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Physical and Thermo-Mechanical Properties of Composite Materials Based on Raw Earth and Crushed Palm Leaf Fibers (*Borassus aethiopum*)

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Abstract

The objective of this study is to seek solutions to reduce the impact of buildings on climate change and to promote the use of local bio-sourced or geo-sourced materials for sustainable construction. Different samples of raw earth from 3 sites were taken in the commune of Mlomp. Geotechnical tests showed that the raw earth samples from sites 2 and 3 have more clay fraction while site 1 contains more sand. The fact of integrating fibers from crushed palm leaves (*Borassus aethiopum*) (2%, 4% and 6%) into the 3 raw earth samples reduced the mechanical resistance to compression and traction of the 3 raw earths. The experimental results of thermal tests on samples of earth mixtures with crushed Palma leaf fibers show a decrease in thermal conductivity as well as thermal effusivity as the percentages increase (2%, 4% and 6%) of fibers in raw earth for the 3 sites. This shows that this renewable composite material can help improve the thermal insulation of building envelopes.

Keywords

Raw Earth, Palma Leaf Fibers, Ecological Composite Materials, Physical, Thermo-Mechanical, Thermal Conductivity, Thermal Effusivity

1. Introduction

In Africa, decently housing populations are becoming a major concern for states. The need for energy for lighting and air conditioning leads to high consumption of fossil energy, increasing air pollution which contributes to global warming. Indeed, according to [1], in 2021, more than 80% of the world's population has no access to electricity and of this, 43% of the total population lives in sub-Saharan Africa [2].

Despite this observation, we note that in Africa, the residential sector consumes 60% of energy and produces 32% of CO_2 emissions [3]. In addition, 40% of the total energy consumption of member states of the West African Monetary Union concerns urban areas [4]. In this region, most buildings are built with industrial materials, notably cement, without taking into account the quality of the envelopes, and therefore the thermal comfort of the occupants. According to [5], in Senegal, 69.6% of buildings have their walls constructed of cement, particularly in urban housing, which represents 85.7% with roofs made of concrete slabs or corrugated iron.

Energy demand is also increased by the use of electric air conditioning due to energy inefficiency in existing buildings. For cooling needs, air conditioning in the energy balance of public buildings can reach 60% [6]. Faced with this, it is imperative to reduce electricity consumption in buildings by finding alternative materials to concrete. As a result, several researchers have become interested in studying the mechanical and thermal performances of bio-sourced and geo-sourced materials.

From this perspective, the earth, which is the most widespread and ecological of construction materials, and accessible to all social categories [7], can be explored. Some researchers have focused on studies of the mechanical performance of earth mixed with plant fibers. Like [8], by the combination of rice straw stems and *néré* decoction. He showed that the composition of these materials provided an improvement in compressive strength. [9] studied the mechanical behavior of clay-sandy earth from the Souk-Ahras region (Algeria) mixed with date palm fibers and straw fibers. They noted an improvement in strength and good ductility. According to these two studies, the fibers do not necessarily deteriorate the mechanical capacities of the earth.

As for [10], he tested the mechanical and thermal properties of clay stabilized by gum arabic and reinforced by rice straw. It was found that gum arabic improves the mechanical resistance of the clay while the addition of rice straw causes the mechanical properties to drop but improves the thermal properties of the mixture. [11] explored mixing earth with flax and rice straw and obtained the same results on lowering mechanical properties and improving thermal properties. [12], like the aforementioned authors [8]-[11], mixed "poto-poto" earth with bamboo fibers, which resulted in a drop in the thermal conductivity of the material just with a rate of 2% fiber.

Other authors have made improvements with natural fibrous materials, such as [13] who explored the thermal performance of a biomaterial based on earth and plant fibers and the results conclude that the plant fiber has a positive influence on thermal conductivity. It's like [14] who confirmed through their study that the addition of straw, to clay, up to 4.81% can improve the thermal conductivity by more than 44.92% and the thermal effusivity by more than 33, 81%. Satisfactory thermal results were also obtained by [15] on the thermo-mechanical characterization of compressed terracotta bricks which were reinforced with thatch fibers, coming from Adamawa in Cameroon. As for [16], they experimented with the use of a mixture of soil and Hibiscus cannabinus L. for a cell wall with thermal lag results of 7.5 hours.

Other studies have made mixtures with plant products such as [17] who used baobab trunk fibers to improve the thermo-physical characteristics of concrete, or as [18] who studied and obtained thermal improvements with typha concrete. This is the case of the study by [19], regarding the improvement of the thermal and energy performance of masonry blocks with date palm ash. [20] also experimented with the insulating potential of stabilizing the mixture of earth and Hibiscus fibers with lime. Even if the thermal performance of the mixtures thanks to natural fibers has been noted, the use of industrial products does not militate for sustainable construction and the limitation of atmospheric pollution.

Plant fibers are widely available and low cost [21]. As for the use of plant fibers, apart from their renewable, biodegradable nature, neutral with regard to CO_2 emissions, they require little energy to be produced. Their valorization allows the reduction of the environmental impact of mineral, industrial or polymer fibers [22].

The specificity of our study lies in the exclusive use of bio-sourced and geo-sourced materials locally available in the locality of Mlomp, in the humid tropical climate zone of Casamance located in the south of Senegal. Our approach also aims to carry out a comparative geotechnical and thermo-mechanical study of three types of raw earth with various percentages of mixture of crushed palma (*Borassus aethiopum*) leaf fibers. These 3 types of raw earth are also different from those used by the various authors mentioned above. Compression and traction tests are carried out on these samples, as are conductivity and thermal effusivity tests.

2. Materials and Methods

2.1. Sample Preparation

2.1.1. The Palm Tree (*Borassus aethiopum*)

With a view to reinforcing the earth with a plant fiber as a bio-sourced material, the palm palm (*Borassus aethiopum*) from Mlomp is chosen (**Figure 1**). The tree is abundant in the region and throughout the tropical zone of Africa, in Asia up to New Guinea. It has a single stem which forms the trunk with a diameter between 30 and 50 cm and can reach 19 to 30 m depending on the country and climate [23]. It is a versatile tree, from the roots to the leaves, everything is exploited [24]. The leaves are used to make basketwork, walls for buildings, furniture and roofs. For this study, the palm leaf is used as an additive to the various earth samples taken. To do this, the leaf was harvested and dried in the laboratory in the open air for 15 days. Then, it was crushed to obtain fine fibers (**Figure 2**) to be mixed in proportions of 2%, 4% and 6% with the earth.

Figure 1. Palm tree (*Borassus aethiopum*).

