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Thermomechanical Characterization of Laterite Matrix Reinforced with Typha Material for Thermal Insulation in Building

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Abstract

Every person, in every country and on every continent, will be affected in one way or another by climate change. A climate cataclysm is looming on the horizon due to greenhouse gas emissions. This explains a strong demand for air conditioning in the years to come, hence the need for good thermal insulation at a lower cost. However, a policy of prevention, adaptation, and resilience is necessary for the protection of the environment in the future. This work aims to respond to the United Nations SDGs 7, 11 and 13. This paper presents the results of thermomechanical characterizations of the Typha additive (0%, 5%, 10%, 15%, 20%) in laterite matrices. First, we carried out a thermal characterization using the asymmetric hot plane method, which led to thermal conductivity and effusivity in different proportions. Next, mechanical tests were carried out to determine the traction and compression of each material with a matest press. Those which made it possible to obtain results according to the percentage for the thermal tests: a conductivity varying between 0.7178 W/m·K to 0.0597 W/m·K and an effusivity varying between 942.5392 $J/m^2 \cdot K \cdot s^{1/2}$ at 287.0855 $J/m^2 \cdot K \cdot s^{1/2}$ and for mechanical tests: traction varying between 0.035 MPa to 0.034 MPa and compression varying between 0.1115 MPa to 0.0805 MPa for the different samples. The exploitation of the results allowed us to study the conductivity, effusivity, traction, and compression as a function of their densities.

Keywords

Characterization, Asymmetrical Hot Plane, Conductivity, Effusivity, Traction, Compression, Press and Density

1. Introduction

On the African continent, the building sector (residential and tertiary) represents 80% of energy consumption (excluding fuelwood and biomass) and greenhouse gas emissions (GHG). Today, if the whole of Africa only contributes 4% of global GHG emissions, this contribution could significantly increase in the future. The causes of this increase are demographic growth, massive urbanization, the increase in GDP per capita, and the rural exodus, which leads more inhabitants to rely on commercial energies of fossil origin [1]. In other words, buildings are long-lived infrastructures and represent almost a level of global energy consumption, or even more so in African cities, through the impact they have on air conditioning needs without any hassle for Sahelo-tropical countries such as Senegal. Acting on the promotion of architecture and construction provisions (choice of materials) that favor good thermal insulators is a necessity [2]. In March 2023, the IPCC (Intergovernmental Panel on Climate Change) confirmed in its published reports that global temperature warming is accelerating: it will reach 1.5˚C around 2030 and could then exceed 2˚C if the United States does not accelerate efforts to reduce emissions [3]. This explains a strong demand for air conditioning in buildings in the years to come for Sahelo-tropical zones (for example, Senegal). Thus, thermal insulation is considered a very important part of socio-economic development. It makes it possible to control energy through energy efficiency [4]. The latter has encouraged researchers to develop new accessible bio-sourced materials for thermal insulation. Hence, the interest in insulating at low investment costs. In addition, bio-based materials represent an area of research in materials science and technology [5]. Corresponding to Senegal, an invasive species (Typha) causes enormous problems to the physical and human environment [6]. The expansion of Typha in the Senegal River valley developed at very high speed along the hydraulic axes due to a lack of fluctuation in water level and salinity resulting from the construction of the Diama and by Manantali. Covering more than 80,000 hectares with an annual proliferation of around 15%, its massive presence in the River Delta and Lake Guiers constitutes a very serious threat with considerable socio-economic impacts on agriculture, water consumption, livestock farming, health, fishing, and biodiversity. As a result, many methods of fighting (mechanical, chemical, biological, and manipulation of water levels) have been initiated but have not produced results [7] [8]. This pushes researchers towards its valorization as an insulating material in buildings. In addition, the valorization of local materials could constitute an alternative to synthetic materials (polyurethane, polystyrene, glass or rock wool, etc.), which are too expensive and cause many environmental problems. Hence the purpose of this study.

Much research has been carried out on bio-sourced materials, leading to results on the thermal side and on the mechanical side for good thermal comfort in buildings. Thus, studies have been carried out on Typha concrete and cement [9], Typha alone and their density [10] and Typha and clay [11] leading to important results. In addition, wood and date palm [12], laterite incorporating natural pozzolan or sawdust [13] [14]. It is also used in kapok, coconut, peanut shell fiber, and rattan [15]. All these studies carried out on materials led to important results from a mechanical and thermal point of view.

