Vol. 20(1), pp. 1-11, January-March, 2025
DOI: 10.5897/IJPS2024.5087
Article Number: DCEA8B572948
ISSN: 1992-1950

http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Full Length Research Paper

Study of the thermo-hydro-mechanical characteristics of prismatic compressed earth specimens from two brick quarries in the city of Abéché, Chad

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Received 17 November, 2024; Accepted 17 January, 2025

The study focuses on the thermo-hygro-mechanical characterization of prismatic samples compressed earth specimens (CECs). Firstly, various sampling sites were located in order to identify them. Thus, the 4 × 4 × 16 cm^3 specimens were used for the mechanical tests and the absorption test. In addition, 4 × 5 × 8 cm^3 specimens were used for the thermal test. The wood ash content was varied from 0 to 12% of the total dry mix mass. The results of the absorption test showed that the addition of wood ash to the mix enhanced the degree of absorptivity of the test specimens. However, the results of the thermal test showed that thermal conductivity, thermal effusivity, and thermal diffusivity decreased with the percentage of wood ash. Similarly, the results of the mechanical properties test showed that flexural strength and compressive strength decreased with the addition of more than 4% wood ash to the mix.

Key words: Mechanical properties, soils, thermal conductivity, thermal effusivity, thermal diffusivity, capillary absorption.

INTRODUCTION

Chad is a country in the heart of Central Africa, with a surface area of 1,284,000 km^2 and a hot, dry tropical climate. It is the fourth largest country after Libya, Algeria, and the Democratic Republic of Congo. Chad's population is estimated at over 17.4 million in 2022, with a growth rate of 3.6% (Annual Results Report Chad, 2022). By 2050, it will be around 35.1 million (United Nations Population Division, 2015). This population needs to be housed in buildings that comply with standards as well as with the concept of thermal comfort in buildings. Current trends favor the use of cementitious materials, which contribute to global warming.

According to a report by the International Energy Agency (IEA, 2016c), the building sector alone consumes

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over 32% of all energy produced worldwide and contributes around one-third of global greenhouse gas emissions (Cazacova and Yapicioglu, 2019). Of the 136 million tonnes of waste generated annually in the building sector, half can be attributed to the demolition sector (Yung and Chan, 2012; Tam and Tam, 2006). In light of this data, it is essential that the construction industry evolves and participates in the reduction of greenhouse gas emissions on a global scale by using environmentally friendly building materials (which consume little energy and emit few greenhouse gases throughout their lifecycle), and by moving towards sustainable construction. Moreover, the use of ecological building materials is a concept that mankind has been employing for a very long time, for example in the construction of certain archaeological sites that have been discovered in a number of geographical areas across the planet. It has been asserted that mankind has mastered earth-based construction techniques, more specifically raw earth (Abessolo et al., 2020). Although rammed earth is often criticized for its vulnerability to water and its inherent lack of durability, it nevertheless offers a number of advantages when it comes to building sustainable, comfortable, and affordable housing in its current form. However, several additives have been used by researchers in the course of technological and scientific progress in order to improve the mechanical and hygroscopic characteristics of BTC stabilized from raw earth (Houben et al., 1996; Saadi and Belouttar, 2009). The use of residues from wood combustion incorporated into clay bricks for local use could represent the optimum solution for recycling this material while preserving the environment. This work aims to examine the behavior of clay specimens stabilized by wood ash, and then to carry out mechanical and thermal tests.

MATERIALS AND METHODS

Study location

The base materials used are extracted from three different quarries in the town of Abéché, with the following geographical coordinates:

1) Soil EE: 13°50'52'' Latitude North and 20°48'54 Longitude East.
2) Soil EM: 13°50', 52'' Latitude North and 20°48'30'' Longitude East.

All two quarries are exploited by local residents on an artisanal basis. However, they are easily accessible and supply almost the entire population of Abéché with building bricks.

Samples

Clay

The various physical and geotechnical parameters of Abéché clay are given in the article (Abdel-Khadir et al., 2023). All these physical parameters have contributed to the classification of the clays from three quarries in the town of Abéché as "Low plasticity clay".

Wood ash

Wood ashes are products also known as residues resulting from combustion or incineration. It is much more widely used in agriculture as a fertilizer, as a material in industrial manufacturing processes, or as a construction material for building and public works (Bouvot, 2001). Wood ash is used in the construction of backfill and pavement sub-bases. However, it can also play a vital role as a binder with low pozzolanic content and a granulometric tester or filler, whose role is to complete the granulometry of a material with a low fine fraction (less than 500 µm) (Khellou et al., 2015).

Figure 1 gives an image of the hearth where the wood ash is extracted as well as the sieving of the wood ash.

