RESEARCH ARTICLE OPEN ACCESS

Thermal and Shrinkage Behavior of Compressed Earth Bricks Stabilized with Wood Biomass Ash

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Abstract:

Due to its ecological and economic benefits, earth construction has garnered global attention. Earthen bricks are widely embraced for their low energy consumption during implementation, aesthetic qualities, and favorable thermal inertia. However, earthen constructions exhibit a deficiency in strength and are susceptible to systematic cracks caused by shrinkage. Shrinkage and crack development significantly impact the performance and quality of earthen bricks. This experimental study aims to investigate the influence of wood ash, primarily derived from biomass combustion, on the thermal properties as well as the shrinkage behavior of compressed earth bricks. The results obtained suggest that an increase in wood biomass ash content from 5% to 20% effectively mitigates crack formation due to the stabilization of the earth through pozzolanic reactions. Additionally, the thermal conductivity of earthen bricks decreases with curing time and wood biomass ash content, ensuring good thermal comfort with a 20% soil substitution for wood biomass ash. This reduction is also associated with the size of the pores contained in the wood biomass ashes.

Keywords — **Wood biomass ash**, **Thermal properties**, **Shrinkage behavior**, **Compressed earth bricks**.

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I. INTRODUCTION

Earthen construction is an ancestral technique that deserves special attention in the current context of sustainable construction [1], [2]. This method, which uses locally available floors to make bricks and raise walls, has many advantages [3], [4]. It stands out in particular for its low environmental impact during manufacturing, its remarkable structural durability, undeniable aesthetic qualities, excellent thermal inertia, and minimal maintenance [5], [6].

However, this traditional technique is not without its flaws. Earthen constructions have some weaknesses, including limited mechanical strength, a tendency to crack due to shrinkage, and a particular sensitivity to water [5], [6]. Faced with these challenges, the scientific community has explored various stabilization solutions, using cement and lime as well as natural materials, biomass wastes, and industrial by-products [2], [5]-[7]. Compressed earth bricks are thus a solution for the future, combining ecology and energy savings [8].

Environmental concerns are becoming increasingly pressing, particularly regarding the carbon impact of building materials production and waste management, making it crucial to develop innovative alternatives [9], [10]. Using recycled materials and by-products to manufacture mud bricks is a promising solution, reducing energy consumption and carbon emissions [11], [12].

This study focuses specifically on developing new economical and environmentally friendly building materials, using wood ash from the calcination of biomass waste. The methodology adopted consists of making compressed earth bricks by incorporating different proportions of wood biomass ash (WBA) from (0% to 20% by weight) as a partial replacement for the soil and then compacting them under a pressure of 10 MPa. To evaluate their performance, the bricks are subjected to a curing period of 7, 28, and 60 days under controlled laboratory conditions (temperature 20 ± 2 °C, relative humidity 75 ± 5%), before proceeding with thermal properties and shrinkage tests.

II. MATERIAL AND METHODS

This study uses soil from a local source in Algeria. Specifically, the material is extracted from a quarry in Remila, in the country's north-east. This quarry is known for its large production of fired bricks.

The research also incorporates wood biomass ash, designated WBA. This biomass ash comes from burning domestic firewood, mainly used in rural homes. The originality of the approach lies in the direct use of these wood biomass ashes, without prior treatment, for the manufacture of compressed earth bricks. The soil and wood biomass ash (WBA) are shown in **Fig.1**.

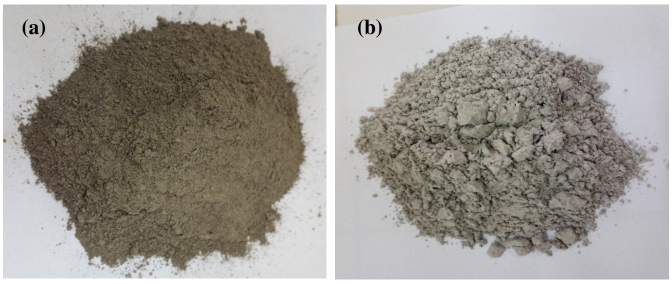

Fig. 1 Raw materials used, (a) soil, (b) WBA.

