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Thermo-mechanical characterization of a building material based on Typha Australis

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ABSTRACT

This paper is a contribution to the valorization of Typha Australis as building material. To do this, the crushed fibers of Typha have been agglomerated using clay as binder. The weight percentage of binder is found to be at least 75% to obtain stable materials. The influence of binder content on mechanical and thermal insulation properties was examined. The mechanical properties were evaluated by using a mechanical press. The measurements of thermal effusivity and thermal conductivity of samples have been performed using the transient hot-plate method. Compression and tensile strengths respectively varies from 0.279 to 0.796 MPa and from 0.340 to 0.969 MPa when the weight percentage of binder range from 77–85%. This values have a strong linear correlation with the weight percentage of binder. The thermal conductivity of dry materials varies from 0.117 to 0.153 $W.\ m^{-1}.\ K^{-1}$ while the thermal effusivity rises from 228.9 to 300.0 $J.\ m^{-2}.\ {}^{\circ}C^{-1}.\ s^{-\frac{1}{2}}$. The results show that the thermal conductivity and thermal effusivity increases with increasing moisture content of materials.

1. Introduction

The building industry is the main energy consumer in Senegal with 54.7%, according to the Energy Information System of SENEGAL. According to the data base of the Typha-based thermal insulation materials production project in Senegal, in West Africa, 25–30% of the electric produced is consumed by this sector. In addition to energy consumption, it is noted that the most important part of the CO_2 emitted comes from houses (49%). Building represents a key sector for the reduction of greenhouse gas emission. Using concrete without insulation increases building energy consumption. Thermal insulation is an important factor for reducing energy consumption as well as reducing CO_2 emissions [1–3]. The insulation materials available (polystyrene, polyurethane, glass and rose wool etc.) are mainly imported and are very costly [4]. It is therefore necessary to find insulation materials based on vegetable fibers as an alternative to imported insulation materials. This study deals with the use of *Typha australis* fibers to make a building material. *Typha australis* is an aquatic plant which is found on wetland and belongs to the Typhaceae family. This plant which can reach a height up to 3 m [5] is particularly widespread on the valley of Senegal River. *Typha australis* is nowadays considered as a harmful plant. Indeed, the proliferation of this plant on the valley of Senegal River affects its ecosystem and reduces the socio-economic activities of populations living along the river. The global objective of our study is to transform the harmful *Typha australis* as an opportunity by its transformation as a building material.

This paper aims to do a mechanical and thermal characterization of building materials based on *Typha australis* fibers. Several research works have been carried out in order to develop vegetal product based on local materials [1–4]. Meukam et al. [1], in his work, shows that the use of sawdust improves the thermal performances of stabilized earth bricks. The cannabis fibers influence on the physical and mechanical properties of BTC (compressed earth bricks) were studied by Millogo et al. [2]. The authors show an improvement on mechanical performance of the BTC. Bal et al. [3] studied the influence on thermal properties of laterite bricks with millet waste additive. The investigation of the mechanical properties and hygroscopic behavior of compressed earth block filled by date palm fibers was done by Taallah et al. [6]. The thermal behavior of hollow clay bricks made up of paper waste has been studied by [7]. The authors showed that the thermal conductivity of the brick materials with additives reduced from 0.68 W/m K to 0.39 W/m K compared with that of the sample without additives. Cherki et al. [8] studied the thermal behavior of an ecological composite material based on granular cork embedded in plaster. Their

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findings indicated that the composite is better than plaster without cork in term of thermal insulation and lightness. Belkarchouche et al. [9] determined the influence of adding natural fibers (olive pomace) on concrete thermal and mechanical properties. Their results showed that the addition of fibers improve slightly the thermal and mechanical performance. Benmansour et al. [10] evaluate the possibility of using a new material, composed with natural cement, sand and date palm fibers, as insulating building materials. Toguyeni et al. [11] focus their study on the thermal characterization of an insulating board made with lime and vegetable fibers of the Hibiscus sabdariffa. Palumbo et al. [12] studied the possibility of developing insulation materials for the construction sector made of non-industrial crop wastes and natural binders. The authors assessed the thermal behavior, equilibrium moisture content and water vapor permeability of experimental insulation panels obtained. Their results showed that crop wastes can perform adequately as insulation materials. Efendy et al. [13], in their study, performed a physical and mechanical characterization of untreated and chemically treated harakeke fibers. These fibers were compared with those of hemp to assess their use as potential reinforcements in composite materials. Other studies were carried out on concrete materials reinforced with *Typha australis*. Diatta et al. [14] showed that thermal insulation of concrete materials has been improved with additives. Diagne et al. [15] showed that the mechanical properties of concrete materials are improved by combining Typha, sisal pulp and polypropylene fibers. Georgiev et al. [16] report qualitatively the results of testing different combinations of clay with *Typha latifolia* fibers for their suitability as a universal plaster. Their authors demonstrated clearly the superior properties of Typha fibers as a reinforcement material for clay plaster mortars. Luamkanchanaphan et al. [17] studied study physical, mechanical and thermal properties of insulation boards prepared from narrow-leaved cattail fibers by using Methylene Diphenyl Diisocyanate (MDI) as a binder. Their test results showed that the insulation boards had good physical and mechanical properties and thermal conductivity values of the board with a density of 200–400 kg/m^3 were less than that of fibrous materials and cellular materials.

