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Characterization of Thermal and Mechanical Properties of Red Clay Mixed with Rice Straw for Thermal Insulation of Buildings

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Abstract: This article presents an experimental study on the determination of the characteristics of local materials used for the construction of building walls. The use of these materials makes it possible to solve two major problems in the building sector, namely the reduction of the cost of constrictions and the reduction of carbon dioxide (CO_2) emissions. The objective of this work is to evaluate the thermal and mechanical properties of red clay used in construction in the peri-urban areas of the city of Ouagadougou in Burkina Faso. The thermal properties were estimated with the box method and the compressive strengths were determined using a press equipped with a hydraulic cylinder. The thermal conductivity evolves according to the mass of the straw in the clay. It is 0.328 $W.m^{-1}.K^{-1}$, for a clay without straw. This value decreases by 32.26%, 43.29% and 57.01% respectively when 1%, 2% and 3% of the straw mass is added to the mixture. The mechanical resistance is 0.786 MPa for a clay without straw. This value decreases by 22.26%, 43.76% and 28.88% respectively when 1%, 2% and 3% of the straw mass is added to the mixture. These stabilized bricks will improve the thermal and mechanical performance of building walls.

Keywords: Clay, Straw, Stabilisation, Strength, Conductivity

1. Introduction

Energy consumption in buildings worldwide represents nearly 40% of the total energy consumption. It is responsible for 25% of total carbon dioxide (CO_2) emissions [1]. But the economies of energy can be made if the choice of building materials takes into account the thermal behavior of buildings in order to minimize the need for air conditioning. The prediction of the energy and thermal performances of a building depends on the properties of the materials to be used. Construction products used in structures that incorporate modern techniques are largely imported. The proportion of imports of manufactured products related to the construction sector is now around 45% [2]. Faced with the economic and social problems facing the african countries, many people are calling for genuine promotion of its natural resources. Indeed, the promotion of local materials of construction is to be encouraged. This sector contributes to the fight against poverty, to meeting the demand for housing and to fighting against housing insecurity. However, it is well known that earthen constructions suffer from a lack of resistance, from systematic cracking related to shrinkage and come up against problems related to their sensitivity to water [3]. To remedy these problems, the stabilization of the earth is one of the best indicated means. This stabilization can be done by physical, mechanical or chemical means. Physical stabilization modifies the properties of soils by improving the characteristics of the material by correcting the granularity. The mixture obtained leads, depending on the case, either to reducing the plasticity index of the base material, or to giving it a cohesion [3]. The brick of clay and very sandy raw earth is obtained in molding the paste of the mixture, then dried in the sun or in the shade. These blocks are assembled with a mud mortar made from the same earth. Rice straw is very rich in cellulose. This rice straw and clay are readily available in the countryside. The compressive strength of materials is an important property in building design. The thermal resistance of a material gives it a certain insulating power depending on its thickness, this resistance is in particular inversely proportional to the coefficient of thermal conductivity. Emmanuel Ouedraogo et al. [3] have shown that adding paper (cellulose) to the soil reduces the thermal conductivity on average by 11.93% and increases mechanical resistance by 38.75%. As to Kossi Bouto Imbga and al [4], they showed that stabilizing the soil with Nere pods can economize 42% of energy. Karim Toussakoe and al [5] in their study on the Nubian vault showed that the choice of the good earth for making the adobes used in the walls allows a strong reduction of the internal temperature. N. Laaroussi [6] determined the thermal properties, using the hot plane method, of clay taken from a Sloui industry in Morocco. The value of the thermal conductivity found is 0.35 $W.m^{-1}.K^{-1}$ this value is very close to the one we found with the box method. Aurelie Michot [7] determined the thermal conductivity and specific heat of Kaolin clay using the laser flash technique, the value of the thermal conductivity found is 0.3 $W.m^{-1}.K^{-1}$ for a temperature lower than 1050°C and this value increases when the temperature increases, it is worth 3.2 $W.m^{-1}.K^{-1}$ when the temperature is 1400°C. Thus, the main objective of this work is to optimize the mechanical and thermal properties of clay mixed with rice straw for possible use in construction.