Several studies have been carried out on bio-sourced materials. Those who explain its importance in the building sector as a thermal insulator. Therefore, given the accessibility of laterite. A study on Typha-Laterite would be interesting. In addition, laterite occurs in many sites in Senegal, and the problems posed by Typha. Its recovery could constitute promising materials for the environment. To do better, this work starts with the sample preparation procedures and their thermomechanical characterizations, and then the study of the change of thermal conductivity, thermal effusivity, traction, and compression as a function of their densities is carried out.

2. Experimental Method

2.1. Typha Cutting and Grinding

Typha comes from the Senegal River valley. After having cut it and dried it, put it in the form of bunches of Typha. As shown in **Figure 1** below.

Figure 1. Typha bunches.

Figure 2. Crusher and ground Typha.

The next step is to grind these bundles of Typha with a grinder to obtain smaller aggregates. Figure 2 shows the machine used to grind and the Typha granulates obtained.

2.2. Preparation of Thermal and Mechanical Samples

The samples for the thermal tests were chosen in size 10 cm × 10 cm × 2 cm and those for the mechanical tests in 4 cm × 4 cm × 16 cm. These matrices are based on laterite with the additive of Typha in proportion by mass: 0%, 5%, 10%, 15% and 20%. The presence of water in these formulations is calculated by the following formula.

$$m_e = 0.3 \times m_l \text{ avec } m_l = \text{mass of laterite and } m_e = \text{masse of water}$$

The molds used for the manufacturing and the thermal and mechanical samples are presented in Figures 3 and 4. These samples have a lifespan of 3 months, and their drying was done in the shade in the laboratory. In addition, a sieve with a 4 µm hole is used to have smaller laterite aggregates. A scare balance is used to measure the masses of components before and samples after their manufacture. The sieve and balance are shown in Figure 5.

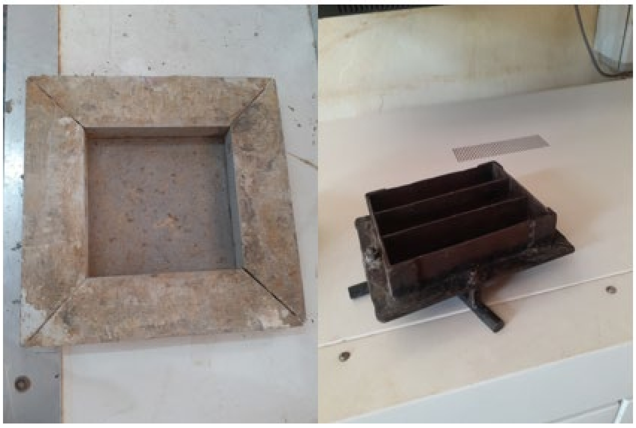

Figure 3. Thermal (a) and mechanical (b) molds.

Figure 4. Thermal and mechanical matrix.

Figure 5. Sieve and balance.

3. Thermomechanical Characterization

3.1. Thermal Characterization

The device below shows us the thermal characterization device of the asymmetric hot plane (see Figure 6). It is made up of a metal structure (bracket + clamping device), carrying two polystyrene insulating blocks between which the sample to be characterized and the thin heating resistor (3×10^{-4} m) are placed, onto which a K type thermocouple (Chromel-Alumel) is attached. All of these latter components are sandwiched between two aluminum blocks. The maintaining pressure is obtained using a threaded metal axle, which ensures perfect contact between all the components of the stem plate and the clamping disc.

The heating resistor has a stabilized power supply and is coupled to a central acquisition unit (Picolog TC 08) of the temperature measured using the thermocouple [16].