In this paper, the potential of the use of clay as binding material to make Typha fibers panels was assessed. In this order, the influence of binder content on mechanical and thermal properties of panels with and without humidity were studied. Mechanical properties into investigation were compression and tensile resistances and thermal properties concerned conductivity and effusivity.

2. Materials and methods

The test panels were made with fibers obtained from crushed Typha leaves and clay as binding material.

2.1. Materials

2.1.1. Binder

The clay used was produced from local quarries and do not need any transformation. The results of the granulometric analysis of the clay are illustrated in Fig. 1. These results showed that this clay is mostly made up of close grains with a 1.015 good – quality module. The binding material was composed with equivalent masses of clay and water mixed until a sticky viscous liquid was obtained. The mixing was done in a stainless steel beater having specific speed of 62 or 125 rpm and a capacity of 5 l. The mixing time was about 5 min.

2.1.2. Fibers

Fibers were from *Typha australis* leaves extracted and sun dried before being crushed by means of a hammer grinding machine. The fibers obtained are presented in Fig. 2. The fibers length ranged from 1 mm to 42 mm with a mean value of 13 mm. The fibers density value was determined by calculating the mean value for five measurements is 86.5 kg/m^3.

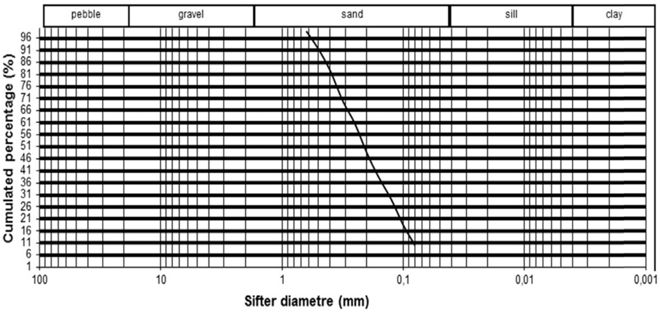

Fig. 1. Granulometric graph of clay used.

Fig. 2. Crushed Typha fibers.

2.2. Sample preparation

Samples were made by mixing typha fibers with the binder material in the beater during 5 min. The mixture was malaxated using a mixer type E095. The mixer had specific speed of 62 or 125 rpm and a capacity of 5 l. The mass composition of the different samples is given in Table 1.

For mechanical tests, a mould of dimensions 4×4×16 cm^3 was used to prepare samples and for the thermal test samples were prepared in a mould of dimensions 10×10×2 cm^3. The material obtained by mixing fibers and clay was poured in the moulds and tamped. After 24 h in an indoor environment of about 27 °C, the moulds were removed and test specimens were cured in air about 14 days. Figs. 3 and 4 show respectively a sample for the thermal test and a sample for the mechanical test. The density and the porosity of the specimens are presented in Table 2.

2.3. Mechanical characterization

Mechanical characterization consists in the determination of the compression resistance and the tensile strength. Test was performed with three specimens for each mix. This characterization was done using a E0160 type mechanical press with a maximum force of 250 kN. The specific speed of the force application was 2 kN/sec. For the

Table 1
Masses of the different compounds.

Samples	Binder percentage (%)	Binder mass (g)	Crushed typha mass (g)	Water mass (g)
E_1	77.13	102.87	30.5	87.63
E_2	78.11	108.81	30.5	92.69
E_3	81.48	134.19	30.5	114.31
E_4	84.22	162.81	30.5	138.69
E_5	84.90	171.45	30.5	146.05

Fig. 3. Picture of a sample for the thermal test.

Fig. 4. Picture of samples for the mechanical test.