2. Materials and Methods

2.1. Clay

Clay minerals are made up of silicon, aluminum and OH^- ions, organised in layers, two types depending on whether the oxygens or hydroxyls are associated in tetrahedral or octahedral. The layers of tetrahedrons are dominated by Si^{4+} and OH^-. Octahedral layers are dominated either by Al^{3+} (di-octahedral layers, two atoms are sufficient to occupy the six vertex sites of the octahedron) and OH^-, or by Mg^{2+} (trioctahedral layers, three magnesium atoms are needed to balance the charges of the octahedral). The layers of octahedral and tetrahedral are joined together along the planes, by pooling O and OH, hence the sheet structure separated by inter-leaf spaces [8, 9]. The geotechnical properties were estimated by [10] where W_p is 26.6%, W_L is 52% and I_p = 26.4%.

2.2. Straw

The straw we used in this work is rice straw. It was harvested and dried in the sun. Straw is the part of the stalk of certain grasses, known as straw cereals, which is cut during harvesting and discarded, free of grain, on the field by the combine harvester. The straw has been dried until its water has evaporated. It can be estimated that dry straw contains about 85-90% dry matter compared to about 20-30% dry matter for green straw [8]. The mixing of the straw into the clay is random.

Figure 1. *Rice Straw.*

2.3. Clay Characteristics Measurement Method

The method used for the determination of thermal properties is the box method. This measurement technique uses prismatic specimens of dimensions 27cm ×27× cm ×5cm. A known unidirectional flow of heat through a test specimen is achieved by placing it between a hot and a cold environment, and measurements are made after steady state is achieved. In order to minimize the heat exchange between the box and the external environment, a suitable heating voltage is applied, so that the temperature of the box is (T_b) as close as possible to the temperature of the experimental room while (T_a) remaining higher than it $\Delta T < 1°C$. Before the start of the measurement, the temperature is set in 24 hours advance, according to the temperature that is to be imposed inside the cold isothermal chamber. Once the specimens is placed in the measuring box, a voltage V is applied across the heating film based on a curve that approximates the voltage value as a function of the density of the specimens in the dry state. Then the temperature rise is T_b recorded for about two hours to check the $(T_b - T_a)$ deviation between $0 \ and \ 1$. After these settings, we wait for the steady state to be reached, which depends on the nature and thickness of the specimens. The temperature difference ($T_c - T_f$) between the sides of the sample must be constant and no longer dependent on time. The temperature of the box remains constant for at least 30 min. In steady state the heat flow through the specimens is:

$$\dot{Q} = \frac{\lambda}{e} S(T_c - T_f) = \dot{Q}_1 - \dot{Q}_2 \quad (1)$$

With $\dot{Q}_1 = \frac{V^2}{R_E}$: the heat flux emitted by the heating film.

$\dot{Q}_2 = c(T_b - T_a)$: the heat flow exchanged between the outside and inside of the box.

In replacing Q_1 *and* Q_2 by their values, equation (1) becomes:

$$\frac{\lambda S}{e}\left(T_c - T_f\right) = \frac{V^2}{R_E} - c\left(T_b - T_a\right) \quad (2)$$

Where c is the thermal loss coefficient. Its expresses the heat loss from the inner air of the box Tb and the external air Ta. It is obtained experimentally by sending two different thermal flux on a well-known properties PVC materials. By imposing two different flux on this material, we could obtain c medium value of 0.19. Experimental values are given in the following table 1. From the equation (2), we obtain the following equation (3).

$$c = \frac{1}{T_b - T_a}\left[\frac{V^2}{R_E} - \frac{\lambda S}{e}\left(T_c - T_f\right)\right] \quad (3)$$

The value of c likewise determined by the equation (2) is introduced as a constant in equation (3).

