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Research Article

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Thermal Characterization of Dry Soil/*Typha australis* Materials for Improving the Energy Performance of Buildings

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Abstract The main purpose of this paper is to contribute to the development of clay-based materials with good thermal performance. These materials will have to contribute to reduce the energy consumption of buildings in the tropical zone. To achieve this goal, a thermal characterization of soil-Typha materials is carried out and then an energy simulation by using retscreen expert software to evaluate energy savings. This thermal characterization shows a decrease in thermal conductivities of 1.67 $W.m^{-1}.K^{-1}$ for soil only to 0.52 $W.m^{-1}.K^{-1}$ for soil treated with 10% typha by mass. This thermal conductivity varies inversely with respect to the thermal resistance which increases from 0.018m²K/W to 0.057m²K/W. This thermal priority shows that the insulating power of the material is increased and therefore its energy efficiency. Indeed, the simulation compared to a conventional concrete material used for the construction of a 3x4m² room shows an energy saving of 62.9%.These results show how clay materials have become useful for thermal insulation in buildings and, in turn, for improving the energy efficiency of buildings.

Keywords thermal conductivity-thermal resistance-typha content-energy efficiency-clay-characterization

Introduction

The tropical zone is marked mainly by huge temperature variations and heavy rains. This requires the adaptation of architectures and a good choice of materials so that buildings are more energy efficient. Like all tropical countries, Senegal also faces the same problem of the adaptability of the materials used. Apart from these problems, the Senegalese capital is facing to a saturation of populations, hence the interest of building a new city to decongest its capital, the town of Diamniadio, characterized by a clay soil that contains difficult conditions to build buildings, is chosen by the Senegalese government. Some work recommends the firing of clay up to 800°C where CaO lime will appear followed by the release of CO_2 [1,2]. Further work has focused on the thermal, mechanical and acoustic characterization of materials [3]. For thermal insulation, characterizations on thermal conductivity as a function of cement with wood and water content are made by other authors [4], the thermal conductivity of stabilized soils is studied by Adam and John [5]. Bal *et al* were able to measure the water content of laterite bricks with millet pod [6]. Jannot *et al* performed work on the measurement of the thermal conductivity of insulating anisotropic materials [7], based on the 3-layer hot plate method that measured the conductivity on the perpendicular direction [8, 9, 10]. The major constraints are due to the inflatable nature of the soils and a high narrowing imposing some specificities. To build there, it is necessary to completely remove this ground and to make piles or micro-pile.

This affects the cost of buildings. The main objective of this paper is to improve the thermal performance of these soil/typha materials of Diamniadio.

Methods and Materials

The working method consists of collecting the soil in the town of Diamniadio and Typha Australis in thiés town. The soil will be individually characterized and then mixed with typha at progressive mass proportions. The land collection site is defined by 14°43’13’’ north and 17°10’57’’ west cordage. The dug depth is 1m10 and the product is this blackish color. Typha is collected in Thiès area in Nguinth district. To achieve these objectives, different materials are used such as sieves for the particle size analysis of soil and typha, the hot wire method for the thermal characterization of materials.

The land and typha are represented by the following Figures 1 and 2:

Figure 1: Sifted soil

Figure 2: Typha crushed

Particle Size Analysis of Typha and Soil Materials

Typha Particle Size Analysis

The particle size analysis of typha allows to give the percentage of material that crosses according to the size of the mesh of the sieves. Figure 3 of this experiment is given as follows:

Figure 3: Particle size experimentation

Typha australis is crushed through a mill before being crushed through sieves.

Soil Particle Size Analysis

The soil is analyzed wet and the experiment is shown in the following figure 4

Figure 4: Soil Experiment

Sample Formulation and Fabrication

The principle is to make 3 sets of formulation. The first one consists of 26.1% of water and 73.9% of soil and is taken as the reference formulation. The second consists of 4.48% typha, 23.88% water and 71.64% soil. The third consists of 70% soil, 10% typha and 20% water. For each formulation 4 block samples for thermal analysis are manufactured. The samples are shown by the following Figures 5 and 6:

Figure 5: Soil samples + typha

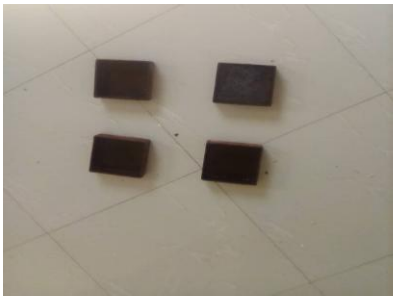


Figure 6: Sample without typha

The sample size is given by:

$$D = 10x10x03cm^3 \qquad (1)$$

The thermal characterization is based on the hot wire modelling. It should be noted that due of the dimensional shrinkage phenomena of the sample made with *Typha australis* only, the size is slightly increased to allow to have 10x10x03cm^{3}after shrinkage. The device that enables the experiment is as follows:

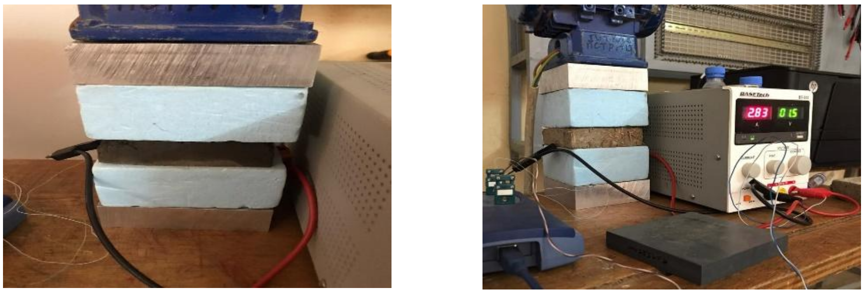


Figure 7: Measurement of thermal properties

Heat Transfer Modelling

The estimation of thermal properties is based on hot wire modelling. Based on cylindrical geometry, the heat transfer by conduction modelling is given by the following equation:

$$\frac{\partial^2 T(r,t)}{\partial r^2} + \frac{1}{r}\frac{\partial T(r,t)}{\partial t} = \frac{1}{a}\frac{\partial T(r,t)}{\partial t} \qquad (2)$$

The resolution of this system by the formalism of the quadrupoles makes it possible to find the following expression:

$$F_s(p) = \frac{\phi_0}{p}\frac{A_0+(A_0R_c+B_0)/Z}{C_0+(C_0R_c+D_0)/Z} \qquad (3)$$

With the following expressions of :

$$B_0 = \frac{1}{2\Pi\lambda qLr_0}\frac{I_0(qr_0)}{I_1(qr_0)} - \frac{1}{\rho C_s \Pi r_0^2 Lp}; \; C_0 = \rho c_s \Pi r_0^2 \, Lp \; et D_0 = \frac{qr_0}{2}\frac{I_0(qr_0)}{I_1(qr_0)}$$

With

$F_s(p)$	Laplace transform of difference $T_s(t)-T_s(t=0)$
$F(p)$	Laplace transform of difference $T(t)-T(t=0)$
R_c	Contact resistance at sample/heater interface
λ	Thermal conductivity of the sample
a	Thermal diffusivity of the sample
p	Laplace Variable
r_0	Radius of the heating wire
L	Length of heating wire
ϕ_0	Power dissipated in the heating resistor

I_0, I_1, are Bessel Functions of first and second kind.

Practical implementation of the method

The hot wire is placed between the materials to be characterized before starting heating and temperature acquisition. This arrangement allows a linear variation of the temperature as a function of the logarithm of time. Thus, the thermal conductivity is proportional to the slope of this equation 4.

$$\mathrm{T_s(t)} - \mathrm{T_0(t)} = \mathrm{f(ln(t))} \qquad (4)$$

This will allow us to evaluate the thermal conductivity of the material to be characterized. Indeed, to minimize the sources of error it is necessary to control the linear heat flow $\frac{\Phi_0}{L}$. In order to achieve this, it is necessary to choose a length of heating sufficient to decrease the errors on the surface S.

Estimation of Volumetric Thermal Capacity

In this part, it is necessary to wait for long times and a one-way heat transfer to the center of the sample. At the moment we have a thermogram of type T=f(t). To obtain the volumetric thermal capacity it is necessary to plot the slope of this graph at the time or effect of the thickness start to be felt. Knowing how to estimate the effusivity and thermal conductivity of materials when heat transfer is unidirectional at the center of the sample so it can be applied to our samples to characterize them.