Capillary absorption test

This capillary water absorption test is described in detail in the experimental standard NF XP 13-901 (Armel, 2017). The principle consists of partially immersing the brick to a depth of 5 mm (Figure 2). The water absorption coefficient Cb corresponds to the absorption rate after a time equal to 10 min. The latter determines the rate or speed of absorption by capillary rise of a 4 × 4 × 16 cm^3 cubic test piece placed in a tray containing water so that the water only touches the test piece to a height of almost 5 mm from the depth of the tray. The increase in the mass of the test tube as a function of time is then measured using the following formula:

$$C_b = \frac{100 \times (P_1 - P_0)}{S\sqrt{t}} \qquad (1)$$

where $P_1 - P_0$ is the mass of water in grams absorbed by the block during the test, S is the surface area of the immersed face, in square centimeters, and t is the block immersion time in minutes. Remember that a brick is weakly capillary when Cb ≤ 20 and slightly capillary when Cb < 40.

Procedures

Specimen formulation

The 4 × 4 × 16 cm^3 parallelepiped test specimens were used for the mechanical tests (bending and compression) and the 5 × 4 × 8 cm^3 for the thermal tests. The choice of wood ash percentages was made to see the influence of wood ash on the clay soil matrix. However, the different formulations are shown in Table 1.

Sample preparation

First, a dry clay mass (450 ± 1 g) is taken and weighed with a balance as shown in Figure 3. Next, the different percentages of wood ash (2, 4, 6, 8, 10, and 12%) are weighed against the mass of clay initially taken. The whole mixture (clay + wood ash) is placed in a cup and kneaded for about 2 min to obtain a homogeneous dry mix. Next, a mass of water is weighed and gradually poured into the mixture (clay + wood ash) while mixing with a trowel, until an almost

Table 1. Formulation of 4 × 4 × 16 cm^3 specimens of different soils mixed with wood ash.

Soil	Clay (%)	CB (%)	l (cm)	b (cm)	h (mm)	Number
	100	0	16	4	4	4
	98	2	16	4	4	4
	96	4	16	4	4	4
EE	94	6	16	4	4	4
	92	8	16	4	4	4
	90	10	16	4	4	4
	88	12	16	4	4	4
	100	0	16	4	4	4
	98	2	16	4	4	4
	96	4	16	4	4	4
EM	94	6	16	4	4	4
	92	8	16	4	4	4
	90	10	16	4	4	4
	88	12	16	4	4	4

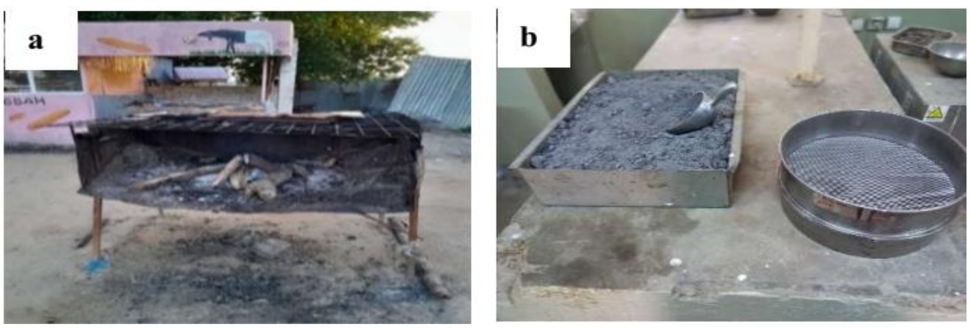

Figure 1. a) Wood ash extraction furnace; b) sieving wood ash.

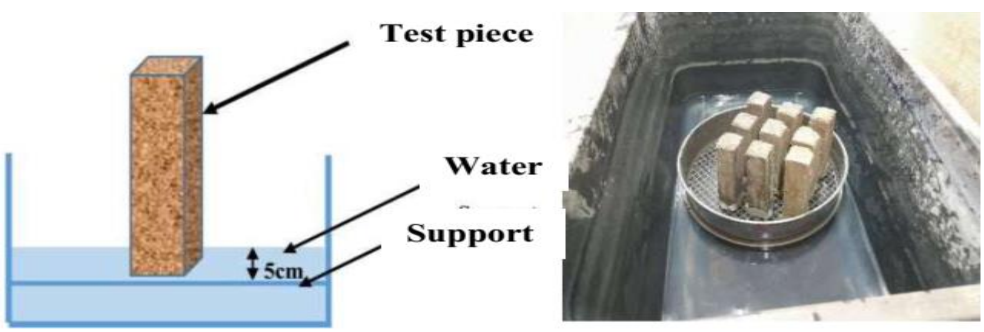

Figure 2. The principle of capillary absorption test.

homogeneous wet mixture is obtained. Once this mass has been obtained, pour it into a plastic bag and leave for 15 to 20 min to homogenize and prevent the water from evaporating (Figure 3).

Manufacture of 4 × 4 × 16 cm^3 specimens for mechanical testing

For the manufacture of test pieces, a balance was used to measure the masses (clay + wood ash) previously prepared and stored in plastic bags. These weighed masses are approximately 450±10 g for each formulation. These are then introduced into the 4 × 4 × 16 cm^3 molds through a crucible, the molds are closed, and the manual press is used to compress the specimens to the same dimensions (4 × 4 ×16 cm^3) as shown in Figure 4.

