du fleuve Sénégal, pp. 147–156. Presses Universitaires de Bordeaux, Bordeaux (2011)
29. Amadou, B.A.: Le parc national du diawling: experience de cogestion pour la restauration des plaines inondables, Strategies for wise use of wetlands: Best practices in participatory management. Dakar, Senegal (1998)
30. Al-Ajlan, S.: Measurements of thermal properties of insulation materials by using transient plane source technique. Appl. Thermal Eng. **26**, 2184–2191 (2006). https://doi.org/10.1016/j.applthermaleng.2006.04.006
31. He, Y.: Rapid thermal conductivity measurement with a hot disk sensor: Part 1. Theoretical considerations. Thermochimicaacta **426**, 122–129 (2005). https://doi.org/10.1016/j.tca.2005.07.003
32. Warzoha, R.J., Fleischer, A.S.: Determining the thermal conductivity of liquids using the transient hot disk method. Part II: Establishing an accurate and repeatable experimental methodology. Int. J. Heat Mass Transfer. **71**, 790–807 (2014). https://doi.org/10.1016/j.ijheatmasstransfer.2013.10.062
33. Laibi Babatoundé, Comportement hygro-thermo-mécanique de matériaux structuraux pour la construction associant des fibres de Kénaf à des terres argileuses .Thèses de doctorat Spécialité Chimie, Université de Caen Normandie, France, en partenariat international avec l'Université d'AbomeyCalavi, Benin (2017).
34. Asdrubali, F., Dalessandro, F., Schiavoni, S.: A review of unconventional sustainable building insulation materials. Sustain. Mater. Technol. **4**, 1–17 (2015). https://doi.org/10.1016/j.susmat.2015.05.002
35. Omrani, H., Hassini, L., Benazzouk, A., Beji, H., Elcafsi, A.: Elaboration and characterization of clay-sand composite based on Juncusacutusfibers. Constr. Build. Mater. **238**, 117712 (2020). https://doi.org/10.1016/j.conbuildmat.2019.117712
36. Brzyski, P., Barnat-Hunek, D., Suchorab, Z., Łagód, G.: Composite materials based on hemp and flax for low-energy buildings. Materials **10**, 510 (2017). https://doi.org/10.3390/ma10050510
37. Wuzella, G., Mahendran, A.R., Bätge, T., Jury, S., Kandelbauer, A.: Novel, binder-free fiber reinforced composites based on a renewable resource from the reed-like plant *Typha* sp. Ind. Crops Prod. **33**, 683–689 (2011). https://doi.org/10.1016/j.indcrop.2011.01.008
38. Marques, B., Tadeu, A., Antonio, J., Almeida, J., Brito, J.D.: Mechanical, thermal and acoustic behaviour of polymer-based composite materials produced with rice husk and expanded cork by-products. Constr. Build. Mater. **239**, 117851 (2020). https://doi.org/10.1016/j.conbuildmat.2019.117851

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39. Wang, Y.X., Guo, P.P., Ren, W.X., Yuan, B.X., Yuan, H.P., Zhao, Y.L., Shan, S.B., Cao, P.: Laboratory investigation on strength characteristics of expansive soil treated with jute fiber reinforcement. Int. J. Geomech. **17**, 1532–3641 (2017). https://doi.org/10.1061/(ASCE)GM.1943-5622.0000998
40. Olacia, E., Pisello, A.L., Chiodo, V., Maisano, S., Frazzica, A., Cabeza, L.F.: Sustainable adobe bricks with seagrass fibres. Mechanical and thermal properties characterization. Constr. Build. Mater. **239**, 117669 (2020). https://doi.org/10.1016/j.conbuildmat.2019.117669

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