Table 1. *Experimental values recorded at the first and second steady test.*

Paramètres	Tf	Tc	Ta	Tb	V (volt)	R (Ohms)	Tc-Tf	Tb-Tf
Test1	18.44	25.76	30.14	30.23	14.89	226.00	7.32	0.09
Test2	17.53	24.18	27.76	28.30	12.53	266.00	6.65	0.54

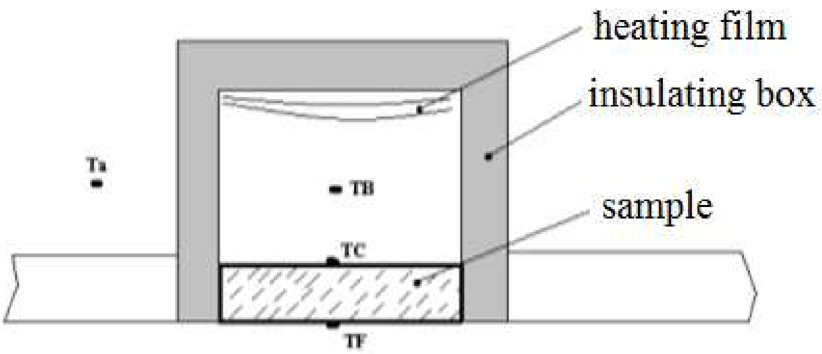

Figure 2. *Cross-section of a box for measuring thermal conductivity.*

When the specimens is small (smaller than standard cross-sections), the thermal conductivity is measured by embedding. To do this, the specimens is placed in a parallelepipedal polystyrene matrix of dimension 27cm×27 cm×5cm. In steady state, part of the flow passes through the specimens and part through the polystyrene. In this case the conservation of flow is written as follows:

With: V (V) is the voltage across the heating film of resistance R; e (m) is the thickness of polystyrene and S_p (m^2) is the surface of polystyrene.

In steady state, the value of the conductivity of the specimens is obtained from the expression.

$$\lambda_e = \frac{e}{S(T_c - T_f)}\left[\frac{V^2}{R_E} - c(T_b - T_a) - \frac{\lambda_p}{e} S_p (T_c - T_f)\right] \quad (4)$$

3. Experimental Study and Measurement Results

3.1. Specimens Formulations

For the determination of the mechanical and thermal properties of clay material mixed with rice straw, we made cylindrical specimens of 11 cm diameter and 22 cm height for the measurement of the compressive strength. The results of the mechanical compression were obtained by the mechanical press of mark CONTRELAB according to the Standard NF 18-406 [11] and prismatic specimens of 27cm ×27× cm ×5cm for the thermal properties determination. Water mass had been added to the mixture in accordance with the Atterberg limits and the mass of the used clay.

Table 2. *Composition of mixtures.*

Specimens	Clay (wt% by mass)	Straw (wt% by mass)	Mass of water added to the mixture
E1	100	0	140g
E2	99	1	149g
E3	98	2	153g
E4	97	3	160g
E5	0	100	150g

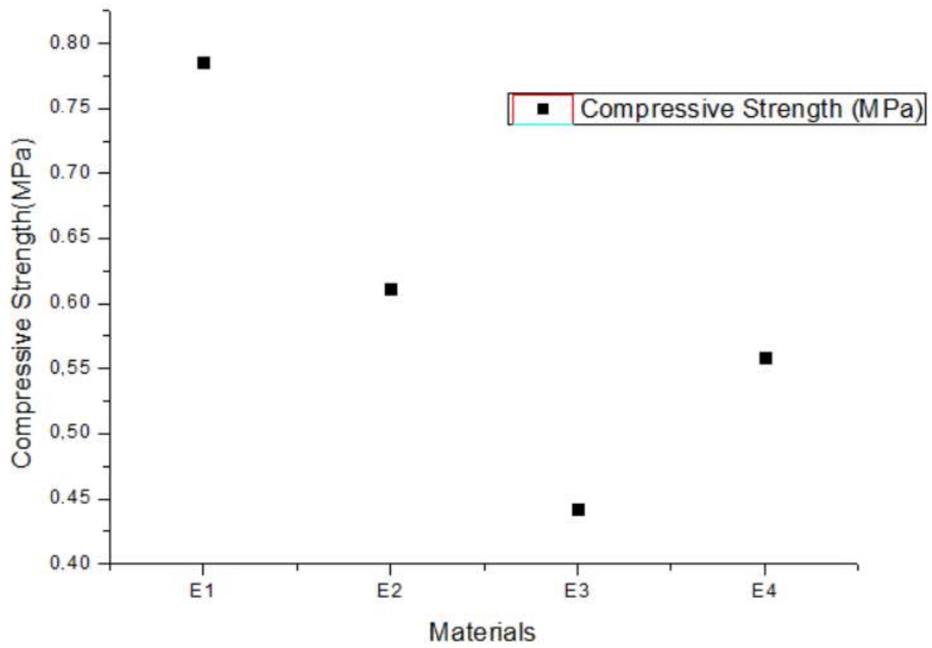

Figure 3. *Evolution of the mechanical strength as a function of the percentage of straw mass in the mixture.*