Once the specimens have been made, they are carefully extracted once the top cover has been removed and the jack

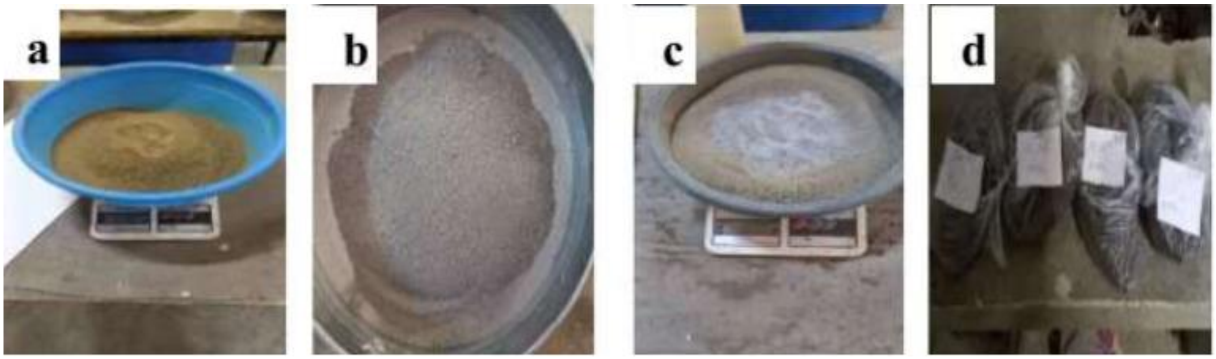

Figure 3. a) Soil, b) wood ash, c) soil+ wood ash, and d) preserving the mixture.

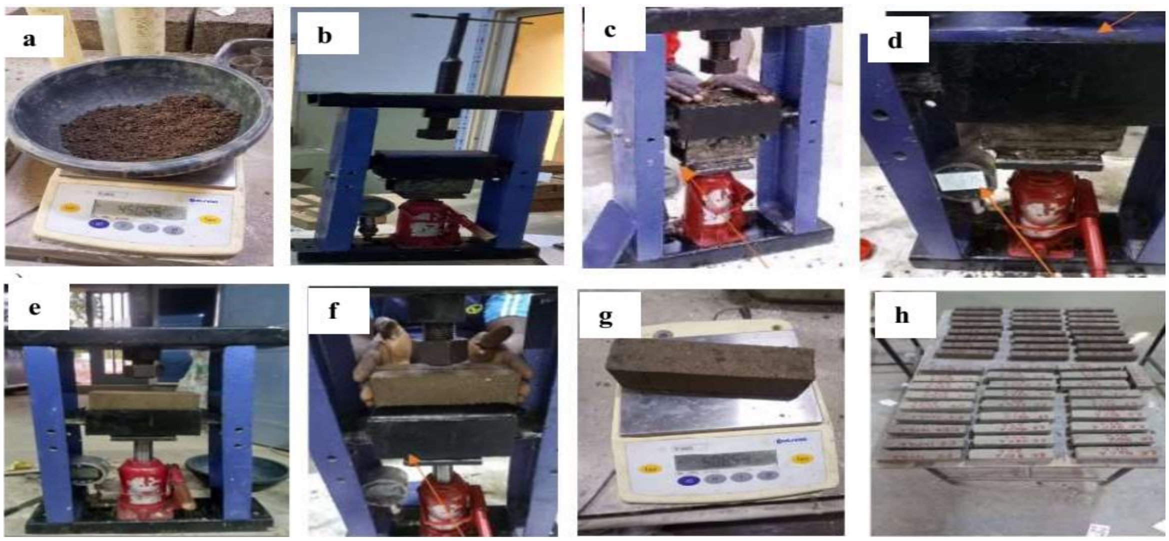

Figure 4. a) weighed sample, b) hydraulic press, c) mold, d) pressure gauge, e) manufactured sample, f) extraction g) weighed sample, h) dried sample.

applied. Drying is carried out in the shade at the ambient temperature of the National Higher School of Public Work (ENSTP) laboratory (approx. 30°C ± 2) for 3 days, then in the oven for 24 h at 105°C to obtain a stable mass.

Manufacture of 4 × 5 × 8 cm³ specimens for thermal tests

The specimens for thermal characterization were manufactured using the same manual press, but with a 4 × 5 × 8 cm^3 mold. The drying process and packaging are the same as for the 4 ×5 × 16 cm^3 test pieces. The figure 5 (a) shows us the press used for the manufacture of the specimens and Figure 5 (b) the manufactured pieces.

Mechanical characterization of specimens

This crushing operation is carried out using a 250 KN compression machine (Figure 6). The machine consists of 153 mm compression platens with a 150 mm gap between platens. The cylinder stroke is 45 mm. The machine has a weight of 300 kg. It is class 1 and complies with EN 196-1/EN ISO 679/ASTM C109.