Sensitivity study

This study is essential at the probe level to make the data more accurate. It is done as follows: $\mathrm{k_i}$ is a given physical property, we call temperature sensitivity to the $\mathrm{k_i}$ property the following relation $\mathrm{k_i}\frac{\partial \mathrm{T}}{\partial \mathrm{k_i}}$. The relationship represents a temperature induced by the $\mathrm{k_i}$ property. This important concept provides insight into the dataset that influences temperature. A necessary and sufficient condition for sensitivity to exist is to impose $\sum_i \mathrm{C_i}\frac{\partial \mathrm{T}}{\partial \mathrm{k_i}} = 0$ between functions $\frac{\partial \mathrm{T}}{\partial \mathrm{k_i}}$. In order to enforce these laws, we will consider our study material that is soil of Diamniadio treated by 4, 48% of Typha Australis. Indeed, the Laplace transform of the front face temperature is written as follows:

$$F = \frac{\varphi_0}{P}\frac{1}{\left(\frac{D}{B}+\frac{D_i}{B_i}\right)} \qquad (5)$$

The temperature T will be deduced by the inverse transformation by applying the Stehfest method.

$$\frac{\partial \mathrm{T}}{\partial \mathrm{k_i}} = \frac{\mathrm{T(k_0,k_1 \ldots\ldots\ldots\ldots\ldots\ldots k_P,t)}}{\epsilon} \qquad (6)$$

The following curves 8 and 9 show the reduced temperatures and sensitivities for our material 4.48% crushed typha at long times.

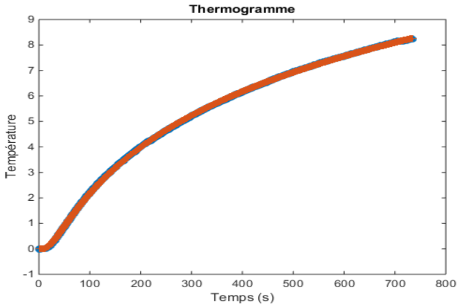


Figure 8: Overlay of experimental and theoretical long-time curves

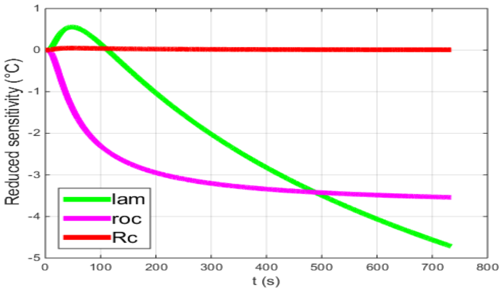


Figure 9: Reduced sensitivity to long-time curves

Curve 8 shows that the quadratic deviation tends towards zero, that show the accuracy of the theoretical model compared the experimental one. The Curve 9 shows that temperature is sensitive to conductivity and thermal capacity. Moreover, at the level of curve 9 the thermal capacity starts to be linear from 300s so it will be possible to determine it by the determination of the tangent. The short-time representation for our material with 4.48% typha mass is given by the following curves 10 and 11.

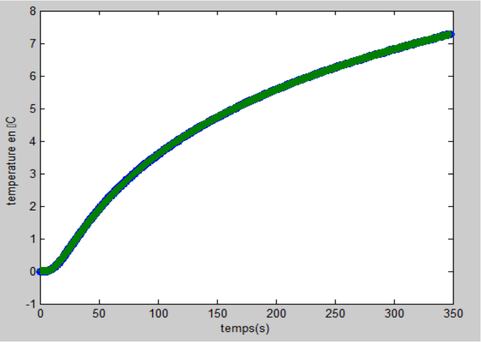


Figure 10: Experimental and Theoretical Curve Overlay in Short Time

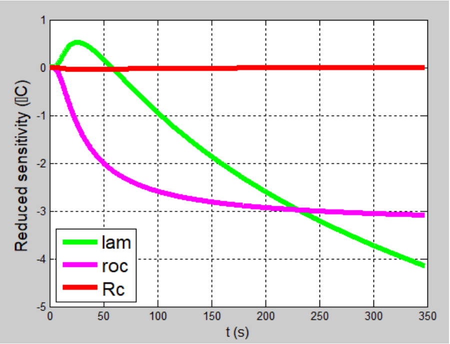


Figure 11: Reduced Sensitivity in Short Time

These curves still show that the temperature is not sensitive to the contact resistance but is sensitive to thermal capacity and thermal conductivity. The simulation was carried out over a period of 350s. In addition, this curve is used for the determination of thermal conductivity.