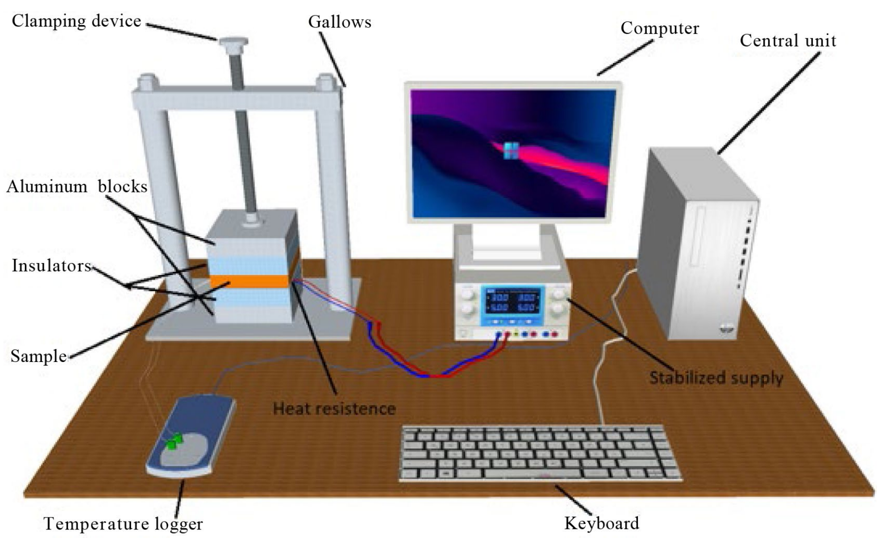

Figure 6. Diagram of the thermal characterization device.

The measurement principle consists of imposing a constant heat flow on the lower face of the sample using a heating resistor and recording the temperature variation at the center of the device while ensuring that the hypothesis of unidirectional heat transfer is respected. This offers the possibility of estimating the thermal effusivity and conductivity of the material. A simulation program written in software makes it possible to trace the experimental and theoretical curves representing the evolution of the temperature as a function of time and to identify the heating duration from which the hypothesis of unidirectional transfer is respected. The thermo-physical parameters of the sample are estimated in the part of the thermogram where the curves merge with good sensitivity of the parameters for a temperature rise of around 10˚C.

The duration of parameter estimation at the part where the curve of the residuals (difference between the theoretical and experimental curves) is centered on the value 0 [17]. The residual curve is centered on the value 0, as shown in **Figure 7** below.

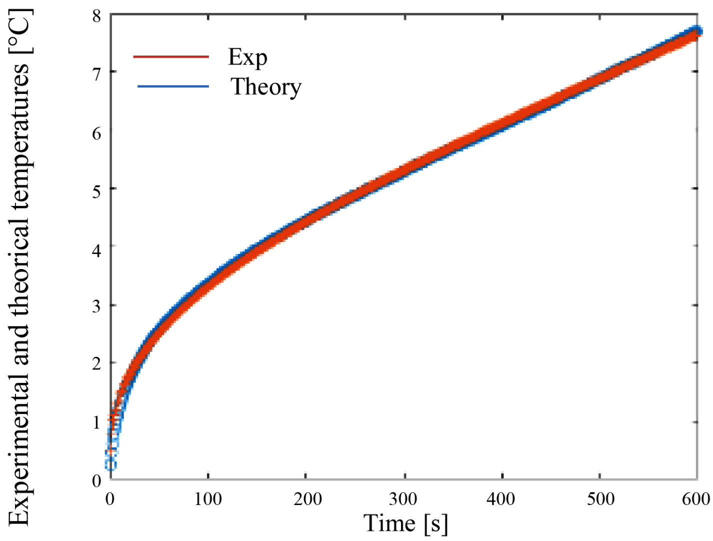

Figure 7. Thermal characterization curve.

3.2. Mechanical Characterization

The press is matest brand. It allows us to know traction and compression. The device is composed of two different metal cylinders, one for the tensile test and the other for compression. Thus, the device is located at the Experimental Center for Research and Studies for Equipment (CEREEQ). Additionally, the press has a correction coefficient of 1.00535 with limited validation in May 2024. The device of the measuring device is shown in the figure below.

For the case of our study, we chose the example of the press, which can be found in **Figure 8**. It allows us to directly record the applied force and its traction corresponding to the level of the press screen. In addition, it is easy to use. You just have to place the 4 cm × 4 cm × 16 cm sample in the metal cylinder, which serves as traction, before introducing it into the cavity of the press. Speed is kept constant for all the tests until the specimen completely ruptures [18]. Compression is the force exerted on a material until it completely ruptures or irreversibly deforms so that compressive resistance is assimilated to the force reached at the deformation limit. In the compression test, two parts of the broken specimen following the previous tensile tests are used [19]. Then, it is put into a metal cylinder for compression before being fed into the press cavity. For each portion, we determine its force in KN and its compressive resistance MPa in order to average the two compressions to give its average force F_m and its average compressive resistance R_m. The two metal cylinders represent in **Figure 9**.