Table 2
density and porosity of samples.

Sample	Density (kg/m^3)	Porosity (%)
E_1	1000.0	46.7
E_2	1111. 1	40.0
E_3	1176.5	36.3
E_4	1230.8	23.3
E_5	1304.5	21.9

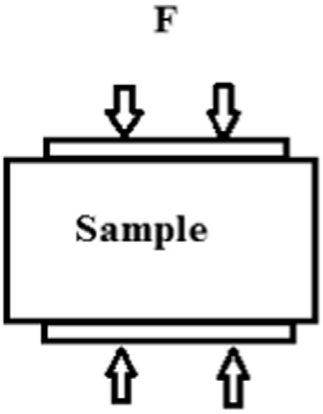

Fig. 5. Compression test.

determination of the compression resistance, the prismatic sample described in 2.2 was placed in the press as represented schematically in Fig. 5. For the tensile strength measurement, the sample was placed as shown in Fig. 6. The mechanical tests consist in applying a force F on the standardized sample and measuring its strain on breaking point. The maximum stress which the sample can bear before breaking is the tensile strength or the compression resistance. It is defined by:

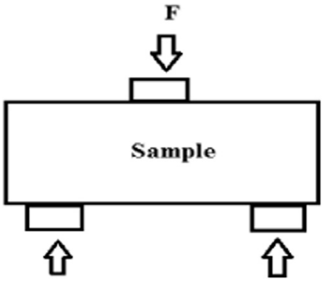

Fig. 6. Tensile test.

$$\sigma = \frac{F}{S} \tag{1}$$

S is the sample section in mm^2, F is the force applied (N) and σ is the stress in MPa.

2.4. Thermal characterization

There are different methods for determining the thermophysical parameters of a building material [3,18–20]. These methods include the hot plate transient method.

Jannot et al. [20] had successfully measured with this method, in symmetrical configuration, the thermal conductivity and the thermal diffusivity of a thin insulating material by maintaining constant the temperature of the rear face of the sample. The same configuration cannot be used here as it is quite impossible to have two identical samples. The hot plate method was then used in an asymmetrical configuration. It consists in embedding a heating element on which a thermocouple was fixed, between the material to be characterized and a 5 cm thick polystyrene plate. The whole set was put between two aluminum blocks with a thickness 4 cm as shown in Fig. 7.

The principle of the measurement consists in sending a heat flux step constant flow into the heating element and recording the transient temperature Ts (t) at the center of this same heating element.

The following hypotheses were considered in the modeling of the system:

- heat transfer remains unidirectional at the center of the heating element,
- temperature at the level of the aluminum block is constant.

In this case, the thermal quadrupole method [21] can be used to solve the thermal transfer problem. Indeed, in Laplace's space, the heat equation depends only on the space variable. The method makes it possible then to relate the input and output flows and temperatures

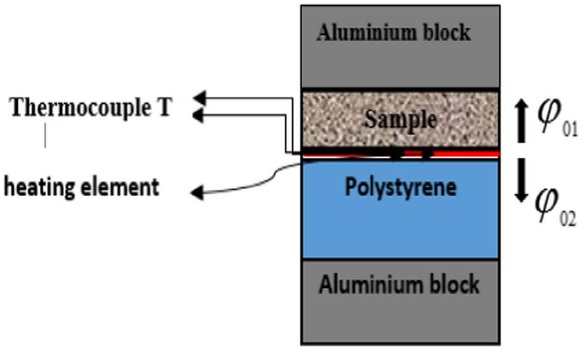

Fig. 7. schema of the experimental asymmetrical hot plate device.

using a passing matrix.

$$\begin{bmatrix} \theta_s \\ \phi_{01} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ CsSp & 1 \end{bmatrix} \begin{bmatrix} 1 & R_c \\ 0 & 1 \end{bmatrix} \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} 0 \\ \phi_1 \end{bmatrix} = \begin{bmatrix} A_1 & B_1 \\ C_1 & D_1 \end{bmatrix} = \begin{bmatrix} 0 \\ \phi_1 \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \theta_S \\ \phi_{02} \end{bmatrix} = \begin{bmatrix} A_i & B_i \\ C_i & D_i \end{bmatrix} \begin{bmatrix} 0 \\ \phi_2 \end{bmatrix} \tag{3}$$