Three-point bending test

The 4 × 5 × 16 cm^3 specimens manufactured are first dried to a stable mass before being subjected to the crushing operation. First, the specimen is placed on the 4 × 4 × 16 cm^3 mortar prismatic bending device, which in turn is attached to the machine (Figure 6). This device complies with standard EN 196.1. It comprises two lower blades spaced 100 mm apart and one upper blade, with a blade diameter of 10 mm. The latter weighs 11 kg. The three-point bending test was carried out in accordance with French standard EN 1015-11. Flexural strength was determined using the following expression:

$$R_f = \frac{\frac{3}{2} \times F \times L}{h^3} \tag{2}$$

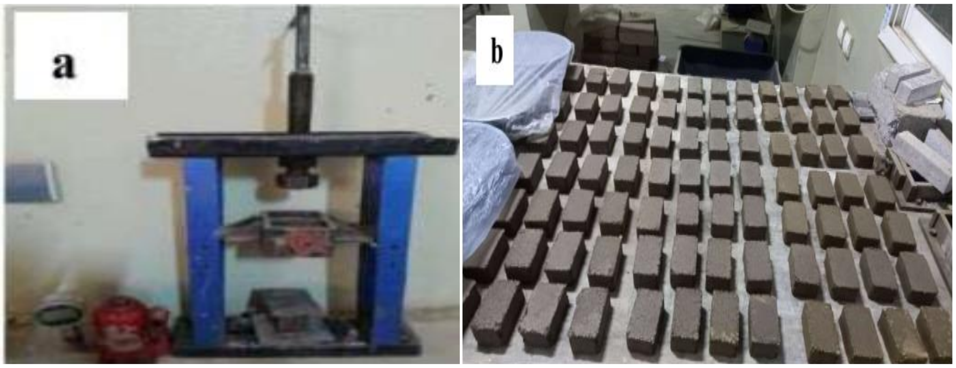

Figure 5. a) manual press, b) 4 × 5 × 8 cm^3 test pieces.

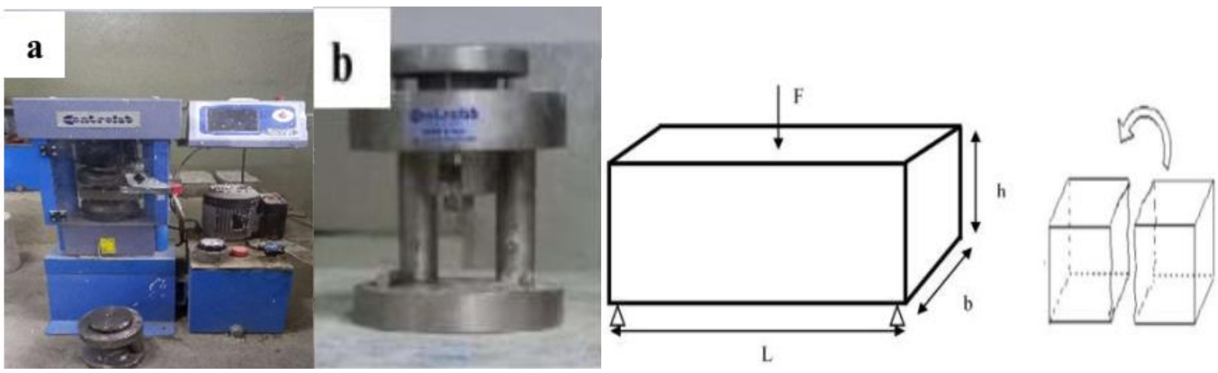

Figure 6. a) CBR press, b) bending device.

where Rf: breaking strength (MPa), F: breaking load (N), h: specimen height (mm), and L: distance between the two supports (mm).

Compressive strength

After the specimen has been broken, the two pieces are recovered and subjected to a compression test. The device for compression tests on mortar half-prisms 40 × 40 × 160 mm (to be inserted in the test space of a machine) with dimensions of Ø 140 × 180 mm and a weight of 7 kg. The device is established according to EN 196-1 / EN ISO 679 / ASTM C349. The CBR press and compression device are shown in Figure 7. Compressive strength is determined according to the following formula:

$$R_c = \frac{F_c}{a^2} \tag{3}$$

where Rc: compressive strength (MPa), Fc: breaking load (N), and a: edge of bearing surface (mm).

Thermal characterization

The hot wire method was used to determine thermal conductivity. The other thermal characteristics were deduced by calculation. The apparatus used is as shown in Figure 8.

This FP2C device is equipped with:

1) A probe for determining thermal conductivity using the hot-wire method.
2) Simulation software.
3) An acquisition box.

To set up the device, the probe is first connected to the acquisition box and sandwiched between two identical test specimens (same material), and a flow of heat is applied. The following equation relates thermal conductivity to temperature vs. time:

$$\Delta T = \frac{q}{4\pi\lambda} \times (\ln(t) + cste) \tag{4}$$

where λ: $W.m^{-1}.K^{-1}$ thermal conductivity, q the injected linear flux in W/m, ΔT the temperature difference in K, and the test duration in s. For reliable results, testing is recommended. CSTB developed the probe principle and device. They are based on ASTMD5930-97 and RILEM recommendation AAC 11-3 (Benmansour, 2015).