The analysis of the laser particle size distribution, illustrated in **Fig. 2**, made it possible to precisely characterize the composition of the materials studied. The results reveal that the soil used consists mainly of silt (87%) and clay (12%). It is important to note that this clay content is below the minimum thresholds recommended by the AFNOR NF XP 13-901 [13] standard for the manufacture of compressed earth bricks.

The particle size analysis of wood biomass ash (WBA) highlights an excellent composition: 96% of the particles are smaller than 20 µm.

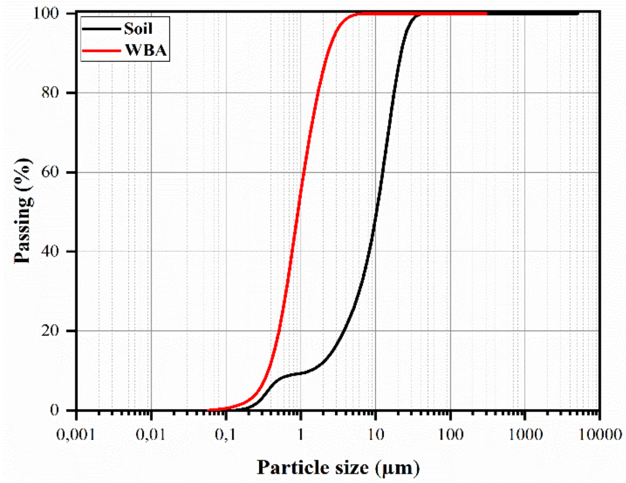

Fig.2 Particle size distribution of soil and WBA.

To complete the soil characterization, several physical properties were evaluated and documented in **Table 1**. These analyses include the determination of the Atterberg limits, carried out by the NF P 94-051 [14] standard, and the methylene blue test, carried out following the requirements of the NF-P18-592 [15] standard.

TABLE I
PHYSICAL PROPERTIES OF SOIL.

Physical properties	**Soil**
Methylene Blue Value	2.7 g/100g
Limits of Atterberg	
Plasticity limit Wp (%)	19
Liquidity limit WL (%)	39
Plasticity index Ip (%)	20

The mineralogical composition determined by X-ray diffraction (XRD), summarized in **Fig. 3**, shows that the main phases present in the soil and wood biomass ash are calcite and quartz. The soil also contains kaolinite, while the wood biomass ash has calcia.