With:

$$A = D = \cosh\left(\frac{E}{\lambda}\sqrt{p}\ e\right);\ B = \frac{\sinh(\frac{E}{\lambda}\sqrt{p}\ e)}{ES\sqrt{p}};\ C = ES\sqrt{p}\ \sinh\left(\frac{E}{\lambda}\sqrt{p}\ e\right)$$

$$A_i = D_i = \cosh\left(\frac{E_i}{\lambda_i}\sqrt{p}\, e_i\right);\ B_i = \frac{\sinh\left(\frac{E_i}{\lambda_i}\sqrt{p}\ e_i\right)}{E_i\ S\sqrt{p}};$$

$$Ci = E_i\ S\sqrt{p}\ \sinh\left(\frac{E_i}{\lambda_i}\sqrt{p}\ e_i\right)$$

λ is the sample thermal conductivity; E the sample thermal effusivity; e the sample thickness; λ_i the polystyrene thermal conductivity; E_i the polystyrene thermal effusivity; e_i the polystyrene thickness; θ_s the Laplace transform of the temperature Ts(t); *Cs* the thermal capacity of the heating element per area unit: $Cs_{=}\rho_s\ c_s\ e_s$; R_c the thermal contact resistance between the heating element and the sample; ϕ_1 the Laplace transform of heat flux input on the upper aluminum block; ϕ_2 the Laplace transform of heat flux input on the lower aluminum block; ϕ_{01} the Laplace transform of the heat flux density living the heating element (upstream); ϕ_{02} the Laplace transform of the heat flux density living the heating element (downstream).

After developing the matrix products (2) and (3), the following relations were obtained:

$$\phi_{01} = \theta_S \frac{D_1}{B_1} \tag{4}$$

$$\phi_{02} = \theta_S \frac{D_i}{B_i} \tag{5}$$

The total flow was:

$$\phi_0 = \phi_{01} + \phi_{02} \tag{6}$$

$$\phi_0 = \theta_S \left(\frac{D_1}{B_1} + \frac{D_i}{B_i}\right) \tag{7}$$

Inferring θ_s from (7), the following equation was finally obtained:

$$\theta_s = \phi_0 \frac{1}{\left(\frac{D_1}{B_1} + \frac{D_i}{B_i}\right)} \tag{8}$$

The established model is able to describe the system answer to the thermal excitation. The model is function of unknown parameters λ and *E*. Besides, the experiment provided the real response of the system which depends on the real material parameter values. The identification then consisted in at the best adjusting the theoretical graph to the experimental graph by giving to the model unknown parameters appropriate values along a time interval for which the transfer at the heating element center is 1D. The Laplace inverse transformation is achieved by using De Hoog's algorithm [22]. Validation tests of the back asymmetric finished hot plate method of the sample maintained at a constant temperature was carried out on the known thermal. The test results are presented on Table 3.

These results agree with those obtained by [20] who used the symmetrical hot plate method. The thermal properties measured are thermal conductivity and thermal effusivity. As these thermal properties are very dependent on humidity content, the samples were oven – dried at 105 °C for 24 h. After cooling in a desiccator, the dry samples were thermally characterized.

Table 3
Measurement results on polystyrene.

e (m)	λ ($W.m^{-1}.\ K^{-1}$)	E ($J.m^{-2}.\ ^{\circ}C^{-1}.\ s^{-\frac{1}{2}}$)
0.007	0.034	54

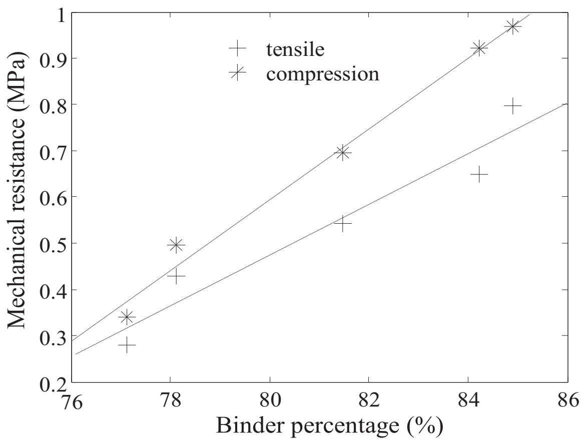

Fig. 8. Variation curve of mechanical resistance in function of the binder percentage.