We waited the time it takes to have a good consolidation (28 days) of the specimens before doing mechanical and thermal tests of the mixtures from E1 to E4. The particle size and sedimentometric analysis showed 3% coarse sand, 24% fine sand, 15% silt, 58% clay and more than 90% of the grains by weight pass the 80 µm sieve. The plasticity index is 25.6% and the liquid limit is 52%. Therefore, these values indicate a high shrinkage after drying of bricks made from this raw material [10].

3.2. The Results of the Mechanical Tests

The compressive strength is measured by uniaxial compression of straight cylinders of revolution of section S and a height double their diameter. In this process, the cylindrical specimen is placed between the platens of a press and the axial force is increased until the specimen breaks. The load speed must be constant during all the testing, and shall be equal to 0.5 ± 0.2 MPa per second. Le maximal value F of the force allow to calculate the axis compression strength of the material according to the relation:

$$R_C = \frac{F}{S} \quad (5)$$

Where R_C (MPa) is the compressive strength, F (N) the axial force and S (m^2) the surface area.

The strength of the clay without straw mixture is 0.786 MPa , yet that found by Makinta [12] is 0.641 MPa. This value decreases by 22.26 wt%, 43.76 wt% and 28.88 wt% respectively when added 1 wt%, 2 wt% and 3 wt% of straw in the mixture.

3.3. Thermal Measurement Tests

The results of the thermal tests are recorded in the following table.

Table 3. *Results of thermal measurements as a function of the straw content of the mixture.*

Specimens	Clay (% by mass)	Straw (% by mass)	Density ($kg.m^{-3}$)	Thermal Conductivity ($W.m^{-1}.K^{-1}$)
E1	100	0	1671.948 ± 16.509	0.32 ± 0.0175
E2	99	1	1557.299 ± 15.163	0.22 ± 0.0153
E3	98	2	1506.944 ± 15.011	0.18 ± 0.0138
E4	97	3	1483.200 ± 14.523	0.14 ± 0.0131
E5	0	100	55.456 ± 0.254	0.05 ± 0.0122

We can observe the thermal behavior of clay combined with straw at different dosage rates. Bulk density was determined using a 0.01 g precision scale for weighing and 0.01 mm precision callipers to measure sample sizes. For each composition, 3 measurements were made, in order to obtain an average of thermal conductivity and dry bulk density. The water content is defined by the following relation:

$$w(\%) = \frac{m_0 - m}{m_0} \times 100$$

With m (g) is the mass of the sample in dry state after 24 hours at 105°C and m_0 (g) is the mass of the sample in given wet state. The moisture content of samples E1, E2, E3, E4 and E5 are respectively 2.90%, 1.87%, 1.80%, 1.60% and 1.00%.

