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Experimental Study of Thermophysical and Mechanical Properties of Refractory Clay Tilled into Straw-fiber Stabilized Blocks

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Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

In this experimental study, we have determined both thermo-physical and mechanical properties of raw soil blocks stabilized with fiber straws. Also was studied, the influence of straw content incorporated in the blocks for both properties. Thermophysical properties are determined using a device we designed and produced in the Technical Block of the University of Antananarivo between November 2014 and September 2015. This device uses a hot plane. Mechanical properties are determined using a mechanical press.

The results of our study show that the stabilization of raw mud blocks with straws enables to improve both its thermal and mechanical properties. Indeed, stabilization has enabled to decrease thermal conductivity by 44.92%, diffusivity and thermal effusivity by 30.77% and 33.81% respectively relative to the blocks without stabilizer. But it increases the heat capacity of 6.81%

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compared to blocks without stabilizer.
The compressive strength has been increased by 58.96% and drying shrinkage has been decreased by 22.25%. The resistance to the maximum deflection is 0.477 MPa for 4.81% of straw rate.
Stabilizing the clay with a straw has improved these thermophysical and mechanical properties respectively in insulation and increased strength, showing that it can be used bearing material in the construction of bioclimatic habitats.

Keywords: Mud blocks; straw; stabilized; thermophysical properties; mechanical properties.

NOMENCLATURES

C_p : *Heat capacity (kJ/(kg ℃))*
e : *Mud block thickness (mm)*
E : *Thermal effusivity (J/(m^2 ℃ s$^{1/2}$))*
F_c : *Compressive strength (N)*
F_f : *Flexural strength (N)*
L : *Distance between supports (mm)*
L : *Width (mm)*
L_h : *Wet block length (m)*
L_s : *Dry block length (m)*
P : *Power given to the heating plate (W)*
R_c : *Compressive strength (MPa)*
R_f : *Flexural strength (MPa)*
r : *Drying shrinking %*
S : *Sample surface area (m^2)*

Greek letters

α : *Thermal diffusivity (m^2/s)*
ρ : *Sample density (kg/m^3)*
λ : *Thermal conductivity (W/(m ℃))*
ΔT (℃) : *Difference between temperature T_c of the hot face and T_f of the cold face*
T_c : *Temperature of hot face (℃)*
T_f : *Temperature of cold face (℃)*

Notations

bP_s : *refractory clay block without straw*
bP_1 : *Straw stabilized refractory clay block at 1%*
$bP_{1.6}$: *Straw stabilized refractory clay block at 1.6%*
bP_2 : *Straw stabilized refractory clay block at 2%*
$bP_{3.2}$: *Straw stabilized refractory clay block at 3.2%*
$bP_{3.96}$: *Straw stabilized refractory clay block at 3.96%*
$bP_{4.81}$: *Straw stabilized refractory clay block at 4.81%*

1. INTRODUCTION

The problem with the use of building materials is related first to their mechanical strengths to ensure long live to the facility and second to their capacity to ensure thermo-hygrometric comfort within them. Additionally, energy remains another issue, while building industry is an energy intensive industry, as shown by the global energy consumption in the building sector that represents 40% of total energy consumption in the world [1]. Therefore, it is critical to find materials which, together with an appropriate designing, will reduce energy consumption in buildings. Moreover, according to the European Parliament Industry Committee, after December 31, 2018, all newly constructed buildings should be able to produce their own energy [2].

To contribute to develop local materials and reduce construction costs and the bill of energy consumed for heating or air conditioning, many researchers have been investigating on soil [3,4].

This material has often been criticized for its water sensitiveness and its unsustainability (its low resistance to weather including heavy rain) and its low mechanical strength.