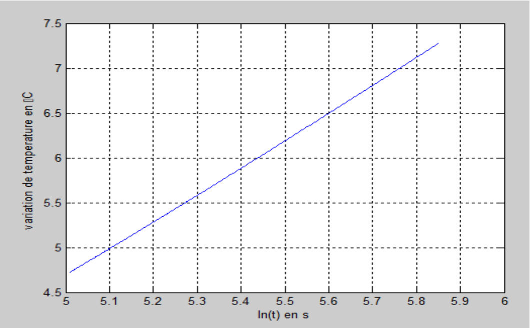


Figure 12: Temperature as a function of ln(t)

The residue curve (in red) below gives an idea of the validity of the experiment. This residue curve must be centered around the zero so, it is sure that the heat transfer to the center of the sample is at 1D.

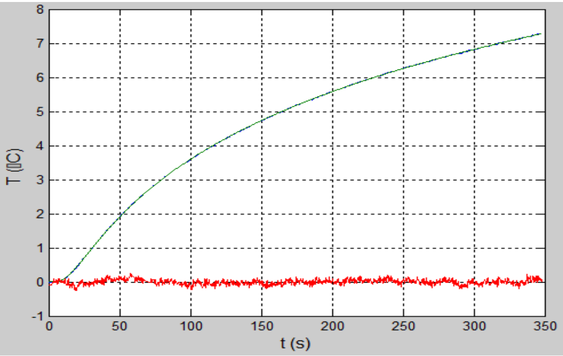


Figure 13: Soil-Typha Residue Curve

Results and Discussion

Results

The particle size analysis of the soil and typha allowed us to have the following table 1 and Figure 14:

Table 1: Results of Wet Particle Size Analysis of Soil

Sieve diameter	Partials refusals	Cumulative refusals	%cumulative refusal	% passing
8mm	0	0	0	100
5mm	4	4	0.55	99.45
2mm	6.2	10.2	1.39	98.61
1.60mm	1.7	11.9	1.62	98.38
1mm	5.9	17.8	2.43	97.57
800µm	5	22.8	3.11	96.89
500µm	19.3	42.1	5.75	94.25
250 µm	287.4	329.5	45.00	55
200µm	152.3	481.8	65.81	34.19
125 µm	207.6	689.4	94.61	5.39
100 µm	26.3	715.7	97.76	2.24
63 µm	8.7	724.4	98.94	1.00

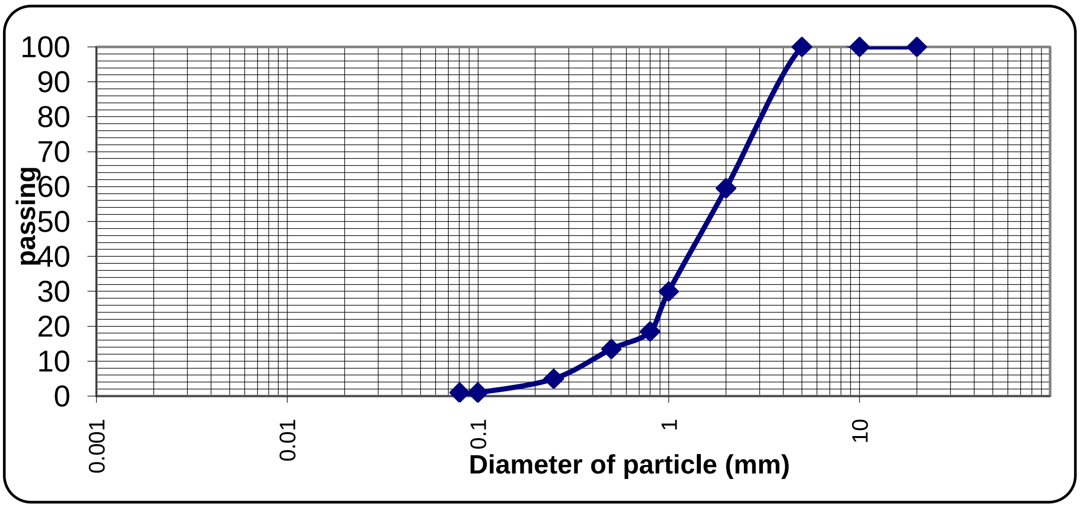


Figure 14: Particle size analysis results

Certainly in this paper the emphasis is not on these particle size results but it is important to show it in order to give an idea of the percentages of each particle size according to the mesh of the sieves. This was very important during the mixing of the soil and the Typha. The following results show the evolution of the thermal conductivity of materials as a function of *Typha australis*.