Thermal resistance

Thermal resistance (R) is used to measure the insulating capacity of materials for a specific thickness. It is expressed in $m^2.K.W^{-1}$. The

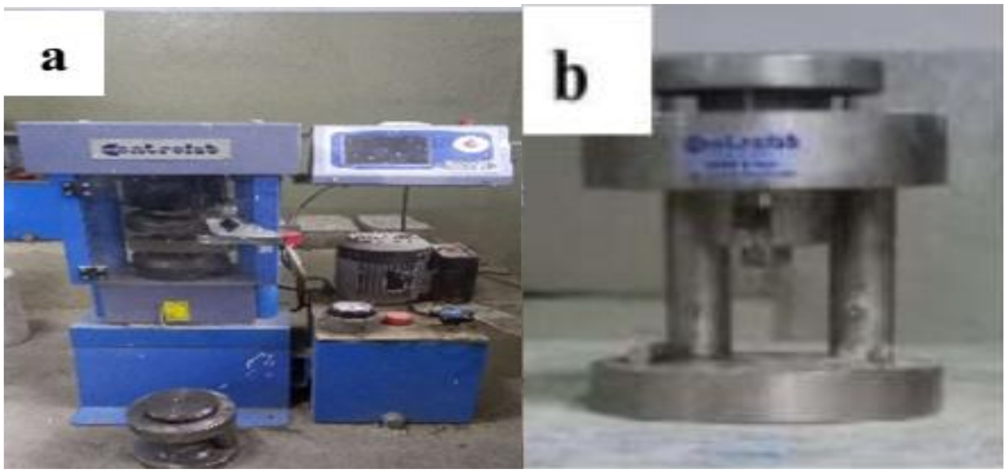

Figure 7. a) CBR press, b) compression device.

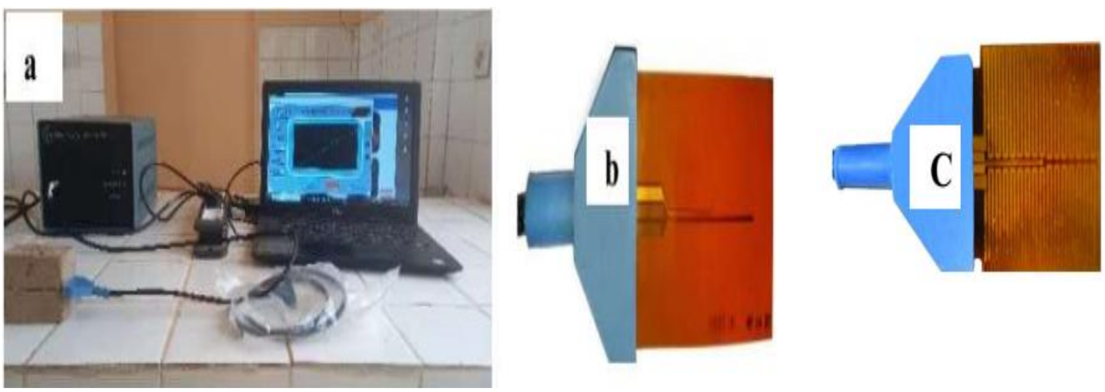

Figure 8. a) FP2C device, b) hot-wire probe, and c) hot-plane probe.

higher the thermal resistance of a wall, the more insulating it is. This measurement is mainly used in the field of thermal insulation. However, in this study, thermal resistance is measured using a real wall with a thickness of 20 cm. It is calculated as follows:

$$R_{th} = \frac{e}{\lambda} \quad (5)$$

where R is $m^2.K.W^{-1}$ thermal resistance, e is (m) insulation thickness, and λ is $W.m^{-1}\,K^{-1}$ thermal conductivity.

RESULTS AND DISCUSSION

Capillary absorption test

The results of the absorption coefficient as a function of wood ash addition are as shown in Figure 9.

It can be seen that water absorption increases as the percentage of wood ash increases for both soils. The minimum value obtained is that of the specimens without adding wood ash. The maximum value is 82.08 g/cm² for the EE soil with 12% wood ash, while for the EM composite, it is 71.40 g/cm². This value is equal to 26.50 g/cm² for the EE soil without the addition of wood ash. The same results were found by Benmansour (2015) who shows that the addition of date palm wood fibers increases water absorption. At 10% wood ash absorption is similar for both soils. The load applied for compaction affects water absorption, because if the specimens were compacted with a load of less than 4.30 MPa, the absorption coefficient would have increased. This is probably due not only to the porous structure of the soil but also to the compaction pressure. Furthermore, this increase also indicates that wood ash has a lower capacity to fill pores than clay soil. This can be attributed to variations in the composition and microstructure of the ash, which affect its ability to develop water-permeable porosity. According to Izemmouren (2016), almost all bricks can absorb water by capillary action. Furthermore, this characteristic is clearly distinct from the ease with which water can penetrate a brick (Herki, 2017).