To solve this, a significant number of satisfactory solutions are now available, including: mechanical stabilization (compression), chemical stabilization (mixing cement with earth), physical stabilization (mixing organic matter with soil) and the firing of stabilized soil blocks or not through literature. Firing, compression, stabilization with cement or the combination firing-compression and compression-stabilization often improve the mechanical properties to the detriment of the thermal properties. Yet, the physical stabilization of soil, precisely that stabilized with organic materials such as coconut fibers [5], date palm fibers, palm fibers [6], sugar cane wastes [7], cellulose [8] and straw [7,9] enable to improve in most cases both the mechanical and thermal properties provided that dosage is respected. However, it should be noted that this is not always the case because in some special cases, for example, mixing cement with soil reduces thermal properties such as thermal conductivity [10].

In this study, we will focus on both mechanical and thermal properties of refractory clay soil blocks stabilized with natural (wild) straw fiber.

2. MATERIALS AND METHODS

2.1 Soil

Refractory clay is sampled in Antanifotsy career, a village located by roadside that connect Antsirabe to Antananarivo. This is an artisanal family career. The sample was collected when it was wet as the river still contained water. The soil was taken at about 75 cm deep before sampling.

2.2 Experimental Mechanism

2.2.1 Mechanical tests

Mechanical testing, notably pressure resistance and deflection resistance are studied using a PERRIER mechanical press which maximum power is 7500 kN.

Fig. 1 shows the experimental implementation.

After destruction of the block, we read the breaking force using the following formula:

$$R_c = \frac{F_c}{S} \qquad (1)$$

We deduct the compressive strength. R_c is the compressive strength (MPa), F_c is maximum compression force (N) and S is the sample surface area (m^2).

To determine the bending strength, the sample is placed on two supports and strength is applied to its upper face until the block breaks.

The flexural strength is:

$$R_f = \frac{3F_f L}{2le^2} \qquad (2)$$

R_f (MPa) is the flexural strength F_f (N) is maximum flexural force, L (mm) is the distance between supports, l (mm) the width and e (mm) is the depth of soil block.

2.2.2 Drying shrinkage or Alcock test

Length is measured before and after the drying of the material and the difference between these lengths is the shrinkage of the material [11]. It is expressed in percentage and given by the following formula:

$$r = \frac{L_h - L_s}{L_h} \times 100 \qquad (3)$$

L_h is the length of the wet block (m), L_s is the length of the dry block (m) and r is the shrinkage after drying.

One of the major problems with soil mortars, especially with non-stabilized mortar (100% soil-made), is the appearance of shrinkage cracks. These cracks can impact on the homogeneity of the masonry and its sustainability. Not coated, water can get into through cracks [12]. One method to reduce the drying shrinkage is to add sand (possibly in addition to cement) or natural fibers [13].