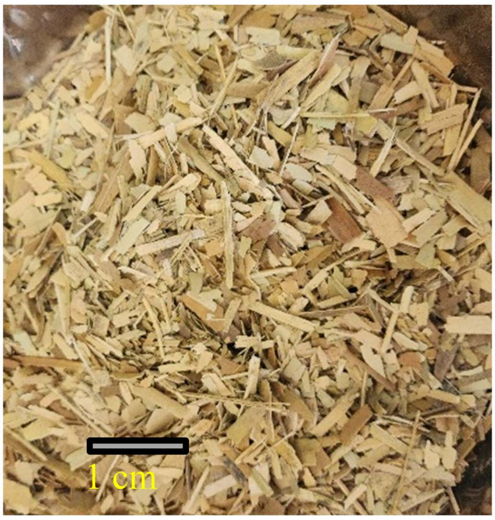


Figure 2. Palm leaves crushed into fibers.

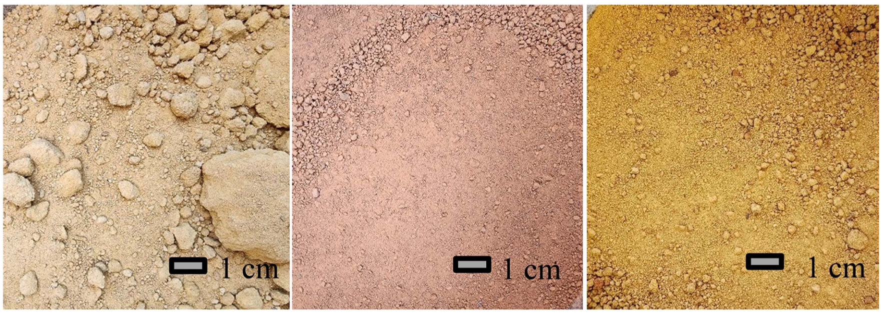
Drying took place around 31˚C and the grinding of the palm leaves to obtain fibers was done with a mini plant grinder. These conditions can be applied to other different environments.

2.1.2. The 3 Types of Raw Construction Earth and Mixtures of Crushed Palma Leaf Fibers

In order to find the right construction land to sustainably develop buildings, analyzes and measurements were carried out on 3 sites in the commune of Mlomp. In fact, Momp has buildings of different colors due to the coloring of the construction earth. The 3 types of earth were extracted on site, for the 3 sites, around the houses (**Figure 3**).


(1) (2) (3)

Figure 3. The three main colors of buildings: ash beige (site 1), brick red (site 2) and yellow ocher (site 3) in the commune of Mlomp in Casamance.



(1) Ash beige raw earth (2) Brick red raw earth (3) Yellow ocher raw earth

Figure 4. Raw earth samples from the three sites (1), (2) and (3).

Site 1 appears blocky but very crumbly to the touch. The sample gives a very grainy appearance (**Figure 4(1)**). Site 2 presents with smaller fine grains (**Figure 4(2)**). Site 3 is presented with compact blocks (**Figure 4(3)**). To characterize these 3 types of raw earth, we will carry out the granulometric analysis, the Atterberg limits and the Proctor test.

Granulometric analysis is fundamental for the identification and classification of soils. Granulometry has a great influence on the geotechnical properties of earth [25]. The particle size tests are carried out on the raw earth of sites 1, 2 and 3 according to the standard NF P 94-056.

The Atterberg limits are carried out according to the standard NF P 94-051.

The Proctor test is carried out according to the standard NF P 94-093. The samples are compacted in a standardized mold (**Figure 5(1)**), using a standardized checker according to a well-defined process and conventional energy. We obtain earthen cylinders (Figure 5(2)).


(1) (2)

Figure 5. Raw earth samples from the 3 sites with the normal Proctor mold.

2.1.3. Sample Constitution Procedure

Regarding the mechanical and thermal tests, the different samples of raw earth or mixed with crushed palm leaf fibers, for sites 1, 2 and 3, were made at the optimum water content. The same mixtures were used to make the samples for both the mechanical tests and the thermal tests. The percentage of material contained in each test sample is described in the table below (Table 1).

Table 1. Table of composition of materials at the sample level for each site.

Samples	1	2	3	4
Earth (%)	100	98	96	94
Palma fibers (%)	0	2	4	6

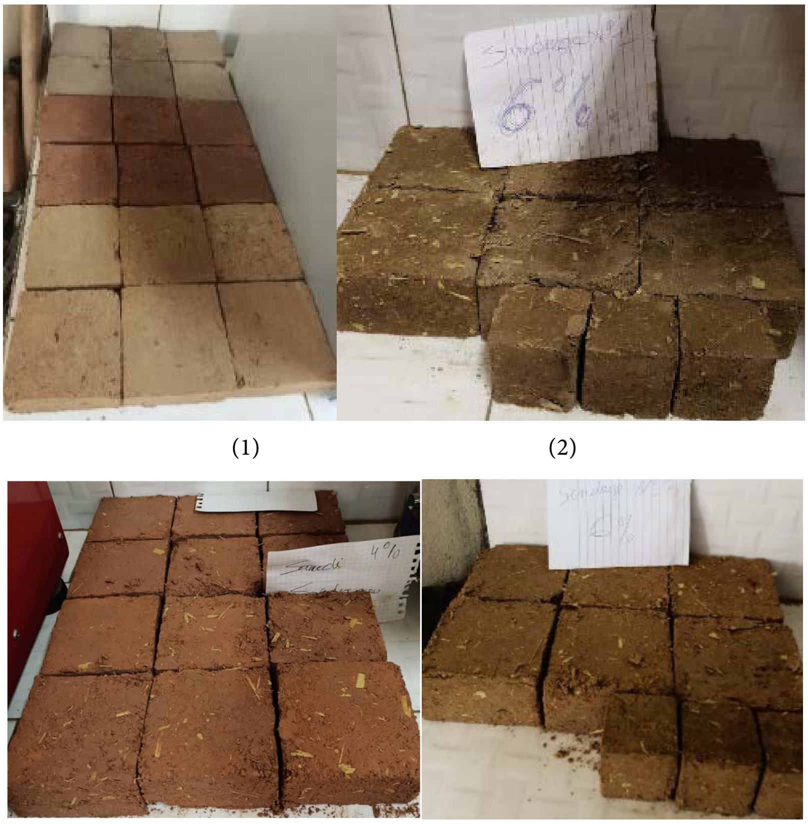
The 3 types of raw earth are mixed with crushed palm leaf fibers at percentages of 0%, 2%, 4% and 6% in order to test their mechanical and thermal performances. Greater length and thickness of the fibers lead to difficulties in homogeneity of the mixture and greater segregation of the composite material. It was observed during mixing that samples with fiber dimensions greater than 10 cm present transverse cracks which lead to segregation of the material and transverse cracks during drying.

Compressive and tensile strength tests were carried out in accordance with standards NF EN 13286-40 and NF EN 13286-41 July 2003. For this, molds of 10 × 10 × 5 (Figure 6(1)) are used to make test pieces in the form of test specimens of 10 cm × 10 cm × 5 cm (Figure 7(1)). For thermal tests, molds of 10 × 10 × 3 cm (Figure 6(2) are used. All the test specimens obtained are then spread out to dry in the ambient air of the laboratory for a week before the start of the various tests (Figure 7).