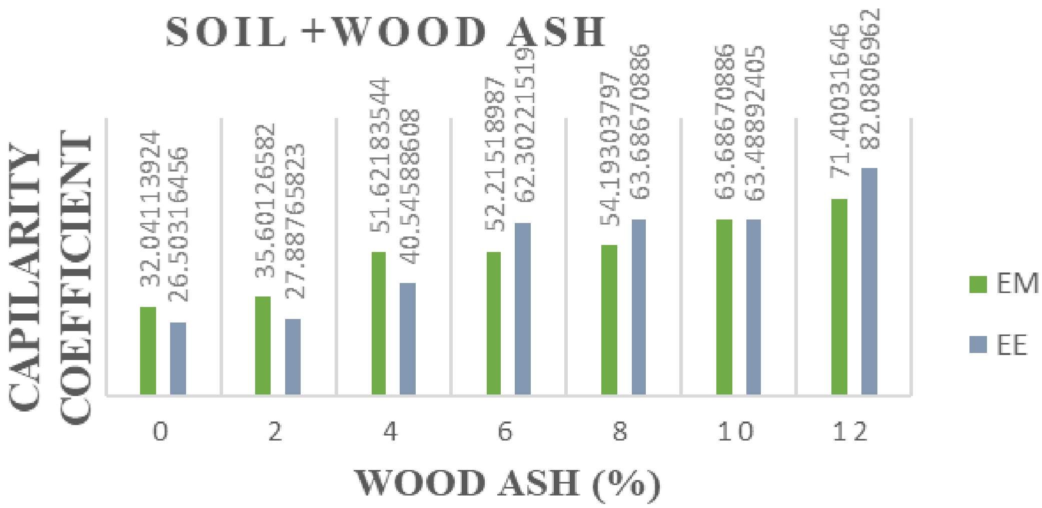

Figure 9. Evolution of the absorption coefficient as a function of the addition of wood ash.

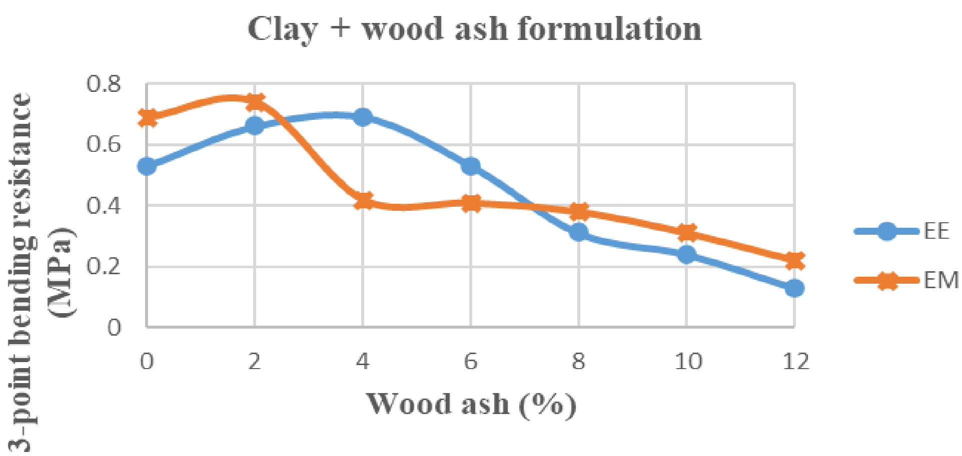

Figure 10. Bending strength.

Mechanical behavior of the two soils

Bending test

Figure 10 shows the evolution of the curves as a function of the percentage of wood ash.

It is clear that incorporating ash into the raw earth does not improve the mechanical properties of the specimens. This reduction in strength is due to the role played by wood ash in the mixture. In bending, from 0 to 4% of wood ash, the strength value for EE soil increases. Above 4% wood ash in the mixture, a descending peak for this same soil can be seen. However, for the EM soil, 2% wood ash is the maximum content with a flexural strength value equal to 0.74 MPa. In fact, 8% of the wood ash is the maximum rate that can be used in the mixture, because beyond that, a lack of adhesion between the wood ash and the soils studied was observed, which leads to a very sharp reduction in strength caused by the sintering phenomenon. The sudden drop in bending strength is due to the breaking of the atomic bond. It diffuses almost immediately through the material (Milohin, 2019). The existence of defects on a microscopic scale also represents a weakness in the block and could affect its fracture and cracks inside the blocks.

Compressive strength

The curves as shown in Figure 11 give a general idea of the experimental results of the compression test. From 0 to 4% of wood ash, the compressive strength increases