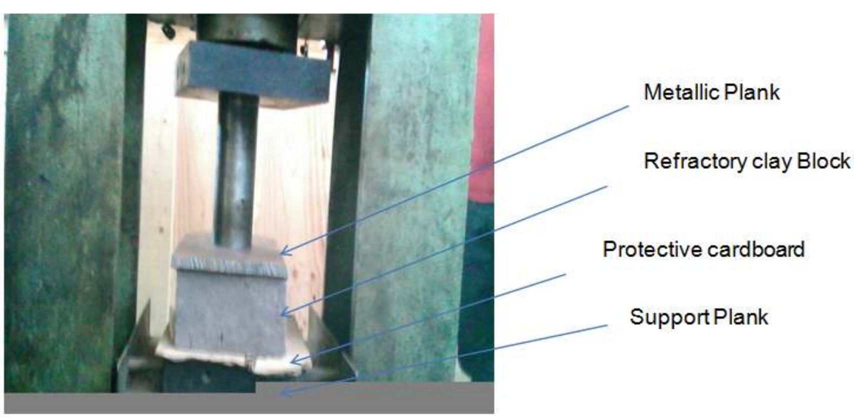

Fig. 1. Measuring compressive strength

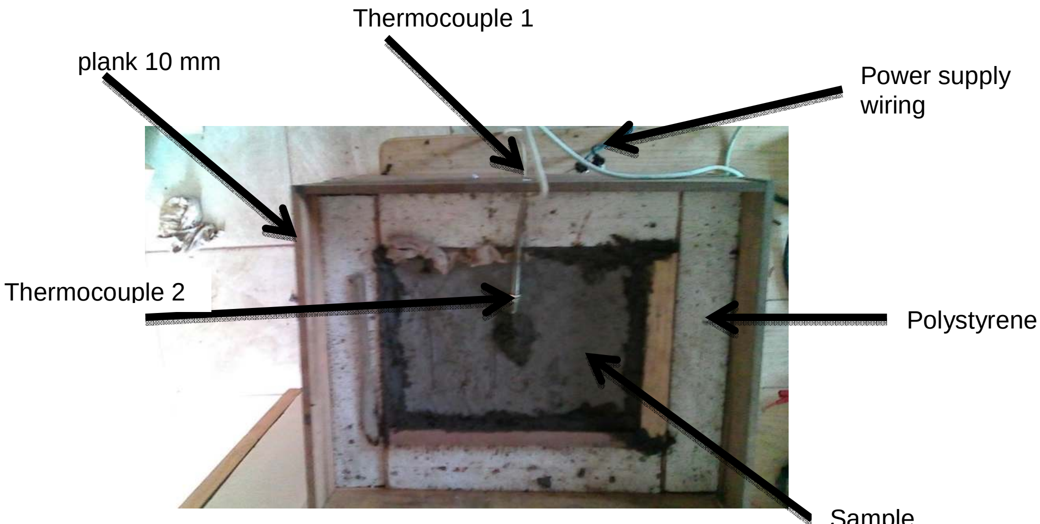

Fig. 2. Temperature measurement

2.2.3 Thermal tests

To study the thermal properties, we have designed and developed a device that works following the hot plane method principle. Due to practical insulation reasons when considering the size of our blocks, it is designed in parallelepiped form. It comprises in its basis, an aluminum metal plate of 32x22 cm^2, an ohmic strength conductor 31 Ω to heat the plate. The ohmic conductor is wound in sinusoidal form on a plate made of refractory clay of the same dimensions as the metal plate to cover its entire surface to make its heating uniform. Refractory clay is spread on plywood which covers 60 mm thick polystyrene, used as insulation. Below the polystyrene is placed 20 mm wood plank.

The four sides of the device comprise from outside to inwards 10 mm wood planks, polystyrene (60 mm) and plywood (4 mm). The opening is closed with a lid consisting of the same elements that make up the sides.

The experimental setup consists of an ammeter, a voltmeter, two rheostats connected in series between them and also with the device. With the rheostats, we apply an intensity of 0.5 A to the resistance. With this device, we were able to make the measures that have allowed us to determine the thermal properties. Above Fig. 2 illustrates the measuring prototype.

The figure shows a typical measurement situation within the scope of the study of the thermal properties of the different blocks of land. The thermocouple 1 measures the T_c temperature of the hot face that is to say that in contact with the hot plat. The thermocouple 2 measures the temperature T_f of the cold face that is to say that in contact with the cover. At the sides the small space that exists between the sample and the plywood is closed by the glass wool. Above the glass wool is applied clay kneaded to make it well sealed to prevent there being a convection

2.3 Determining Thermophysical Properties

Thermal properties that best characterize the materials are the thermal conductivity, heat capacity, thermal diffusivity and thermal effusivity. Knowledge of two of them enables to deduct the other two. Our approach consists to determine the thermal conductivity and heat capacity using the hot-plan approach, by measuring the temperatures of the hot and cold sides of the sample to characterize and assess their difference when the permanent regime will be reached. We also measure the time taken to reach the permanent regime because this time is necessary to calculate the heat capacity. We assumed the perfect insulation. So, heat exchange with the outside environment is negligible. In addition, the contact resistance is also negligible. Therefore, thermal conductivity is calculated using the following relation (4)

$$\lambda = \frac{P \times e}{S \times \Delta T} \tag{4}$$

λ (W / (m ℃)): thermal conductivity, e (m) : thickness of the tested block, P (W): power imposed to the heating plate, S (m^2): surface of the tested block and ΔT (℃) : the difference between temperature T_c of the hot face and T_f of the cold face.