Figure 8. Matest traction and compression.

Figure 9. Metallic cylinders.

The content of the thermomechanical characterization procedures here is the thermal and mechanical results represented in 4.1 and 4.2.

4. Results and Discussions

4.1. Thermal Results and Discussions

Table 1. Results of the thermal characterization of laterites with Typha additive in mass proportions.

Sample Typha Laterite (0%, 5 %, 10%, 15% et 20%)	E0	E5	E10	E15	E20
Mass of dry samples in gram	280.93	240.83	188.54	175.85	133.95
Thermal conductivity in W/m·K	0.7178	0.416	0.2841	0.1779	0.0597
Thermal effusivity in $J/m^2{\cdot}K{\cdot}s^{1/2}$	942.5392	891.7225	421.2817	415.22	287.0855
Density kg/m^3 $\rho = \frac{m}{v}$	1404.65	1204.15	942.7	879.25	669.75

Table 1 presents the results of the thermal characterization of laterite matrices with the content of Typha fibers in the following proportions: 0%, 5%, 10%, 15% and 20%. A decrease in thermal conductivity and effusivity is observed depending on the addition of Typha in the samples. Compared with other results, the addition of Typha in the clay matrix decreases the thermal conductivity and effusivity [11] [20]. In addition, for clay samples containing 3% to 6% fibers, the thermal conductivity varies from 0.52 to 0.20 W/m·K [21]. Those who justify these results

In addition, it can be concluded that Typha associated with laterite decreases thermal conductivity and effusivity.

After having the thermal conductivity and effusivity, before carrying out these tests, we weighed the dry masses of each sample in order to calculate the density of the following formulations announced in Table 1. These allowed us to plot the histograms of thermal conductivity and effusivity as a function of their density in Figures 10 and 11.

In this histogram, we notice that the thermal conductivity decreases as its density decreases. As a result, we note a decrease in density from 1404.65 to 669.75 Kg/m^3 and in thermal conductivity from 0.7178 to 0.0597 W/m·K. In addition, air has a lower thermal conductivity (0.0262 W/m·K at 30˚C) than that of solid matrices. In addition, the reduction in air volume by obstruction of pores in the laterite leads to a reduction in porosity in one direction and an increase in density in the other direction. This explains the increase in thermal conductivity as a function of density, and its regression is due to the increase in porosity in the Laterite-Typha samples, thus explaining the presence of Typha fibers in the matrices.

With a comparison of the results of other researchers, the thermal conductivity increases with the density [22]-[24]. Those who argue these results.

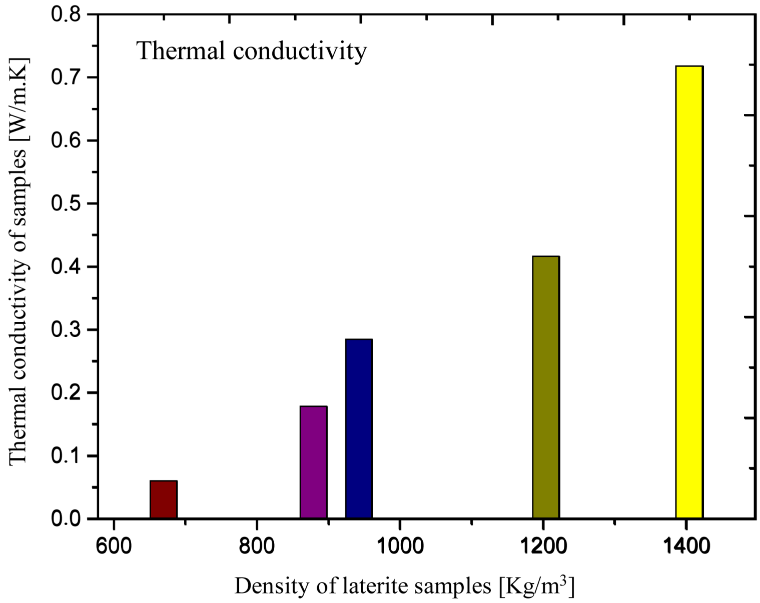

Figure 10. Histogram of thermal conductivity as a function of the density of laterite matrices with Typha additives in mass proportion.