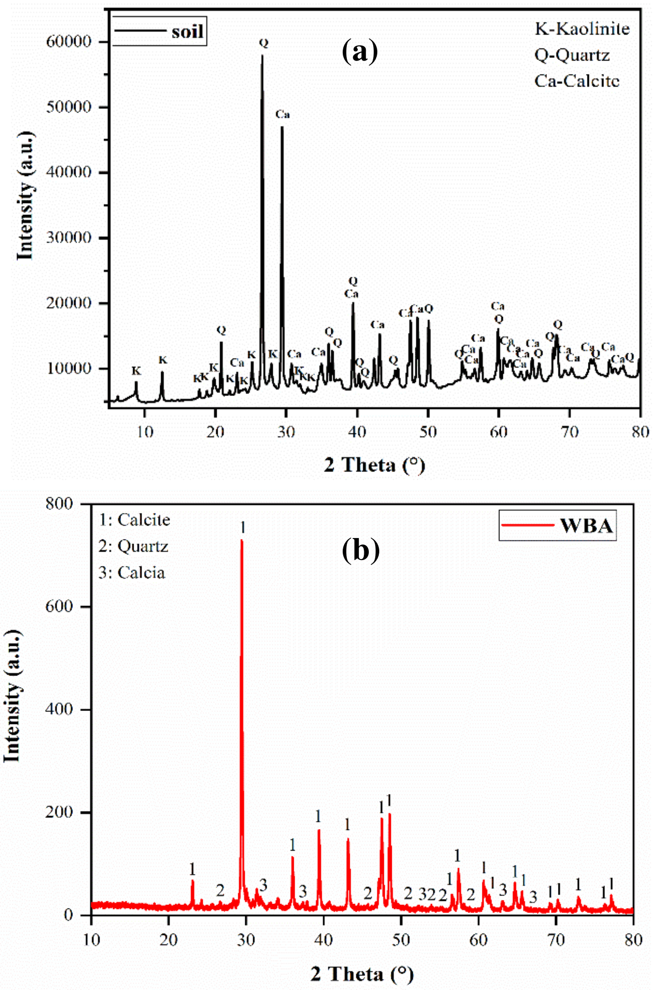

Fig. 3 XRD of raw materials, (a) soil, and (b) WBA.

A. *Manufactured of compressed earth bricks BWBA(0-20%)*

Various mixtures of stabilized compressed earth bricks have been developed by incorporating 0% to 20% of wood biomass ash (named BWBA(0-20%)). These mixtures were intended to partially replace traditional bricks in five different proportions: 0, 5, 10, 15, and 20% of WBA. The manufacturing process followed the following steps: After drying for 24 hours at 105 °C in an oven, the samples were mixed and homogenized using a mixer (**Fig. 4 (1)**). Water was added gradually until the desired moist consistency was achieved. The mixture was then placed in a parallelepiped mold with dimensions of 160 mm x 80 mm x 50 mm (**Fig.4 (2)**), and then compressed using a hydraulic press applying a uniaxial load of 10 Mpa (**Fig.4 (3)**). The compressed earth bricks were removed from the mold (**Fig.4 (4)**), and stored in a controlled environment (temperature of 20 ± 2 °C and relative humidity of 75 ± 5%) to cure for three distinct periods: 7, 28, and 60 days.

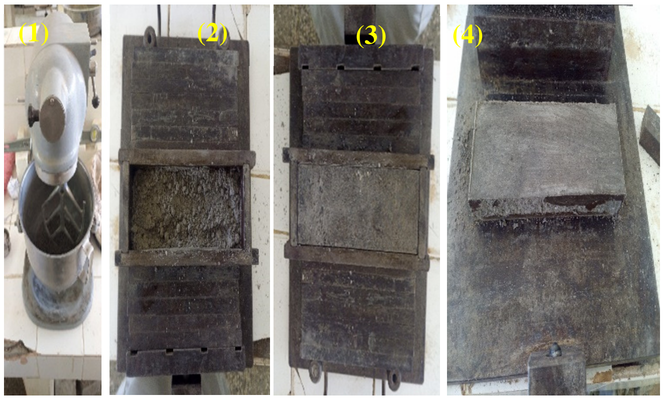

Fig.4 Manufacture of test samples; (1) mixing, (2), molding, (3) before demolding, and (4) demolding.

III. RESULTS AND DISCUSSIONS

A. *Thermal properties*

The high energy consumption required to maintain thermal comfort inside buildings has amplified the economic and environmental impacts in the construction sector. In this context, it is essential to develop lightweight, insulating, and environmentally friendly building materials to reduce energy consumption [16], [17].

Fig. 5 shows the evolution of the thermal conductivity of the bricks as a function of WBA content (0-20% by weight) and curing time (from 7 to 60 days). The thermal conductivity gradually decreases with increasing percentage of WBA, varying from 5 to 20%. For reference bricks, BWBA(0%), the thermal conductivity values decrease from about 1.061 W/mK at 7 days to 0.9565 W/mK at 60 days. The evaporation of water in the bricks over time, in an environment of ambient temperature (20 ± 2 °C) and relative humidity (75 ± 5%), led to an increase in porosity, thus reducing thermal conductivity. Bricks stabilized with 20% WBA offer better thermal insulation than BWBA(0%). For BWBA(20%), the measured thermal conductivity is 0.8055 W/mK at 7 days, 0.747 W/mK at 28 days, and 0.728 W/mK at 60 days. This decrease is explained on the one hand by the quantity of water consumed during the pozzolanic reaction between the soil components and the lime of the wood biomass ashes [18], and on the other hand by the microstructure of the soil used, which has a high porosity [19]. This particle-size structure (low percentage of clay) promotes the connection of the pores, forming a network that facilitates the passage between the pores of the bricks [20].