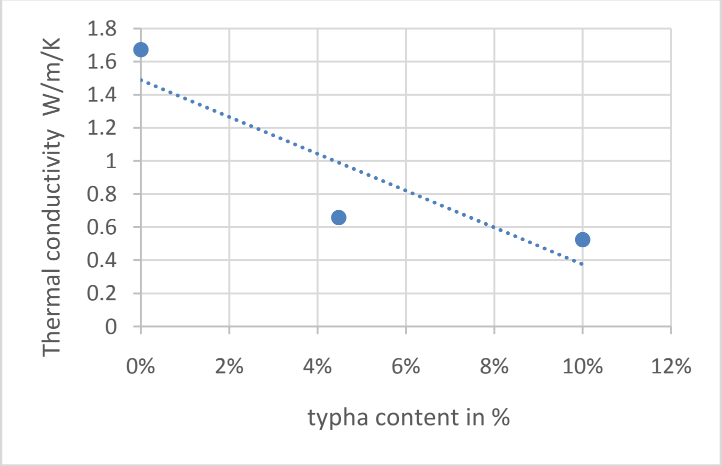


Figure 15: Thermal conductivity as a function of Typha australis content

Thermal conductivity decreases when Typha is added gradually. This is because the thermal conductivity of typhais 0.045 W/m/K [11], more insulating than earth alone. To corroborate better these elements, we represent the evolution of the thermal resistance for a 3cm brick.

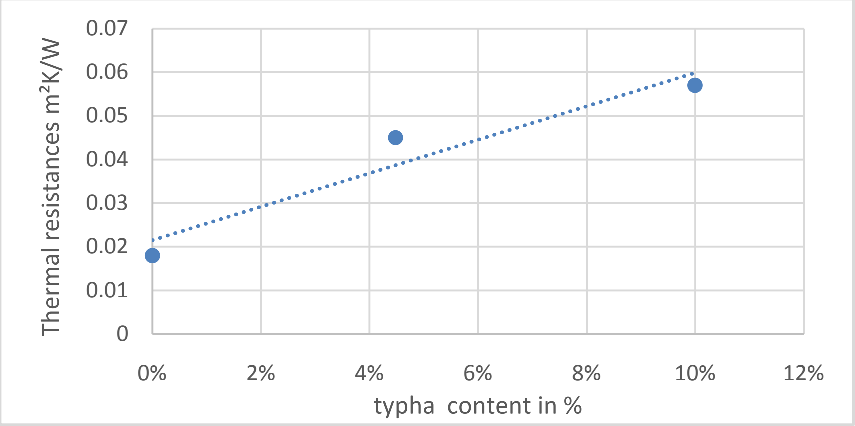
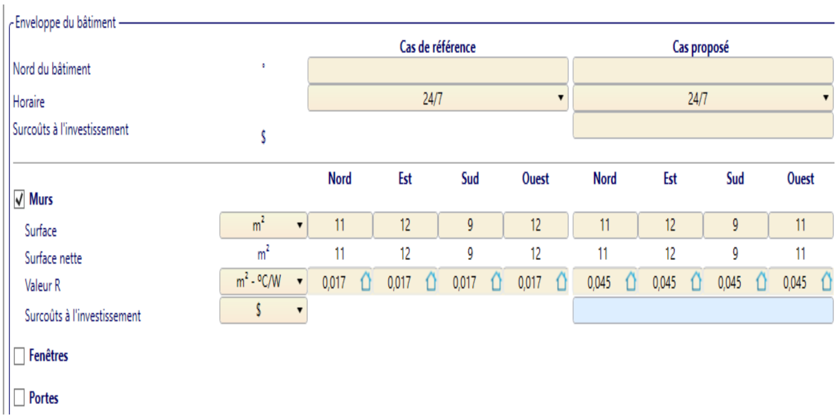


Figure 16: Thermal evolution

The thermal resistance increases when the *Typha australis* content is increased, which improves the insulating power of the earth material. At the end, a comparison of these results is applied with respect to a room of dimension 3x4m² consisting of conventional concrete of thermal conductivity 1.75 $\mathrm{W.m^{-1}.K^{-1}}$.