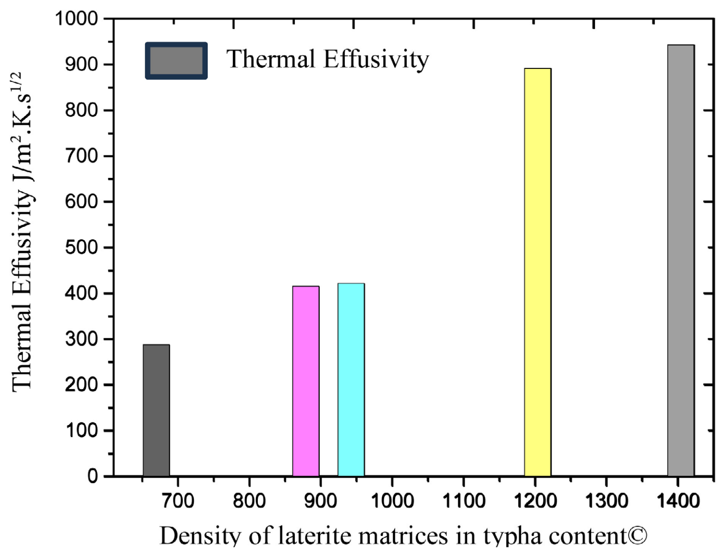

Figure 11. Histogram of thermal effusivity as a function of the density of laterite matrices with Typha additives in mass proportions.

Figure 11 shows us the histogram of thermal effusivity as a function of the density of the laterite matrices with Typha content of 0%, 5%, 10%, 15% and 20% in mass proportion. We note a decrease in thermal effusivity from 942.5392 to 287.0855 J/m2·K.$s^{1/2}$, leading to a drop in density from 1404.65 to 669.75 Kg/m^3. This can be explained by the fact that the thermal effusivity of a material depends on its thermal conductivity, density, and thermal capacity. In addition, the conductivity and density decrease as the mass percentage of Typha fibers in the laterite increases. This decrease in thermal conductivity and density also leads to a decrease in the thermal effusivity of bio-sourced laterites. In other words, the growth of Typha fibers in laterite matrices increases the presence of pores in the samples. The increase in pores in the matrix reduces the density and the thermal conductivity, resulting in thermal effusivity.

After having had the results of the thermal tests and its operations, the mechanics are listed below.

4.2. Mechanical results and discussions

Table 2 shows the results of the mechanical tests and the density of each sample.

Table 2. Traction and compression of Typha Laterite samples.

Mass percentage of Typha-Laterite			E0	E5	E10	E15	E20
Traction		Force in KN	0.156	0.159	0.155	0.155	0.153
		Pression in MPa	0.035	0.036	0.035	0.035	0.034
Compression	C1	Force in KN	2.495	3.641	3.105	3.035	1.448
		Pression in MPa	0.111	0.162	0.138	0.135	0.064
	C2	Force in KN	2.530	3.092	3.306	3.031	2.192
		Pression in MPa	0.112	0.137	0.147	0.134	0.097
	$C_{moyenne}$	Force in KN	2.5125	3.3665	3.2055	3.033	1.82
		Pression in MPa	0.1115	0.1495	0.1425	0.1345	0.0805
Mass in gram			357.09	310.12	273.98	188.95	160.17
Density Kg/m^3			1394.883	1211.406	1070.234	738.086	625.664

This table represents the mechanical test results of laterite samples with the Typha additive in different mass proportions (0%, 5%, 10%, 15% and 20%).

Tensile and compressive strength decreases with a high fiber content. These results correspond with an observation made by other researchers [11] [22] [25] that the progressive addition of fiber in a matrix weakens the mechanical properties.

These results allowed us to obtain the following histograms.

Figure 12 gives us the evolution of traction as a function of the density of laterite matrices with Typha content. We notice that with the presence of Typha fibers in increasing proportion in the samples, the traction decreases as a function of the decrease in density. For the laterite sample, only the addition of 5% fiber increases traction. We can explain it by a significant proportion of the porosity that exists at the level of the Typha fibers, thus weakening the mechanical properties and reducing the traction with that of the density. This is in line with the results in the literature [24] [26]. In the case of laterite alone, during its drying, there is a loss of water. It creates intermolecular gaps, resulting in weak mechanical properties. A little fiber could fill these voids, hence the explanation for the 5% increase.