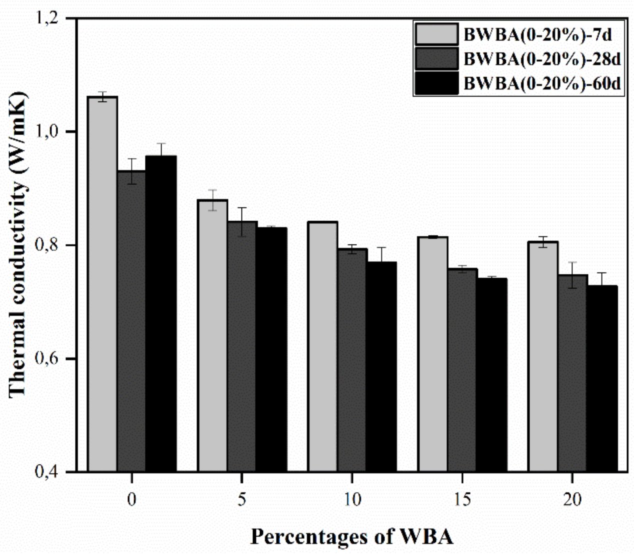

Fig. 5 Thermal conductivities of bricks BWBA(0-20%) at 7, 28, and 60 days.

B. Shrinkage behavior

The shrinkage behavior of compressed earth bricks incorporating wood biomass ash (WBA) was studied over 60 days with different substitution rates ranging from 0% to 20%. The results reveal a significant decrease in shrinkage with the increase in wood biomass ash content, a phenomenon particularly marked in silty-clay soil.

This reduction in shrinkage is mainly due to the interaction between the lime in the wood biomass ash and the clay particles in the soil. Indeed, lime causes a pozzolanic reaction that modifies the structure of the clays and forms cementitious bonds, thus stabilizing the matrix of the material. This stabilization decreases the clays' water absorption capacity and, consequently, their withdrawal potential.

Analysis of the results shows a gradual evolution of shrinkage over time, with values that systematically decrease for all mixtures from 0 to 60 days. The final measurements at 60 days clearly illustrate the positive impact of wood biomass ash: the ashless control brick (BWBA(0%)) shows a shrinkage of 104.16 mm, while the incorporation of 5%, 10%, 15%, and 20% ash gradually reduces the shrinkage to 103.82 mm, 103.40 mm, 103.02 mm, and 101.95 mm respectively. The substitution rate of 20% is therefore the most effective, allowing the lowest withdrawal value to be achieved.

This improvement in dimensional stability can also be attributed to the gradual development of cementitious bonds within the material and to the particle size of the wood biomass ash, which contributes to a better arrangement of the particles. The reduction in shrinkage is particularly significant for this type of silty-clay soil, which is naturally sensitive to dimensional variations. The results show that the incorporation of wood biomass ash is an effective technical solution to improve the dimensional stability of compressed earth bricks, with an optimum achieved for a substitution of 20%. Nagaraj et al., (2014) [21] Demonstrate the positive effect of lime on stabilizing clay soils, similar to the effect of lime-rich wood biomass ash.

The shrinkage-reducing behaviour is explained by complex physicochemical interactions between wood biomass ash and clay particles. The lime present in the wood biomass ash triggers a pozzolanic reaction that transforms the structure of the clays, creating more stable cementitious bonds. This process modifies the microstructure of the material by reducing inter-particle spaces, limiting water absorption and the mobility of clay particles.