Heat capacity from the expression:

$$C_p = \frac{P \times t}{m \times \Delta T} \quad (5)$$

Where C_p (kJ/ (kg ℃)): heat capacity, P (W): power applied to the heating plate, ΔT (℃): the difference between temperature T_c of the hot face and T_f of the cold face, m (kg): the mass of the block and t (s): the time taken to reach the permanent regime.

Thermal diffusivity and thermal effusivity are deducted respectively from both characteristics already determined.

$$\alpha = \frac{\lambda}{\rho C_p} \quad (6)$$

α (m^2/s): thermal diffusivity, ρ (kg/m^3): sample density.

$$E = \sqrt{\lambda \rho C_p} \quad (7)$$

E ($J/(m^2$ ℃ $S^{1/2}$)): thermal effusivity.

3. RESULTS AND DISCUSSION

3.1 Hydro-mechanical Properties

Through the press, we were able to experimentally determine the compressive strength and flexural strength of the blocks. Furthermore, we studied the influence of parameters such as the age of the block and the straw content on these mechanical properties, on the one hand, and on the other hand, the influence of the straw content on water removal and absorption. Tables (1-6) give the results of these investigations.

3.1.1 Compressive strength

Dimensions of newly made large size blocks are 31.5x22x12 cm^3. After drying, the dimension depends on the composition, i.e. straw rate in the mixture.

Considering the results of our research (Tables 1 and 2), we can confirm that the compressive strength of stabilized refractory clay blocks increases when straw content increases, as confirmed by [11,14]. This is due to the fact that straw enhances the quality of the clay as a binder.

However, by comparing results in Table 1 with those in Table 2, it appears that the first small blocks give the largest maximum value of the compressive strength (MPa 3.306 against 2.204 MPa for large blocks). Secondly, by adding 4.81% of straw (rate in dry weight) this improves the compressive strength by 58.96% for small blocks against 47.55% for large blocks. Lastly, we can say that the block size influences the compressive strength since even for single refractory clay blocks without straw, small size blocks give better values (1.357 MPa) than large size blocks (1,156 MPa). Indeed, refractory clay that we used is sticky and difficult to knead. So, the larger the mold, the lesser we can better work the block to make it more impermeable. According to results given in Table 3, we notice that the compressive strength of the blocks increases with age, as shown by [8].

3.1.2 Flexural strength

The method used is that of flexural strength at three points. The results of this study are entered in Table 4. They show that the flexural strength increases when the straw rate in the block increases. Fibers play multiple roles. They increase the flexural strength and therefore the flexibility of the material.

Table 1. Straw rate influence on the compressive strength of large blocks

Type of block	bP_S	bP_1	$Bp_{1.6}$	bP_2	$bp_{3.2}$	$b_{4.81}$
Density (kg/m^3)	1,768.352 ±11.020	1,698.943 ±10.872	1,528.728 ±10,420	1,603.480 ±10.921	1,412.634 ±9.943	1,310.832 ±9.964
Compressive strength (MPa)	1.156 ±0.007	1.651 ±0.008	1.978 ±0.006	2.204 ±0.01	2.0789 ±0.0067	2.167 ±0.009

Table 2. Straw rate influence on the compressive strength of small blocks

Refractory clay l block	bPs	$bP_{1.6}$	$bP_{3.2}$	$bP_{4.81}$
Density (kg/m^3)	1,870.41±12.42	1,589.29±10.30	1,236.57±9.22	1,376.08±9.34
Compressive strength (MPa)	1.357±0.006	2.222±0.008	2.333±0.009	3.3067±0.007

3.2 Measuring Water Absorption Coefficient

This consisted in completely immersing the block in water for two (02) hours. Measuring the mass before and after immersion enables to know water absorption thereof.