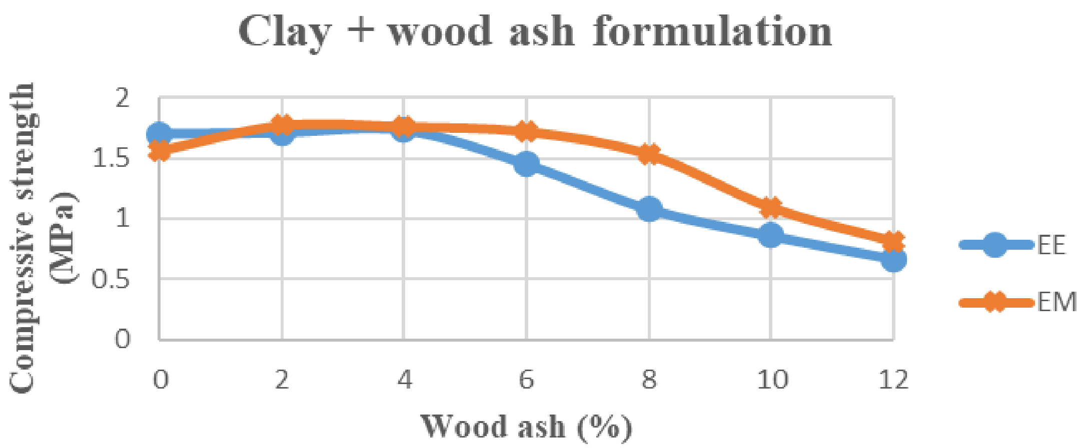

Figure 11. Compressive strength.

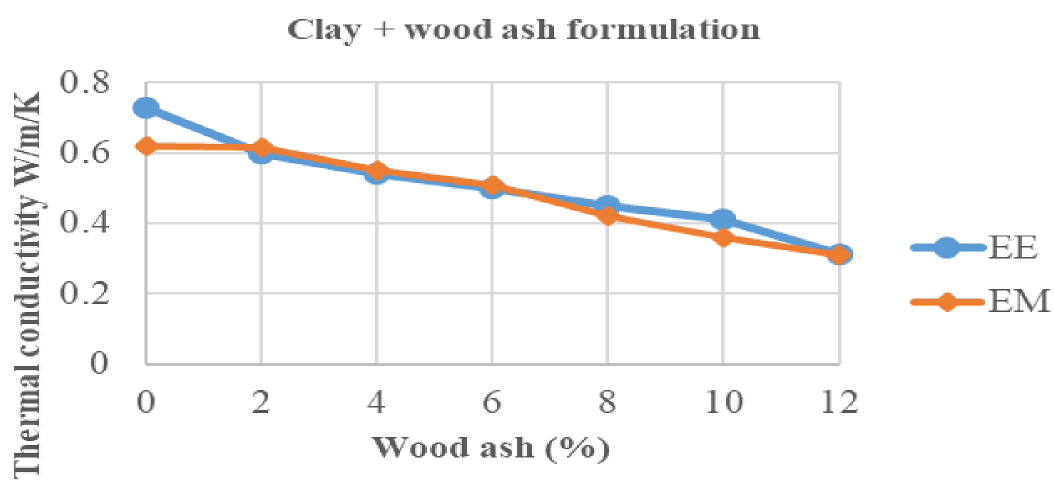

Figure 12. Variation in thermal conductivity depends on the addition of wood ash.

slightly for EE soils. Above 4%, the compressive strength decreases until the lowest value of 0.67 MPa is reached at 12% for the EE soil. For the EM soil, the compressive strength increases up to 2%. Above 2% wood ash, the strength drops to its minimum value of 0.81 MPa at 12% wood ash. It should be noted that, for the purposes of this work, the stress applied to the specimens is 4.30 MPa.

It can be deduced that the stabilization of the soil by the wood ash gives admissible mechanical resistances since these mechanical resistances increase with a certain rate of wood ash. Bachir (2014) recommended minimum mechanical strength values for the construction of an R+1 building:

1) Compressive strength: 2 kg.cm^{-2} (0.2 MPa).

2) Tensile strength: 0 MPa.

From the aforementioned, it can be said that the analysis of the results shows us that the strength with wood ash reinforcement exceeds certain strengths of the specimens without the addition of wood ash. This result can be explained by the natural behavior of wood ash and its chemical composition.

Thermal characterization

Thermal conductivity of materials with wood ash

Figure 12 shows the evolution of the thermal conductivity of clay blocks as a function of wood ash content.

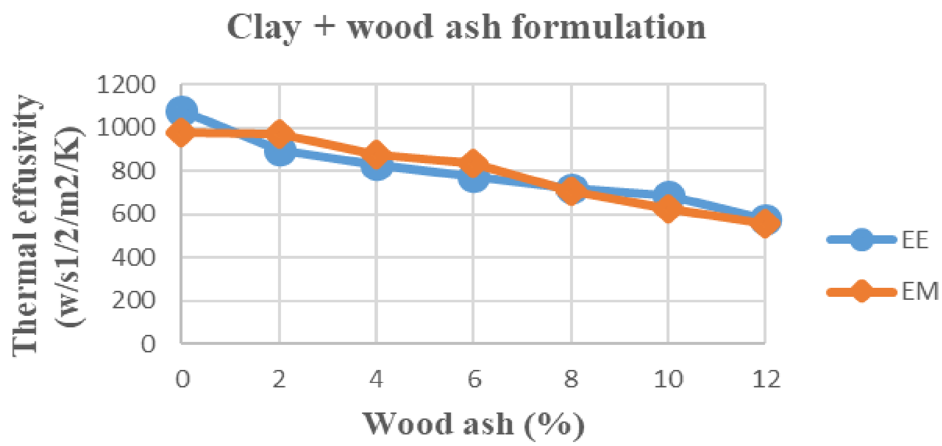

Figure 13. Variation in thermal effusivity as a function of wood ash.