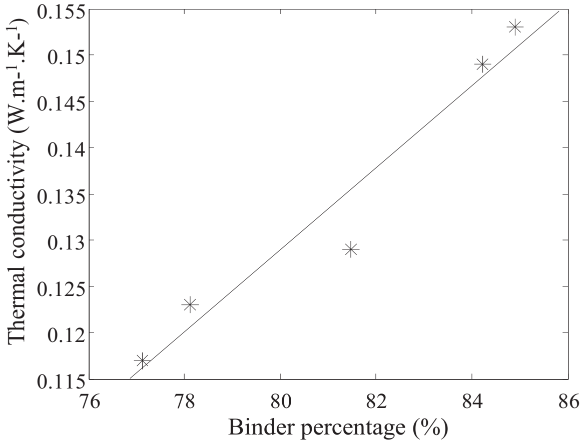

Fig. 9. Dry panel thermal conductivity in function of the binder.

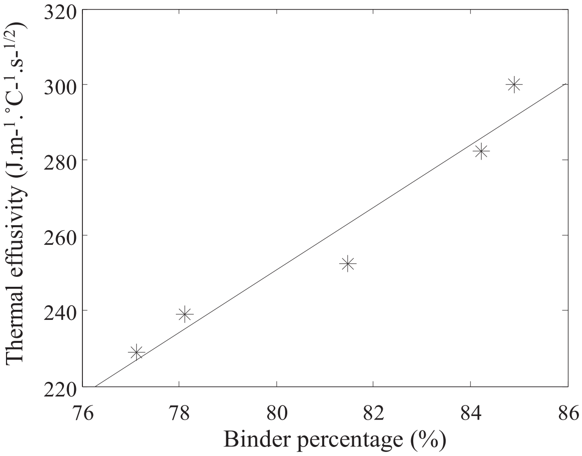

Fig. 10. Dry panel thermal effusivity in function of the binder.

Table 4
Thermal effusivity and conductivity variation of the crushed typha panels in function of clay content for given water contents.

Binder percentage (%)	Mass water content (%)	Thermal conductivity λ ($W.m^{-1}.\ K^{-1}$)	Thermal effusivity E ($J.m^{-2}.\ ^{\circ}C^{-1}.\ s^{-\frac{1}{2}}$)
77.1	10.4	0.127	242.0
78.1	9.6	0.136	259.4
81.5	9.4	0.142	268.9
84.2	6.8	0.158	295.6
84.9	6.2	0.163	315.4

3. Results and discussions

3.1. Mechanical results

The mechanical results concerned the mechanical resistance to compression and tensile strength. Fig. 8 presents the variation of these resistances in function of the binder percentage. It was observed that both mechanical strengths increase in function of the binder percentage. This variation was quasi – linear. It can first be noted that the binder mass percentage was very high (> 75%) to have a stable material. The values of the resistance to compression vary from 0.279 to 0.796 MPa and those of the tensile strength from 0.340 to 0.969 MPa. These results were comparable to those of the lime – hemp concrete [23] whose resistance to compression values vary from 0.15 to 0.83 MPa.

Thermal results. The results are presented in Figs. 9 and 10 respectively for thermal conductivity and thermal effusivity in function of the binder percentage. A quasi – linear evolution of the dry material thermal properties with the binder quantity was observed. Increasing the binder dosage raises the sample density. Indeed, the higher was the density of a material, the higher were the thermal conductivity and effusivity. The thermal conductivity values obtained were low and were of the same magnitude order as those of the hemp concrete [24]. These thermal conductivity values provided a good option to meet the thermal requirements.

The water content had a significant effect on the material properties. Table 4 shows the thermal properties of Typha materials with a moisture content. It can be seen that the higher is the binder percentage the lower is the moisture content. This could be explained by the fact that the clay matrix reduces the fibers porosity. It can be observed that the thermal conductivity and the thermal effusivity of materials with a moisture content were higher than those of dry materials. For instance, for a binding percentage of 77.1%, the thermal conductivity increased about 8% with the moisture content and the thermal effusivity about 6%. However, the values of the thermal conductivity of materials with a moisture content were low and could make these materials good candidates for use in the building. For this purpose, complementary tests as the aging test must be performed.

4. Conclusion

This experimental study was a mechanical and thermophysical characterization of materials based on Typha fibers with a perspective of use as building materials. The binder used in this study was clay. The main results are:

- from a mechanical point of view, the compression resistances and tensile strengths of the achieved materials were low and indicates that these materials in their present form cannot be used as a load-bearing material; they can be used in combination with an load-bearing structure;
- the low values of thermal conductivity showed high thermal insulation capacities of these materials.

These materials, subject to the results of additional tests like aging and fire resistance, can be an interesting alternative for imported and expensive insulation materials.

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