(1) (2)

Figure 6. Molds for testing.

The samples obtained are presented in **Figure 7**.



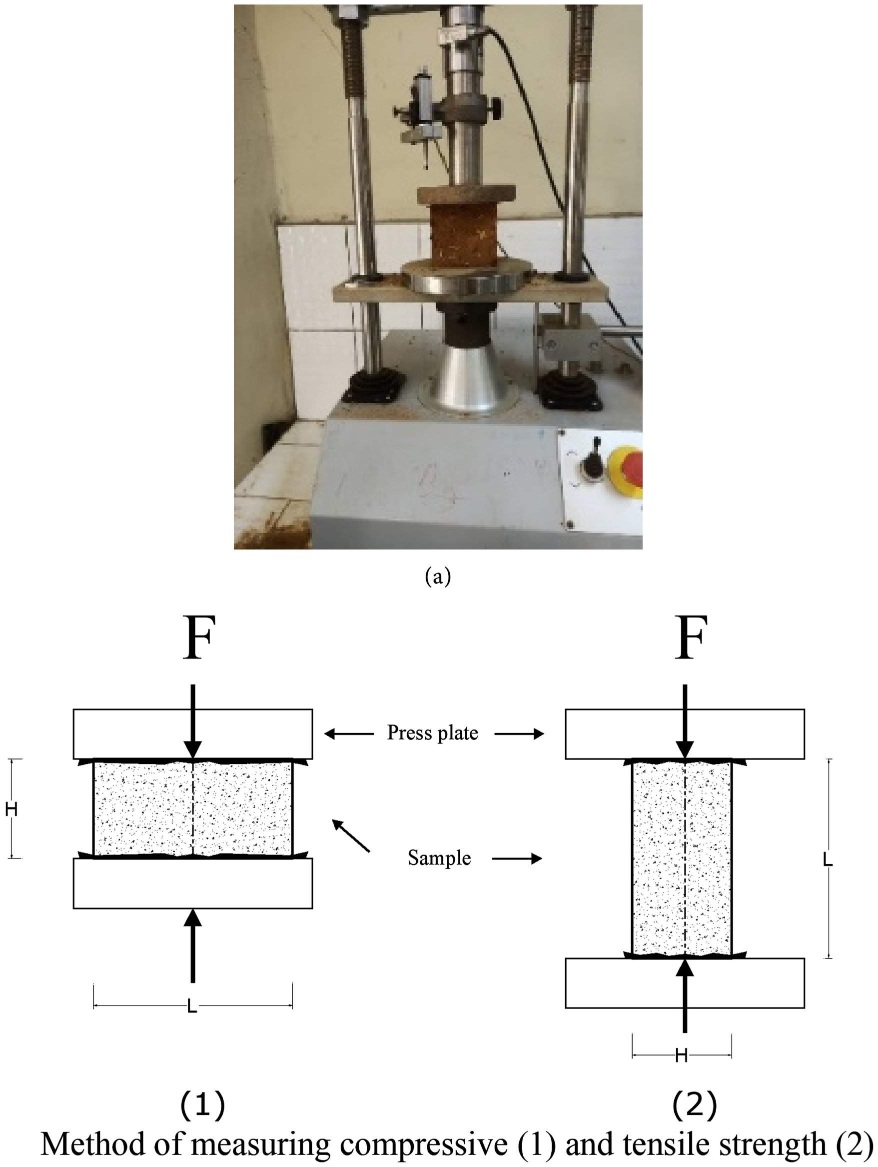
(1) (2)

(3) (4)

Figure 7. Raw earth samples (1) and 3 samples of mixtures with crushed palm leaf fibers (2, 3 and 4).

2.2. Mechanical Characterization Method

The mechanical tests were carried out with a "Multifunction Press" (**Figure 8**). The sample to be tested is placed in the press and subjected to simple compression or tension until rupture as shown in **Figure 8**.



(a)

(b)

Figure 8. Evaluation of the mechanical performances of raw earth samples and raw earth + fiber mixtures.

2.3. Thermal Characterization Method

The thermal characterization of the raw earth from Site 1, Site 2 and Site 3 as well as the raw earth with crushed palm leaf fibers mixtures (2%, 4% and 6%) is carried out. To evaluate the thermal properties of the materials, we determined the thermal conductivity (λ) and thermal effusivity (E). Indeed, as noted by [26] in almost all research programs on construction and insulation materials, importance is given to knowledge of these two parameters. The measurements were carried out using the asymmetric hot plane method which is a technique for measuring the conductivity and thermal effusivity of materials in transient conditions. The measurement time is short, however for heterogeneous materials containing inclusions, care must be taken to ensure that the thickness of the sample is equal to several times the size of these inclusions [27].

The principle consists of sending thermal excitation to the sample using a heating resistor and recording the temperature rise of the probe [28]. This method consists of applying a constant heat flow using a heating resistor on one side of the sample to be characterized and recording the evolution of the temperature T(t) at the center of this same resistance in which a thermocouple was placed. **Figure 9** shows thermal conductivity and thermal effusivity measuring device.

Figure 9. Thermal conductivity and thermal effusivity measuring device.

Figure 10 shows the schematic diagram of the asymmetric hot plane method.

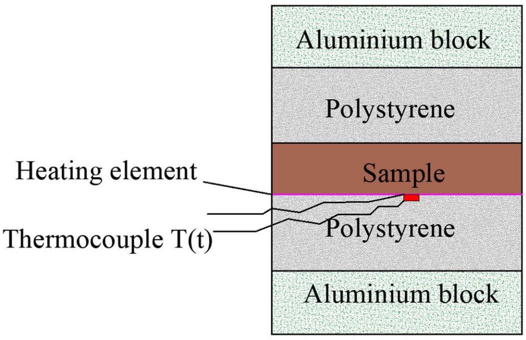


Figure 10. Schema of the experimental hot plate device.

For more details, this method was also used by [15], by [29] in their article for the valorization of millet stem fiber reinforced with gum arabic, for the thermal insulation of buildings, by [30] in the study of the thermal properties of typha-gum arabic and typha-starch, by [31] for the thermochemical study and mechanical properties of laterite bricks stabilised with cements and [17].

3. Results and Discussions

3.1. Sample Identification Tests

3.1.1. Granulometric Analysis

The results of granulometric tests are recorded in the figure below (**Figure 11**).