This was only performed on small size bricks. The results are shown in Table 5 (with an average accuracy of 0.04 kg for mass and 0.3% for absorption). They show that water absorption coefficient increases when straw rate increases [15]. We were not able to measure the mass of the block without straw because two hours after immersion, they turn almost into mud. This shows they are fragile to water.

3.2.1 Drying shrinkage

Drying shrinkage decreases with the increase of straw content in bricks (Table 6). Indeed, the increase of straw decreases water content of the clay-straw composite. So when drying, this may lead to mass (water) loss. That is why the variation of the length decreases. Therefore, we can notice the improvement of the shrinkage by 22.25%.

To make blocks $bP_{1.6}$ and $bP_{3.2}$, the wet sample of clay was not dried before. So they contain more water that is why their shrinkages are greater than that of bP_1. For small blocks (21x8x7 cm) shrinkage is constant, i.e. 4.76% regardless of the composition of the blocks.

3.2.2 Thermal study

3.2.2.1 Thermophysical properties

Concerning the physical properties, notably density, it decreases as the rate of straw content in the block (Tables 1, 2 and 5) increases. This is easily explained because the more the straw, the more porous the composite clay-straw. Also, density of straw is lower in comparison to clay.

Thermal conductivity of blocks decreases as the straw content increases. This is also shown by [5,16], certainly due to straw that increases the porosity of blocks. The lower value in thermal conductivity (0.46 W / m ° C) is achieved when the rate of straw in the mixture reaches 4.81% of the dry mass. Adding 4.81% of straw reduces the thermal conductivity of 44.92% over that of blocks without straw. This means that block insulation capacity improves by 44.92% (Table 7). This decrease is even more significant if the rate of straw added is high [17]. Concerning heat capacity, this increases as straw rate increases. Allowing improvement of 6.81% relative to the blocks without stabilizing. This improvement is obtained when the rate of adding straw to clay reached 3.96%.

Table 3. Impact of the block age on the compressive strength

Refractory clay block	$bP_{1.6}$	$bP_{3.2}$	$bP_{3.96}$	$bP_{4.81}$	Age
Compressive strength	0.917±0.02	1.352±0.04	1.496±0.03	1.966±0.04	14 days
(MPa)	1.651±0.02	1.577±0.03	1.709±0.03	2.145±0.04	21days
	1.978±0.03	2.079±0.03	-	2.167±0.04	32 days

Table 4. Straw rate influence on the flexural strength

Refractory clay blocks	$bP_{1.6}$	$bP_{3.2}$	$bP_{4.81}$
Density (kg/m^3)	1,570.807±8.93	1,504.889±9.13	1,010.760±8.27
Flexural strength (MPa)	0.357±0.013	0.427±0.011	0.477±0.010

Table 5. Variation in straw rate on the absorption coefficient of the block

Refractory clay blocks	bP_s	bP_s	$bP_{1.6}$	bP_2	bP_2	$bP_{4.81}$	$bP_{4.81}$
Dry mass (kg) ±0.212	1.609	1.672	1.624	1.606	1.647	1.575	1.547
Wet mass (kg) ±0.213	Mud	Mud	1.832	1.998	1.898	2	1.963
Absorption (%) ±0.3	-	-	11.36	19.62	13.22	21.25	21.19

Table 6. Variation of drying shrinkage according to straw content in the block

Refractory clay blocks	bP_s	bP_1	$bP_{1.6}$	bP_2	$bP_{3.2}$	$bP_{3.96}$	$bP_{4.81}$
Wet length ±0.1(cm)	31.5	31.5	31.5	31.5	31.5	31.5	31.5
Dry length ±0.1(cm)	27	27.7	27.5	28	27.6	28	28
Shrinkage±0.1 (%)	14.29	12.06	12.70	11.11	12.38	11.11	11.11