The higher the wood ash content, the lower the thermal conductivity of the samples. Thermal conductivity is therefore inversely proportional to the dosage. From 2 to 8% wood ash in the mixture, the conductivity values of the two soils are close. However, at 10% wood ash, the EE soil has a slightly higher value than the EM soil. In addition, above 8% wood ash in the mixture, a sintering phenomenon on the manufactured specimens was observed, and this is due to the non-adhesion of the clay with the wood ash. In addition, the pure clay matrix is a little dense because the clay particles are very fine and the presence of the wood ash creates pores in the mixture, which helps to reduce thermal conductivity. This result is in agreement with the work of Nguyen (2009). Porous materials are considered to be better insulators, while less porous materials (dense and absorbent) have high acoustic insulation properties (Kellati and Bouardi, 2007). Wood ash is obtained from fibrous materials, which are naturally light, and the presence of wood ash in the mixture makes it possible to create voids in the specimens produced. Other research studies have confirmed that thermal conductivity depends on parameters such as the nature of the material components (Zhang et al., 2017) and porosity (Marmoret et al., 1995). Some authors have revealed that the thermal behavior is therefore generally in phase with the evolution of porosity (Mansour et al., 2016). However, it can be concluded that the decrease in thermal conductivity is due to the increase in porosity of the clay matrix plus ash.

Thermal effusivity as a function of the addition of wood ash

Figure 13 shows the thermal effusivity of the specimens as a function of the different percentages of clay and wood ash.

A decrease in thermal effusivity with increasing wood ash percentage for all two soils is as shown in Figure 13. Thermal effusivity is defined by the square root of conductivity, density, and heat capacity ($E = \sqrt{\lambda}.\ \rho.\ Cp$). Indeed, the three thermal characteristics such as λ, Cp, and the ρ decrease as a function of the increasing percentage of wood ash, so the square root of their product also decreases. For example, with 2% wood ash, the effusivity is around 90% compared to the clay matrix without wood ash. However, it can be deduced that for all two soils studied, wood ash favors a decrease in thermal effusivity. This means that a material with a low thermal effusivity is unlikely to heat up or cool down in response to temperature variations.

Thermal diffusivity as a function of wood ash percentage

Figure 14 shows the variation in thermal diffusivity as a function of the percentage of wood ash. There is a decrease in thermal diffusivity as the percentage of wood ash increases, which means that both soils diffuse less as the percentage of wood ash increases. Thermal diffusivity involves the lambda thermal conductivity and heat capacity of a material. The lower the thermal diffusivity value, the longer it will take for the heat front to penetrate the thickness of the material.

Conclusion

The presented research evaluates the thermo-hygro-mechanical properties of prismatic specimens made of

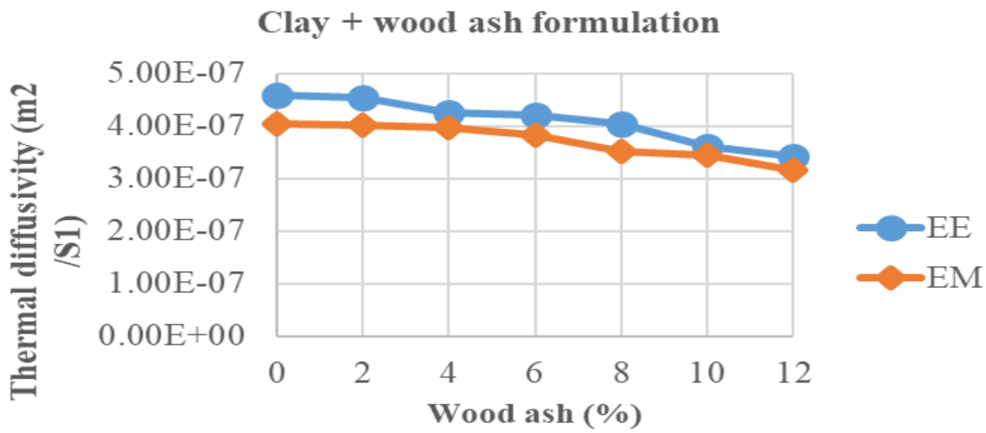

Figure 14. Thermal diffusivity as a function of wood ash.

compressed earth (BTC) sourced from two brickwork quarries in Abéché, Chad. The experimental results show that:

1) The incorporation of wood ash into the BTC matrix improves the absorption capacity, thereby weakening the materials.
2) The mechanical characteristics of the specimens are better for a wood ash content varying between 0 and 4%for the EE soil and 0 to 2% for the EM soil.
3) In addition, the specimens manufactured with the addition of wood ash have better thermal insulation than those manufactured without the addition of wood ash.

Consequently, it reveals that the nature and content of the stabilizer incorporated into the material are influential factors in compressive and flexural strength as well as thermal properties. In view of the mechanical performances recorded for the two soils studied, it would be interesting to remedy the defects due to the adhesion of these products, in order to guarantee sufficient physical and mechanical properties for building applications.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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