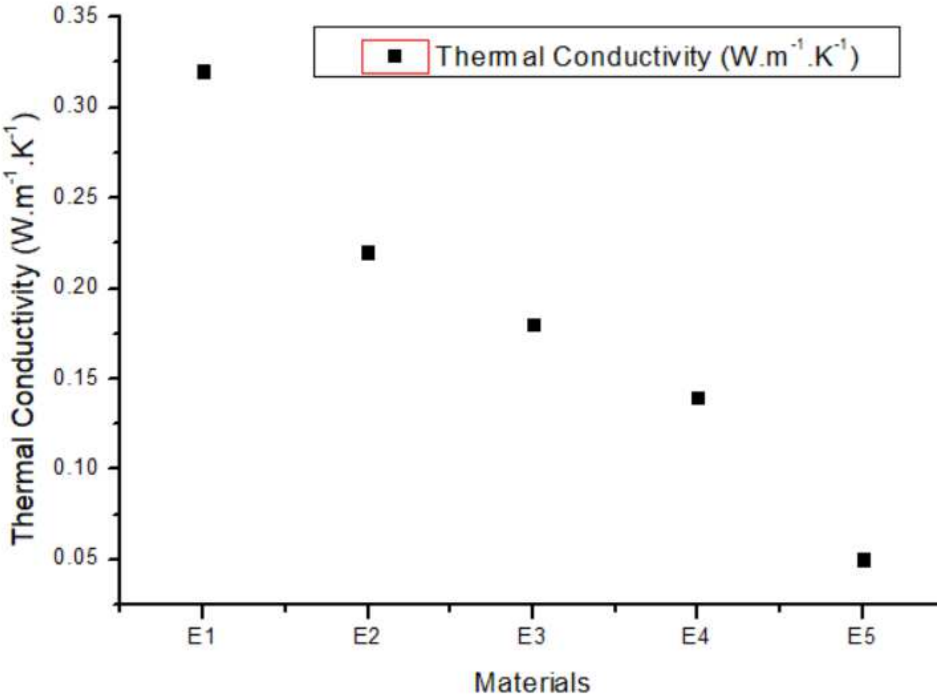

Figure 4. *Thermal conductivity of the clay and straw mixture.*

The thermal conductivity changes with the amount of the straw. The thermal conductivity of clay without straw is 0.328 $W.m^{-1}.K^{-1}$. This value decreases by 32.26 wt%, 43.29 wt% and 57.01 wt% respectively when 1wt%, 2wt% and 3 wt% of the straw mass is added to the mixture. Straw is a fibrous material, its presence in the solid matrix creates pores and its pockets are filled with air whose conductivity is very low. The thermal conductivity of rice straw measured by Gregoire NOBLE is, 0.043 $W.m^{-1}.K^{-1}$ this value is 17.30% close to the one we found. However, the density found is 40 $kg.m^{-3}$ [13]. The value of thermal conductivity obtained by Gollé DIOUF [14] by the box method is 0.063 $W.m^{-1}.K^{-1}$, this value is 17.46% higher than the one we found.

Marthe DIATTA [15] determined the thermal conductivities of two clays MN and NM1 using the Hot Disk TPS 2500, the estimated thermal conductivity values are respectively 0.46 $W.m^{-1}.K^{-1}$ and 0.72 $W.m^{-1}.K^{-1}$. The chemical and mineralogical compositions of the clays NM and MN1 are quite similar. They are essentially composed of kaolinite, quartz and illite in accordance with the results of X-ray diffraction and infrared spectrometry. The thermal conductivity of the MN clay is 28.69% higher than what we found in our measurements. The two clays differ in their particle size. Joshua FOLARANMI [16] conducted an experimental research, his objective was to determine the thermal conductivity of the clay associated with percentage rates of ash and sawdust in the clay, the result obtained indicates that the thermal conductivity of the clay is 0.25 $W.m^{-1}.K^{-1}$, this value decreases by 28% when 30% ash is added to the clay and a reduction of 76% when 30% sawdust is added to the clay. The conductivity value found is 23.78% smaller than the one we found. S. Goodhew [17] using Mat software version 16.00, they obtained the thermal conductivity value of straw λ_{straw} is 0.067 ± 0.002 $W.m^{-1}.K^{-1}$ and a density of the order of ρ_{straw} is 60 $kg.m^{-3}$. The thermal conductivity of the straw estimated is 22% more than the value we estimated in this work.

The thermal conductivity changes according to the amount of the straw. It can be seen that straw alone is an excellent thermal insulator. This confirms the importance of thermal insulation when designing straw bale houses. The thermal conductivity, micro and macro structural analysis of fired clay bricks incorporating cigarette butts was studied by Halenur Kurmus [18], the estimated conductivity on clay without cigarette butts is 0.463 $W.m^{-1}.K^{-1}$, this value is 21.42% higher than that found in our measurements. The thermal conductivity increases when the density is high. The density is high when there is no rice straw in the clay. Lightweight aggregate with low thermal conductivity in lightweight concrete blocks can also reduce the thermal transmittance of blocks and bricks. With a large number of voids in the aggregate, lightweight aggregate concrete possesses a lower thermal conductivity and smaller density compared to normal concrete, Ismaiel and al [19].