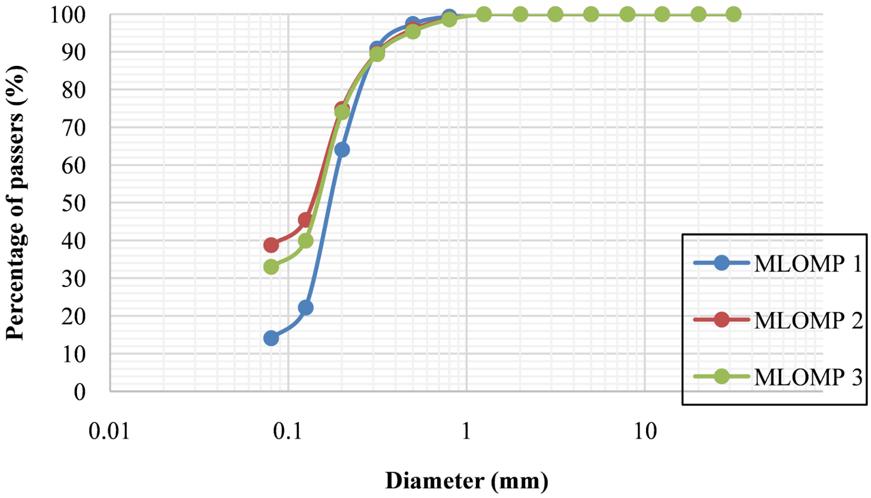


Figure 11. Granulometric curves of samples from sites 1, 2 and 3 of Mlomp.

The distribution of particle size classes is shown in **Table 2**.

The grain size curve of the raw lands of Mlomp (**Figure 11**) shows that they have a fairly tight grain size with the presence of a higher percentage of fines for Site 2 and Site 3. This shows that we know of clayey lands at Site 2 and Site 3. However, Site 1 retains powdery characteristics and is non-plastic (**Table 2**).

3.1.2. Atterberg Limits

Atterberg limits are geotechnical parameters intended to identify a soil and to characterize its state of plasticity using its plasticity index. The Atterberg boundaries were created only on the lands of Site 2 and Site 3. Site 1 does not contain sufficient clay fraction. The results were entered in **Table 2**.

Table 2. Physical characteristics of Mlomp earths.

	% fines	WL	Ip	Wopt	dmax
Site 1	14.1	-	-	10.2	1.98
Site 2	38.8	34	13	8	2.05
Site 3	33	28	17	7.8	2.07

3.1.3. Proctor Test

The results of the Proctor tests on the raw earth samples from the 3 sites are presented in Figure 12.

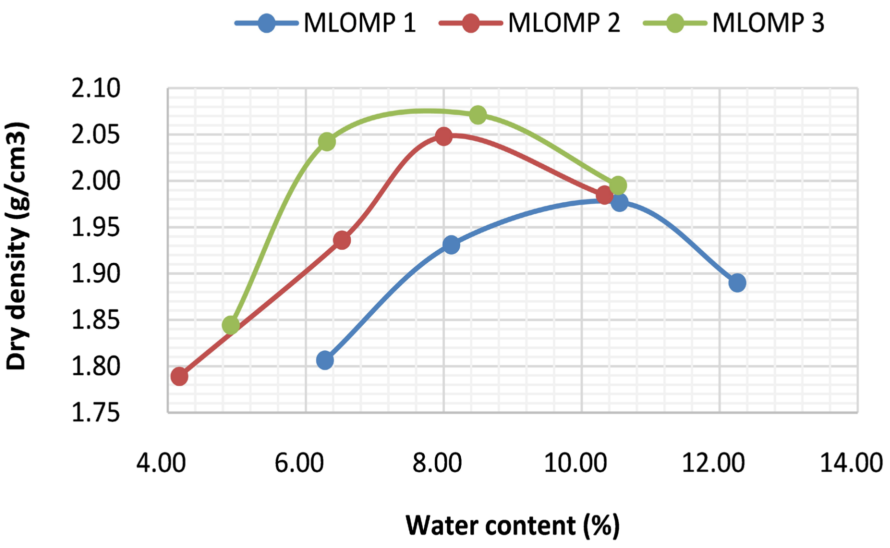


Figure 12. Proctor curves of raw earths from Sites 1, 2 and 3 of Mlomp.

The compaction characteristics show that the raw lands of Site 2 and Site 3 have the highest densities. This is explained by the presence of fine clay elements which increases cohesion, thus facilitating the increase in density. We also note lower water contents on Site 2 and Site 3. This can also explain the older and more resistant nature of the constructions at site 2 and site 3, and the greater fragility of the buildings in site 1.

The results of the Proctor tests on samples of raw earth from sites 1, 2 and 3 of Mlomp mixed with 2, 4 and 6% of palm tree fibers are shown in Figures 13-15.

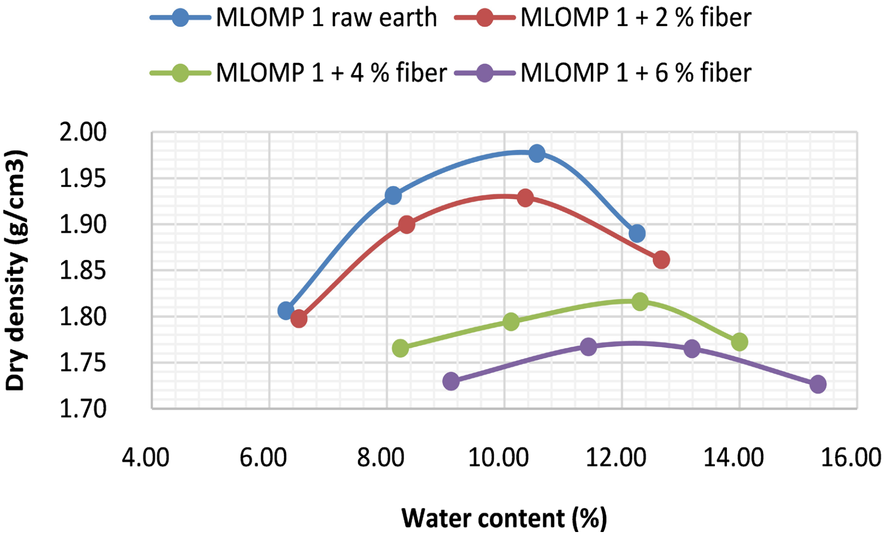


Figure 13. Proctor curves from Site 1 for the raw earth sample and the different mixtures (2%, 4% and 6%).

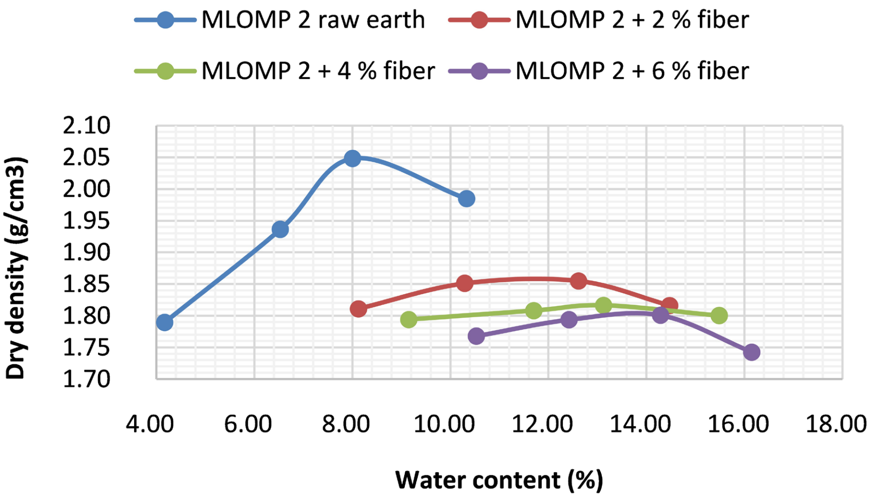


Figure 14. Proctor curves from Site 2 for the raw earth sample and the different mixtures (2%, 4% and 6%).