Table 7. Impact of straw content on the thermophysical properties of blocks

Type of block	bP_S	bP_1	$Bp_{1.6}$	bP_2	$bp_{3.2}$	$bp_{3.96}$	$bp_{4.81}$
Density (kg/m^3)	1,768.35 ±11.02	1,698.94 ±10.87	1,528.73 ±10,42	1,603.48 ±10.92	1,412.63 ±9.94	1,310.83 ±9.96	1,768.35 ±11.02
Thermal conductivity ± 0.021(W/(℃m))	0.838	0.705	0.674	0.631	0.601	0.480	0.461
Heat capacity ±22.401 (J/(kg ℃))	3252.885	3281.5	3355.939	3372.409	3417.011	3490.665	3460.381
Thermal diffusivity (10^{-7}) ±0.003 (m^2/s)	1.456	1.264	1.313	1.166	1.244	1.048	1.008
Thermal effusivity (J/(m^2 ℃.s $^{1/2}$))	2195.026 ±13.567	1982.213 ±12.201	1859.439 ±10.128	1846.928 ±9.989	1702.817 ±9.906	1485.028 ±9.427	1452.901 ±9.204

Table 8. Variation of the thermal conductivity of the block according to its density

Density (kg/m^3)	1,453.231	1,370.257	1,325.620
Thermal conductivity (W /℃ m)	0.615±0.024	0.540±0. 023	0.481±0.021

Considering the results in Table 7 above, this enables us to see that thermal effusivity decreases when straw rate increases. This becomes low (1,452.9014 J/m^2 ℃ S $^{1/2}$) when the straw rate is 4.81%, enabling therefore an improvement of 33.81% compared to that of the single block.

Thermal diffusivity is low (1.008 x10^{-7} m^2/s) for a straw rate of 4.81%. It is less good (1.4561x10^{-7} m^2/s) for simple blocks without adding straws; thus, an improvement of 30.77%.

3.2.2.2 Influence of density on thermal conductivity

We studied the impact of the variation of the density on thermal conductivity. We could say that this is also the impact of moisture on thermal conductivity because these values are closely linked. Indeed, the change in density is due to that of water content of the block because of the loss of water through evaporation during the drying process. We conducted this study on $bP_{3.96}$ block and results are given in Table 8 above. They show that thermal conductivity decreases when the density of the block decreases (Table 8) as shown by [10,18]. This can be easily explained. When the density decreases due to water loss, air quantity in pores increases. Yet, since air is an insulating material, thermal conductivity decreases.

4. CONCLUSION

The stabilization of refractory clay with straw positively influences its thermophysical and mechanical properties. With stabilization, we were able to obtain soil blocks with improved thermo-mechanical properties. The lowest thermal conductivity, diffusivity and effusivity are obtained for a straw rate of 4.81%. These values are respectively 0.46 W/m ℃, 1.008x10^{-7} m^2/s and 1,452.902 J/m^2 ℃ s $^{1/2}$. By adding straw, this substantially improves the thermal properties of the refractory clay. Thermal conductivity is improved by 44.92%; heat capacity by 6.81%; diffusivity and thermal effusivity by 30.77% and 33.81%, respectively. On the mechanical ground, mechanical properties, specifically the compressive strength is improved by 58.96%. Drying shrinkage decreased by 22.25% for blocks without straw and maximum flexural strength is 0.477 MPa for straw rate of 4.81%.

Our results have shown that thermal conductivity, diffusivity and effusivity decrease when straw content in the mixture increases. However, the heat capacity decreases when straw content increases.

They also enable to show that small blocks have better mechanical properties than larger ones.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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