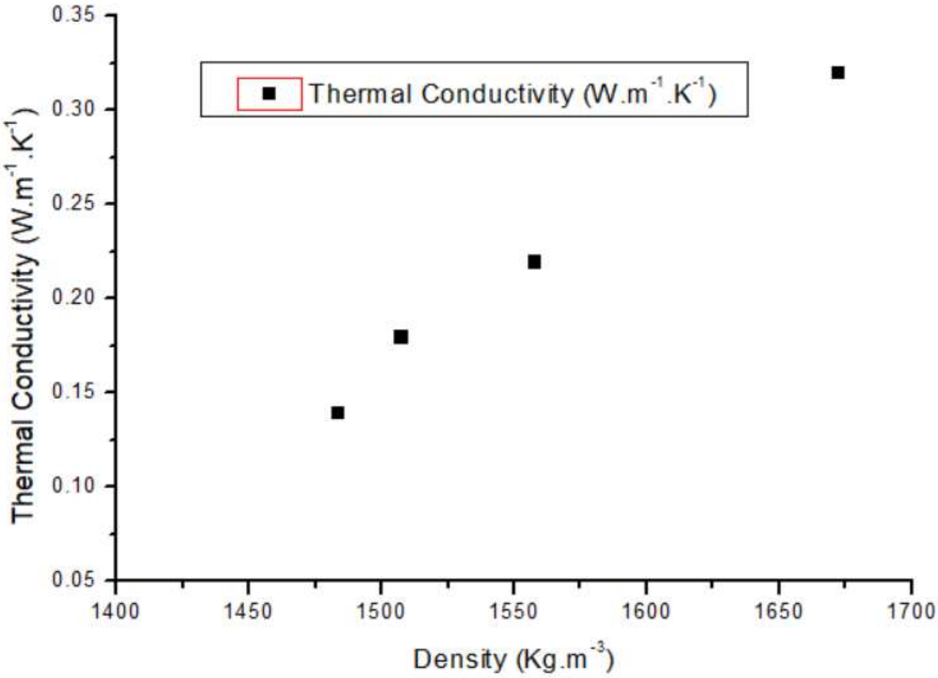

Figure 5. *Thermal conductivity of straw as a function of straw mass.*

4. Conclusion

The main objective of this work was first to evaluate the thermo-mechanical characteristics of clay materials and rice straw mixtures. The thermal conductivity of the clay without straw is 0.328 $W.m^{-1}.K^{-1}$. This thermal conductivity decreases with the increase of straw rate in the mixture. The ad of 1 wt%, 2 wt% and 3 wt% straw rate in the mixture reduces the thermal conductivity respectively at 32.62 wt%, 43.30 wt% and finally 57.01 wt%. In fact, the straw creates pores within the clay matrix and these pores contain air which is an insulator. The higher the straw content in the mixture, the higher the porosity and the higher the volume of air in the material, making it an insulator. The material made only of straw, is a very porous material, which makes it thermally insulating.

The mechanical strength of the formulations decreases as a function of the percentage of rice straw added, but from 2 wt%, it starts to increase. The mechanical strength decreases by 22.26 wt%, 43.76 wt% and 28.88 wt% respectively when added 1 wt%, 2 wt% and 3 wt% of straw in the mixture.

The thermal conductivity of the mixtures decreases with the percentage of straw added. Straw alone insulates well, but it has no thermal inertia, there is no heat storage. It is therefore necessary to provide thermal mass. It would be very interesting in a future study to examine the thermo-mechanical behavior of clay and straw mixtures as a function of temperature.

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References

[1] Fezzioui N and Benyamine M. Patio house: Answers to sociological, cultural and thermal requirements. International Conference: Medina. Urban fabric to save. Tlemcen. 13-14 Mai 2008.

[2] U. Wyss, Construction using “local materials”, state of a sector with multiple potential. Department of Development and Cooperation, Oagadougou, Burkina Faso, December, 2005.

[3] Emmanuel Ouedraogo, Ousmane Coulibaly, Abdoulaye Ouedraogo, Adamah Messan] Mechanical and Thermophysical Properties of Cement and/or Paper (Cellulose) Stabilized Compressed Clay Bricks, Journal of Materials and Engineering Structures 2, 68–76, 2015.