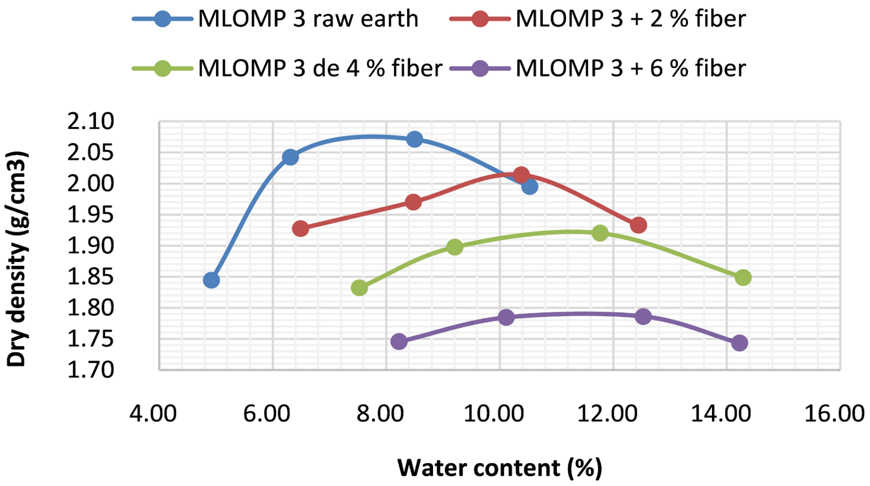


Figure 15. Proctor curves from Site 3 for the raw earth sample and the different mixtures (2%, 4% and 6%).

The results of the Proctor test (**Figures 13-15**) show that, for all 3 sites, the addition of crushed palm leaf fibers at 2, 4 and 6% gradually decreases as the density increases and increases optimal water content. This reduction in density is explained by a non-homogeneous distribution of the fibers and its powdery nature which reduces the cohesion as well as the density of the earth. In addition, the increase in water content is due to the absorbent nature of the fibers. The increase in water content is explained by the absorbent nature of the palm tree, which facilitates its ability to regulate humidity.

3.2. Mechanical Results and Discussion

3.2.1. Mechanical Results

The compressive and tensile strengths of raw earth test specimen and those of raw earth mixed with crushed palm leaf fibers (2%, 4% and 6%) are shown in **Figures**

16-18.

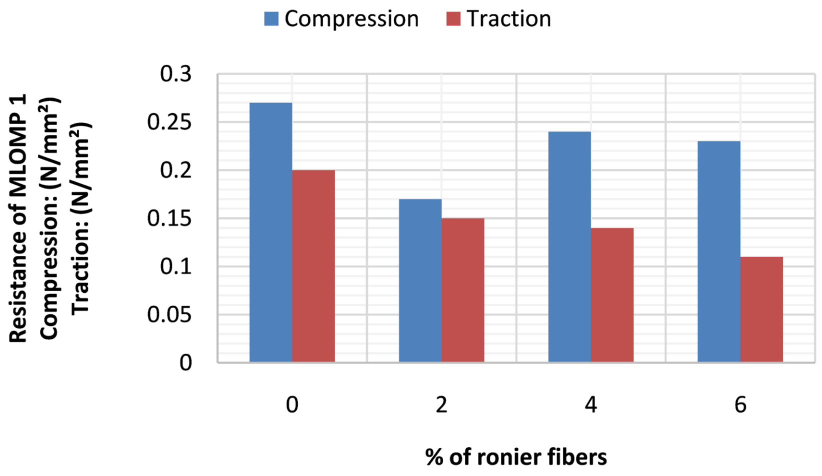


Figure 16. Variation in compressive strength (N/mm^2) and tensile strength (N/mm^2) of the soil from Site 1 depending on the percentage of crushed palm leaf fibers.

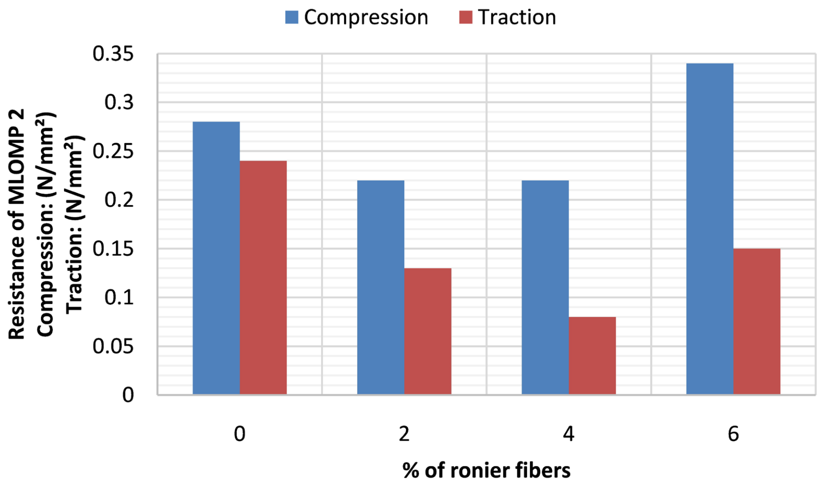


Figure 17. Variation in compressive strength (N/mm^2) and tensile strength (N/mm^2) of the earth from Site 2 depending on the percentage of crushed palm leaf fibers.

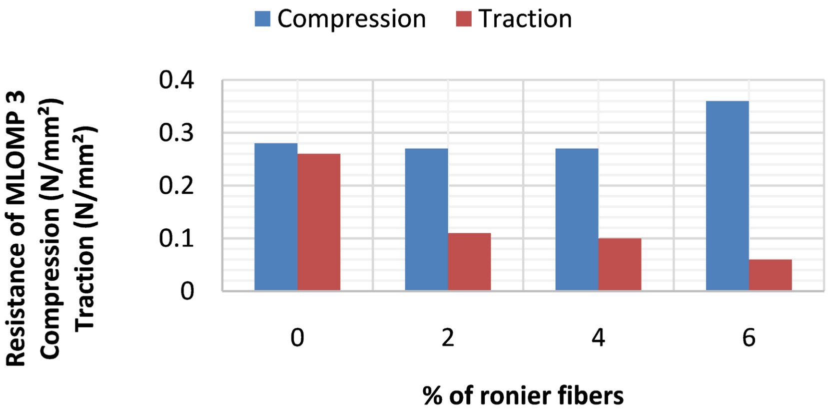


Figure 18. Variation in compressive strength (N/mm^2) and tensile strength (N/mm^2) of the soil from Site 3 depending on the percentage of crushed palm leaf fibers.