For comparison, we used the material that received 4.48% typha with a thermal conductivity of 0.66$\mathrm{W.m^{-1}.K^{-1}}$.We use Retscreen expert software to perform this simulation and the results are as follows:

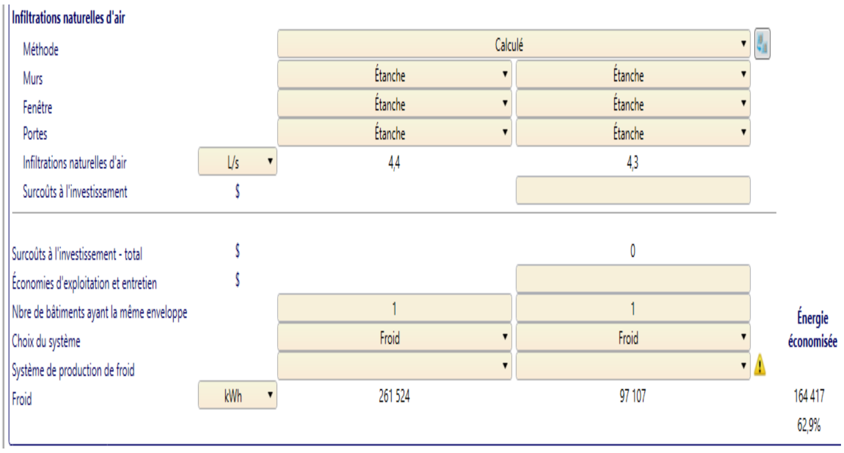
Table 2: Thermal simulation of the room



Enveloppe du bâtiment

		Cas de référence				Cas proposé			
Nord du bâtiment	°								
Horaire		24/7				24/7			
Surcoûts à l'investissement	$								
		Nord	Est	Sud	Ouest	Nord	Est	Sud	Ouest
☑ Murs									
Surface	m²	11	12	9	12	11	12	9	11
Surface nette	m²	11	12	9	12	11	12	9	11
Valeur R	m² - °C/W	0,017	0,017	0,017	0,017	0,045	0,045	0,045	0,045
Surcoûts à l'investissement	$								
☐ Fenêtres									
☐ Portes									

Table 3: Simulation results



Infiltrations naturelles d'air				
Méthode		Calculé		
Murs		Étanche	Étanche	
Fenêtre		Étanche	Étanche	
Portes		Étanche	Étanche	
Infiltrations naturelles d'air	L/s	4,4	4,3	
Surcoûts à l'investissement	$			
Surcoûts à l'investissement - total	$		0	
Économies d'exploitation et entretien	$			
Nbre de bâtiments ayant la même enveloppe		1	1	Énergie économisée
Choix du système		Froid	Froid	
Système de production de froid				
Froid	kWh	261 524	97 107	164 417
				62,9%

The simulation of the results shows an energy saving of 62.9% compared to conventional concrete material.

Discussion

The study shows us clearly that we can improve the insulating power of the land of Diamniadio by adding *Typha australis*. The soil alone having a thermal resistance of about 0.02 m²K/W for a thickness of 3cm and this resistance grows to 0.06 m²K/W. This is an important result in the application of these materials in our tropical areas to minimize energy consumption as shown in the document, a 62.9% energy saving can be saved compared to a room made with conventional materials (cement).

This result seems important for research and development and will also make it possible to better value the clay soil of Diamniadio in Senegal. Therefore, for an eco-construction it would be opportune to adopt an approach based on the mixture between *Typha australis* and earth to have bricks with thermal properties suitable for the comfort of the occupants. The energy saving observed will directly influence the ecological footprint of buildings in Africa but also the reduction of greenhouse gases. The occupants will no longer need to resort to air conditioning for their comfort during the summer.

Conclusion

The characterization of the soil/typha materials shows that, with *Typha australis* it is possible to improve the insulating power of clay materials. This result is reflected in an increase in thermal resistance as shown in Figure 16.This improvement also reduces energy consumption by 62.9% compared to conventional concrete. This is a great contribution for the valorization of these materials in the building.

In perspective, it would be important to study the costs and to reflect on an appropriate surface treatment against water in season and at the end to make the acoustic and pyroscopic characterization of the synthesized materials.

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