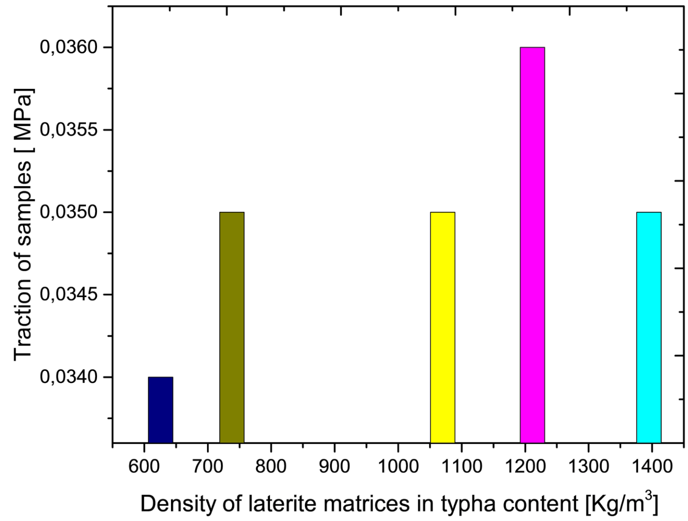

Figure 12. Histogram of traction as a function of density of laterite [Kg/m^3].

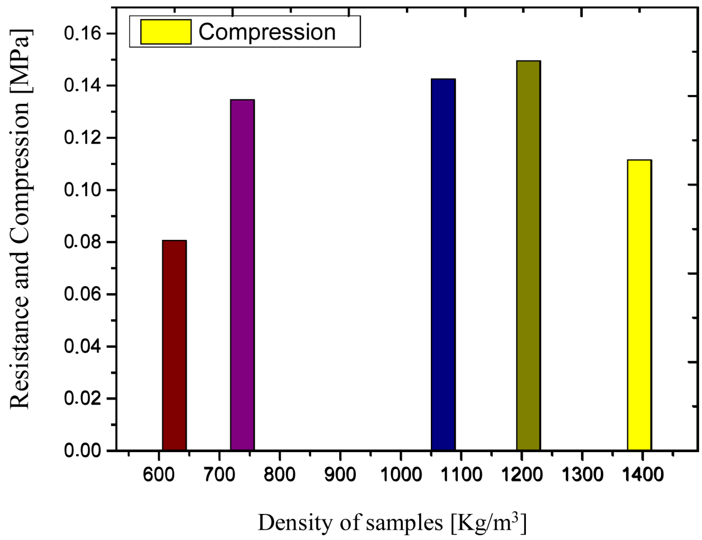

Figure 13. Histogram of the compressive resistance as a function of the density of the laterite matrices with the Typha additives in proportion to mass.

Figure 13 gives us the histogram of the compressive resistance as a function of the density of the laterite matrices in Typha content. Compressive strength increases with density and is opposed to the Typha additive in laterite matrices. This can be explained by constant sample volumes. The addition of fiber increases the pores, which decreases the mechanical properties. Compared with other results [11] [25], the fibers decrease the compressive strength. For the laterite sample alone, we see an increase in compression at 5% fibers. This can be explained by the fact that the two portions used in traction had low values due to their intermolecular bursts.

5. Conclusions

The study of the thermomechanical characterization of laterite matrices reinforced with Typha for insulation in homes gave the following results.

A reduction in thermal conductivity and effusivity as a function of the Typha additive in mass proportion (0%, 5%, 10%, 15% and 20%) from 0.7178 W/m·K to 0.0597 W/m·K and 942.5392 $J/m^2·K·s^{1/2}$ and 287.0855 $J/m^2·K·s^{1/2}$ respectively. With this same mass variation, we had a weakening of tension 0.035 MPa and 0.034 MPa and of compression 0.1115 MPa and 0.0805 MPa except at 0%. The latter undergoes an increase in mechanical properties up to 5% Typha before its fall with progressive addition of fiber. Then, we had the histograms of conductivity, effusivity, traction, and compression as a function of their densities. They decrease with each other with the Typha content, finally, given the results we had on the thermal and mechanical side.

In perspective, the addition of a little cement would be necessary to strengthen the mechanical properties before implementing them.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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