3.2.2. Mechanical Discussion

The study of the variation in compressive and tensile strengths of the earth from sites 1, 2 and 3 of Mlomp (**Figures 16-18**) generally shows a decrease in tensile strength and an increase in the compressive strength when the proportion of fibers increases to 6%. For the Mlomp earths, a drop in resistance of compression at 2% of the palm tree fiber mixture was observed. This is due to the low resistance of the palm tree which behaves in the form of a plate and which reduces the cohesion and shear resistance of the mixture. At high percentages, the palm tree occupies a significant volume in the mixture which promotes adhesion between the fibers and increases strength. The compressive strength at Site 3 keeps very similar values because for the raw earth, the results show 0.28 N/mm^2, the 2% mixture, 0.27 N/mm^2 and the 4% also, 0.27 N/mm^2.

This compressive strength reaches its maximum at 6% palm wood for Sites 2 and 3. This variation in resistance is due to a segregation of the palm tree in the mixture (**Figure 19**) and the random distribution of the palm tree in the mixtures.

Figure 19. Appearance of a sample of raw earth + crushed palm leaf fibers before and after compression.

For tensile strength, the result obtained from the raw earth sample from site 1 (0.2 N/mm^2) is lower than that from sites 2 and 3, respectively 0.24 N/mm^2 and 0.26 N/mm^2 (**Figures 16-18**). This means that the raw earth from site 3 works better in traction than the other two. The mixtures of earth and leaf fibers for site 1 present better tensile results than for sites 2 and 3. But overall, for the earth samples with mixtures of palma leaf fibers, we don't note improvement for tensile strength. The more crushed palm leaf fibers in the mixture, the lower the tensile strength for all three sites. The addition of palm leaf fibers to the various samples of raw earth does not offer sufficient mechanical strength like concrete to be used as load-bearing structures.

3.3. Thermal Results and Discussions

3.3.1. Thermal Conductivity

1) Results

Thermal conductivity λ corresponds to the heat flow that passes through a material. It defines the ability of a material to conduct heat or insulate it. The lower the thermal conductivity, the more insulating the material. It is expressed by the unit (W m^{-1} K^{-1}). The results obtained from the thermal conductivity measurements are presented in **Figure 20**.

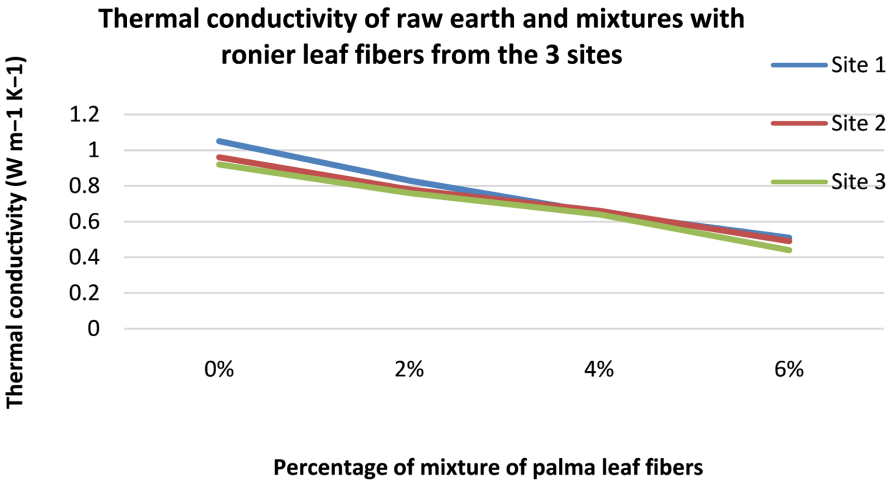


Figure 20. Comparative curves of the thermal conductivity of raw earth samples from the three sites and the different percentages of crushed palm leaf fibers.

For site 1, the curve shows that the value of thermal conductivity decreases regularly, from raw earth (1.05 W m^{-1} K^{-1}) to the mixture of 6% crushed palma leaf fibers (0.51 W m^{-1} K^{-1}). For site 2, the curve shows the same trend as site 1, the thermal conductivity becomes lower with the addition of crushed palm leaf fibers (raw earth: 0.96 W m^{-1} K^{-1} and earth at 6% of fibers: 0.49 W m^{-1} K^{-1}). The trend observed on sites 1 and 2 is also valid for site 3 with the thermal conductivity which drops to 0.44 W m^{-1} K^{-1} with the addition of 6% fibers, while the raw earth is at 0.92 W m^{-1} K^{-1}. Site 3 has lower thermal conductivities than the other two regardless of the mixture used, even if there is a slight variation depending on the sites. These mixtures have a thermal conductivity much lower than that of concrete which is around 2 W m^{-1} K^{-1}.

2) Discussion

In each of these three sites, the substitution of soil by fibers reduces the thermal properties of raw earth. This is in perfect correlation with the work of [32] in 2020 which also shows the use of clay and sisal fibers to develop materials for construction. The impact of adding sisal fibers on the thermal properties of these materials was studied. This study showed that the addition of sisal fibers significantly reduces the thermal conductivity of composites. In 2019, Lamrani *et al.* [33] developed construction materials based on clay, date palm fibers, straw fibers and olive waste. The impact of these fibers on the thermal properties of pure clay was evaluated. The results showed that the addition of these fibers improves the thermal properties of clay composites.

We note that at the 3 sites, the more crushed palm leaf fibers we add, the more the thermal conductivity decreases (**Figure 20**). This can be explained by the fact that a dense material is replaced by organic matter, a less dense material as evidenced by the conclusions of the mechanical tests on the mixture samples. This makes the material more porous. And the more the thermal conductivity of a material decreases, the more insulating this material is.

3.3.2. Thermal Effusivity

1) Results

Thermal effusivity *E* describes the rate at which a material absorbs and releases heat. The lower the thermal effusivity, the faster the material will heat up with less energy. It is expressed in (W/(Km^2)s$^{1/2}$. The results obtained from the thermal effusivity measurements are presented in **Figure 21**.