[4] Kossi Bouto Imbga, Emmanuel Ouédraogo, Vincent Sambou, Florent P. Kieno, Abdoulaye Ouédraogo and Diendonné Joseph Bathiebo. New Materials for Thermal Insulation in Rural Construction. Current Journal of Applied Science and Technology 29 (4): 1-10, 2018.

[5] Karim Toussakoe, Emmanuel Ouedraogo, Kossi Bouto Imbga, Adamah Messan et Florent Pelega Kieno, Mechanical and thermo-physical characterization of the adobe used in the Nubian vault, Afrique Science, 19 (5), 186-199, 2021.

[6] N. Larousi, G. Lauriat, M. Garoum, A. Cherki, Y. Jannot: Measurement of thermal properties of brick materials based on clay mixtures. Construction and Building Materials 70 (2014) 351-361.

[7] Michot A., Smith D. S., Degot S., Gault C., Thermal conductivity and specific heat of kaolinite: Evolution with thermal treatment. Journal of the European Ceramic Society, 2008, 28, pp. 2639-2644. https://doi.org/10.1016/j.jeurceramsoc.2008.04.007.

[8] ANDRIANARIMANANA Jean-Claude Omer, Research on the development of physical, chemical and biological processes for the preparation of clay materials from Malagasy laterites, 3rd cycle thesis in Materials Science. ESPA, University of Antananarivo, 2005.

[9] PELLIER JL, Contribution to the study of clay minerals from Madagascar, Doctoral Thesis, University of Strasbourg, 1965.

[10] Kossi IMBGA, Thermal Comfort and Energy Efficiency in a Habitat in the Sahelian Zone; Doctoral thesis, Professor Joseph KI-ZERBO University, 2017.

[11] AGGOUNE ZINEB, Comparative study of hydraulic concrete facing a hyperbasic aggressive environment: Numerical modeling and physico-mechanical aspect: Master's thesis; University of ARBI BEN MHIDI D' OUM EL, 2019.

[12] Makinta Boukar, M. B. N'Diaye, Grégoire Sissoko «Thermophysical and Mechanical Properties of clay from Quarry of BangaBana» Department of Physics, Laboratory and semi conductors and Solar Energy. F. S. T UCAD Sénégal. Research Journal of Applied Sciences, Engineering and Technology 8 (20); 2126-2134, (2013). http://dx.doi.org/10.19026/rjaset.8.1208

[13] Gregoire NOBLE, Camargue rice straw, the recipe for successful insulation, 20/12/2021.

[14] Gollé Diouf, Oumar Diallo, Harouna Mamadou Bal, Pape Moussa Toure, Salif Gaye: Improving the Thermal Comfort of a Building by Adding a Layer of Straw over the High Floor; Journal of Building Construction and Planning Research, 2020, 8, 193-202. DOI: 10.4236/jbcpr.2020.83012.

[15] Marthe Tatiana Diatta, Clay raw materials from Senegal: characteristics and applications to mass market ceramic products; Doctoral thesis; Assane Seck University of Ziguinchor and the University of Limoges, 2016.

[16] Joshua FOLARANMI: Effect of Additives on the Thermal Conductivity of Clay, Leonardo Journal of Sciences ISSN 1583-0233, Issue 14, January - June 2009 p. 74-77.

[17] S. Goodhewet R. Griffiths «Sustainable earth wall to meet the building regulations» Energy and Buildings 37 (2005) 451-459. https://doi.org/10.1016/j.enbuild.2004.08.005.

[18] Halenur Kurmus, Abbas Mohajerani: Energy savings, thermal conductivity, micro and macro structural analysis of fired clay bricks incorporating cigarette butts: Construction and Building Materials 283 (2021) 122755. https://doi.org/10.1016/j.conbuildmat.2021.122755.

[19] Maysoun Ismaiel, Yuxiang Chen, Carlos Cruz-Noguezand Mark Hagel: Thermal resistance of masonry walls: a literature review on influence factors, evaluation, and improvement: Building Physics https://journals.sagepub.com/doi/10.1177/17442591211009549