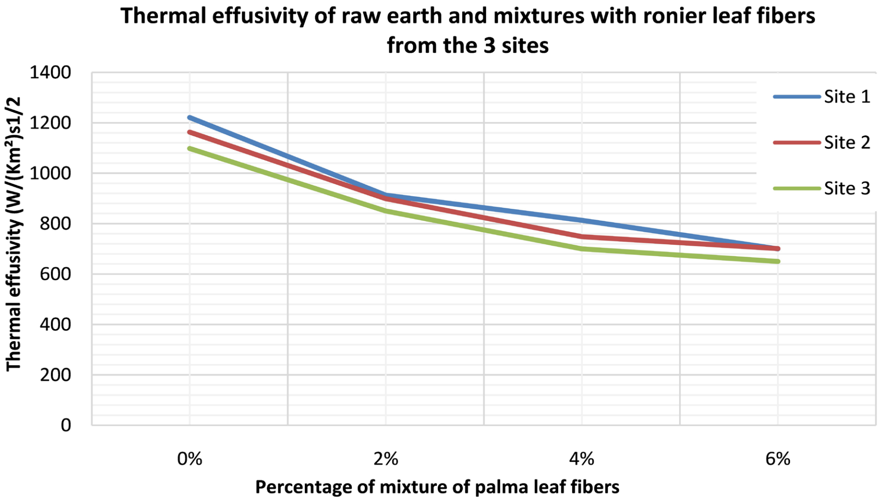


Figure 21. Comparative curves of the thermal effusivity of raw earth samples from the three sites and the different percentages of crushed palm leaf fibers.

We note on the thermal effusivity variation curves (**Figure 21**) that for all sites, the trend is downward with the addition of crushed palm leaf fibers. For site 1, the curve shows that the thermal effusivity value declines regularly from the raw earth (1221 (W/(Km^2) s$^{1/2}$) to the mixture of 6% of crushed palma leaf fibers (700 (W/(Km^2) s$^{1/2}$). For site 2, the curve shows the same trend as site 1. The thermal effusivity becomes lower with the addition of crushed palm leaf fibers (raw earth: 1163 (W/(Km^2) s$^{1/2}$) and earth at 6% fiber: (701 W/(Km^2) s$^{1/2}$). The trend observed for sites 1 and 2 is also valid for site 3 with the thermal effusivity which drops to 650 (W/(Km^2) s$^{1/2}$) with the addition of 6% fibers, while for the raw earth it is 1098 (W/(Km^2) s$^{1/2}$). Site 3 has lower thermal effusivity values than the other 2 sites compared to the different mixtures (**Figure 21**).

2) Discussion

At the three sites, the more crushed palm leaf fibers we add, the more the effusivity decreases. This can be explained by the fact that the quantity of earth is replaced by organic matter, a more porous and less dense material. As fibers are added, this contributes to a reduction in thermal effusivity. From the thermal conductivity and effusivity data, we can conclude that the addition of crushed palm leaf fibers improves the thermal comfort of earth walls. With these results, we can say that the raw earth material mixed with crushed palma (*Borassus aethiopum*) leaf fibers can be an alternative to reduce the energy consumption of buildings. Its use in buildings can contribute to reducing the number of air conditioning hours, and therefore fossil energy consumption, thanks to improving the thermal performance of the envelopes.

4. Conclusion

This study aims to facilitate the choice of the construction earth in order to improve its energy performance. The mixture of crushed palma leaf fibers with the 3 types of earth resulted in a progressive reduction in thermal conductivity and thermal effusivity significantly. This bio-sourced and geo-sourced composite material (raw earth and crushed palma (*Borassus aethiopum*) leaf fibers) can help ensure thermal comfort of constructions. Although the addition of crushed palma leaf fibers causes the density and mechanical properties of the mixture to decrease, it appears to have insulating properties. The phenomenon of overheating of concrete facades and roofs by solar radiation, which is very important in sub-Saharan space, can find a solution through the use of this natural material in order to protect the envelopes of buildings. This will help to reduce the use of electric air conditioning in buildings and at the same time reduce energy consumption which comes from products derived from fossil materials. The 6% fiber mixture can be used for a wider application to obtain boards for thermal insulation. The study thus aims to promote earth construction with the use of crushed palm leaves with a view to their use in the search for solutions against energy consumption, the search for thermal comfort and the thermal insulation of buildings.

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Conflicts of Interest

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

References

[1] International Renewable Energy Agency (2023) Selon un nouveau rapport, l'accès de base à l'énergie est à la traîne malgré des opportunités en matière d'énergie renouvelable. https://www.irena.org/news/pressreleases/2023/jun/basic-energy-access-lags-amid-renewable-opportunities-new-report-shows-fr

[2] International Energy Agency IEA (2022) Africa Energy Outlook 2022.

[3] United Nations Environment Program (2020) Regional Roadmap for Buildings and Construction in Africa 2020-2025: Towards a Zero-Emission. Efficient and Resilient Buildings and Construction Sector.

[4] UEMOA (2020) Directive n°05/20207cm/UEMOA fixant des mesures d'efficacité énergétique dans la construction de bâtiments dans les états membres de l'UEMOA. https://rise.esmap.org/data/files/library/niger/Energy%20Efficiency/Niger_%20Energy%20Efficiency%20in%20Buildings%20Construction_Directive%20NA%CC%82%C2%B005_2020_CM_UEMOA_2020.pdf

[5] Sow, E.M., Gassama, D., Diagne, M. and Seck, A. (2021) Analysis of the Building Sector in Senegal. Program for Energy Efficiency in Buildings (PEEB). Building and Energy. https://www.peeb.build/imglib/downloads/Synth%C3%A8se_B%C3%A2timent_et_%C3%A9nergie_S%C3%A9n%C3%A9gal_PEEB.pdf

[6] Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) (2021) Evaluation des impacts de la directive et proposition d'orientations pour sa bonne transposition. Bonn et Eschborn, Allemagne.

[7] Dethier, J., Doat, P., Guillaud, H., Houben, H., Anger, R., Bardagot, A.M. and Besnard, A. (2019) Living on Earth: The Art of Building with Raw Earth. Flammarion.

[8] Adagbe, M. T. (2021) Use of Earth Reinforced by Rice Straw Stems as a Material for the Load-Bearing Elements of Buildings Reinforced with Palmyra Palm. Toulouse III University.

[9] Imen, S. and Belouettar, R. (2011) Mechanical Behavior of Raw Earth Bricks Reinforced with Date Palm Fibers and Straw Fibers. *INVACO$_2$ International Seminar*, *Innovation & Valorization in Civil Engineering & Building Materials*, 2p-118.

[10] Abakar, A. (2018) Mechanical and Thermal Characteristics of Clay Stabilized by Gum arabic and Reinforced by Rice Straw. PhD Thèse, Université de Lorraine. https://hal.univ-lorraine.fr/tel-01920664

[11] Phung, P.A. (2018) *Formulation and Characterization of an Earth-Plant Fiber Composite: Cob*. *Civil Engineering*. Ph.D. Thesis. Normandy University.

[12] Eric, K.K., Damfeu, J.C., Ursulala, P.J., Ducourneau, J., Woafo, P. and Pettang, C. (2021) Thermophysical and Mechanical Characterization of Poto-Poto Compressed Blocks for Use as Fill Material. *Materials Sciences and Applications*, **12**, 437-459. https://doi.org/10.4236/msa.2021.1210029

[13] Ennassih, H., Bouferra, R., Zoubir, A., Essaleh, L. and Elhassri, S. (2020) Mechanical and Thermal Characterization of a Biomaterial Based on Soil and Plant Fibers. *Academic Journal of Civil Engineering*, **38**, 29-32.

[14] Ouedraogo, B., Palm, K., Ouedraogo, E., Bathiebo, D. and Kam, S. (2016) Experimental Study of Thermophysical and Mechanical Properties of Refractory Clay Tilled into Straw-Fiber Stabilized Blocks. *Physical Science International Journal*, **12**, 1-8. https://doi.org/10.9734/psij/2016/29586

[15] Nitcheu, M., Meukam, P., Damfeu, J.C. and Njomo, D. (2018) Thermomechanical Characterisation of Compressed Clay Bricks Reinforced by Thatch Fibres for the Optimal Use in Building. *Materials Sciences and Applications*, **9**, 913-935. https://doi.org/10.4236/msa.2019.912066

[16] Sandwidi, S., Compaore, A., Haro, K., Dabilgou, T., Sinon, S., Sanogo, O., *et al.* (2023) Hygrothermal Study of a House Made of Local Biosourced Materials Based on Clay: Experimental Study. *Open Journal of Applied Sciences*, **13**, 60-75. https://doi.org/10.4236/ojapps.2023.131006

[17] Ghabo, A., Touré, P.M., Diéye, Y. and Sambou, V. (2023) Thermophysical Characterization of Concrete Reinforced with Baobab Trunk Fibers (*Adansonia digitata* L.) for Thermal Insulation of Buildings. *Journal of Sustainable Construction Materials*

and Technologies, **8**, 251-259. https://doi.org/10.47481/jscmt.1285031

[18] Diaw, A.S., Bal, H.M., Diallo, O., Ndiaye, M.B., Wade, M. and Gaye, S. (2021) Thermophysical Characterization of Typha's Concrete for Its Integration into Construction. *Journal of Building Construction and Planning Research*, **9**, 56-65. https://doi.org/10.4236/jbcpr.2021.91005

[19] Ashraf, N., Nasir, M., Al-Kutti, W. and Al-Maziad, F.A. (2020) Assessment of Thermal and Energy Performance of Masonry Blocks Prepared with Date Palm Ash. *Materials for Renewable and Sustainable Energy*, **9**, Article No. 17. https://doi.org/10.1007/s40243-020-00178-2

[20] Zoma, F., Yonli, F.H., Malbila, E., Toguyeni, D.Y.K. and Hassel, I.B. (2020) Adding Hydrated Lime in a Material Made of Clayey Soil and Fibres: Formulation and Effects on Thermo-Mechanical Properties. *Journal of Minerals and Materials Characterization and Engineering*, **8**, 149-161. https://doi.org/10.4236/jmmce.2020.83010

[21] Akbulut, S., Arasan, S. and Kalkan, E. (2007) Modification of Clayey Soils Using Scrap Tire Rubber and Synthetic Fibers. *Applied Clay Science*, **38**, 23-32. https://doi.org/10.1016/j.clay.2007.02.001

[22] Baley, C., Grohens, Y. and Pillin, I. (2004) Etat de l'art sur les matériaux composites biodégradables. *Revue des composites et des matériaux avancés*, **14**, 135-166. https://doi.org/10.3166/rcma.14.135-166

[23] Akaza, M.J., Mlan, K.S., Akaffou, D.S. et Gnamou, B.R. (2022) Morphological Characterization of *Palmyra palm* (Borassus spp.) from the Centre-East, Centre-West and Centre-South of the Ivory Coast. *American Journal of Innovative Research and Applied Sciences*, **15**, 91-98. https://american-jiras.com/Moroh%E2%80%93Ref3-ajiras120922.pdf

[24] Ngargueudedjim, K., Mbayngone, E., Nadjitonon, N., Bassa, B., Allarabeye, N., Destrebecq, J.F. and Agnes, R. (2016) Anatomical and Chemical Characterization of the *Palmyra palm* (*Borassus aethiopum* Mart., Arecaceae) from Chad/Central Africa. *International Journal of Innovation and Scientific Research*, **20**, 2351-8014.

[25] Omotoso, O.A., Ojo, O.J. and Adetolaju, E.T. (2012) Engineering Properties of Lateritic Soils around Dall Quarry in Sango Area, Ilorin, Nigeria. *Earth Science Research*, **1**, 71-81. https://doi.org/10.5539/esr.v1n2p71

[26] Bakkouri, A.E., Boussaid, S., Ezbakhe, H., Ajzoul, T. and Bouardi, A.E. (2000) Méthode générale d'identification paramétrique: Application a l'étude thermophysique de quelques matériaux locaux utilisés dans la construction au maroc (platre-liège-brique creuse). *Canadian Journal of Civil Engineering*, **27**, 628-631.

[27] Bodian, S. (2015) Comportement thermomécanique d'une brique en terre crue et en terre cuite. Memoire de fin de stage, Ecole Superieure Polytechnique, Universite Cheikh Anta Diop De Dakar, 1-79.

[28] Dieye, Y., Sambou, V., Faye, M., Thiam, A., Adj, M. and Azilinon, D. (2017) Thermo-mechanical Characterization of a Building Material Based on Typha Australis. *Journal of Building Engineering*, **9**, 142-146. https://doi.org/10.1016/j.jobe.2016.12.007

[29] Ndiaye, M.M.D., Touré, P.M., Touré, Y. and Guèye, P.M. (2019) Thermo-Mechanical Characterization of Building Component with Crushed Millet Stalk Fiber. *International Journal of Innovation and Applied Studies*, **26**, 1230-1239.

[30] Diéye, Y., Gueye, M.P., Toure, P.M., Bodian, S., Sambou, V. and Tigampo, S. (2020) Comparison of Two Types of Binders Naturals on the Mechanical and Thermal Properties of Typha Leaf Powder Panels. *Sigma Journal of Engineering and Natural Sciences*, **38**, 2069-2081. https://eds.yildiz.edu.tr/AjaxTool/GetArticleByPublishedArticleId?PublishedArticleId=5263

[31] Kossi Imbga, B., Bodian, S., M. Toure, P., Dieye, Y. and Sambou, V. (2022) Study of the Thermochemical and Mechanical Properties of Laterite Bricks Stabilised with Cements. *International Journal of Advanced Research*, **10**, 589-603. https://doi.org/10.21474/ijar01/15878

[32] Ouakarrouch, M., El Azhary, K., Mansour, M., Laaroussi, N. and Garoum, M. (2020) Thermal Study of Clay Bricks Reinforced by Sisal-Fibers Used in Construction in South of Morocco. *Energy Reports*, **6**, 81-88. https://doi.org/10.1016/j.egyr.2019.11.045

[33] Lamrani, M., Mansour, M., Laaroussi, N. and Khalfaoui, M. (2019) Thermal Study of Clay Bricks Reinforced by Three Ecological Materials in South of Morocco. *Energy Procedia*, **156**, 273-277. https://doi.org/10.1016/j.egypro.2018.11.141