The wood biomass ash particles fill the microvoids, optimizing the stacking and overall compactness of the material. At the same time, they partially neutralize the electrostatic charges of the clays, reducing water-particle interactions and limiting the molecular movements responsible for shrinkage. These combined mechanisms explain the gradual decrease in shrinkage with the increase in ash content, with the 20% rate representing the optimal stabilization rate for compressed earth bricks.

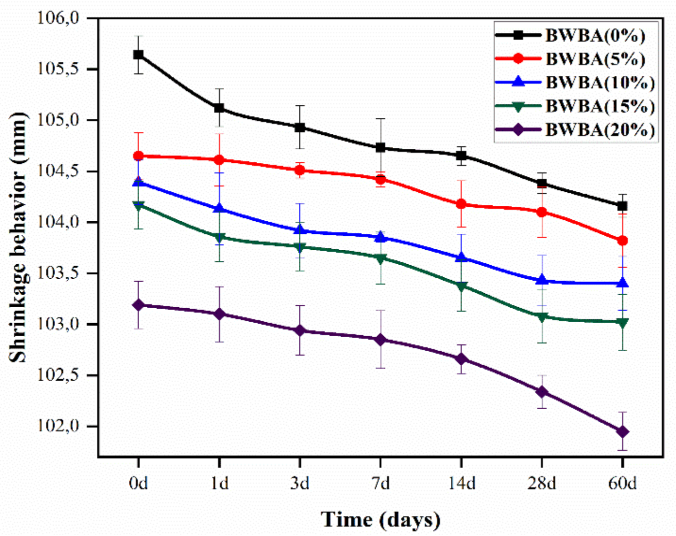

Fig. 6 Shrinkage behavior of bricks BWBA(0-20%).

C. The impact of biomass ash composition on the behaviour of compressed earth bricks

The high calcium oxide (CaO) content in wood biomass ash has remarkable potential to improve building materials, especially compressed earth bricks, through complex physicochemical mechanisms.

The pozzolanic reaction fundamentally transforms the microstructure of the material through the formation of stable cementitious compounds (hydrated calcium silicates and aluminates). This transformation generates several beneficial effects: reduction of thermal conductivity, improvement of insulation, dimensional stabilization, and limitation of volumetric variations.

At the microstructural level, wood biomass ash particles fill microvoids, optimize particle stacking, and increase mechanical strength. Neutralizing the electrostatic charges of clays reduces water-particle interactions, decreasing the potential for shrinkage and swelling.

Between 7 and 60 days, lime (CaO) triggers a reaction that gradually changes the structure of the material. The new mineral compounds create stable cementitious bonds, reducing porosity and limiting molecular movement and heat transfer. The interaction between lime and clay stabilizes the dimensions of the material through a continuous maturation process.

The incorporation of wood ash rich in CaO (0 to 20%) thus represents an innovative solution that recovers biomass waste while developing more sustainable building materials, with increased environmental and technical performance in the fields of green construction and thermal insulation.

IV. CONCLUSION

This study focuses on the recovery of wood ash from biomass waste in the manufacture of stabilized compressed earth bricks. The influence of wood biomass ash substitution (WBA) on the thermal conductivity and shrinkage behavior of compressed earth bricks was evaluated. Wood biomass ash, incorporated into silty-clay soil, allowed the development of a pozzolanic reaction, favored by its chemical composition rich in CaO. This means that the wood biomass ash can be used as a renewable, recyclable, and environmentally friendly raw material to produce sustainable compressed earth bricks.

From this study, several important conclusions can be drawn regarding the valorization of wood biomass ash as a partial substitute in stabilized compressed earth bricks:

First, the decrease in thermal conductivity observed with the increase in WBA percentages is mainly due to the evaporation of the water of the constitution during drying and the porous structure of wood biomass ash. The increase in air-filled pores reduces heat transmission through the material.

Secondly, this experimental investigation highlights the significant advantage of valorizing wood biomass ash with a high CaO content on the shrinkage behavior of compressed earth bricks. The presence of active CaO plays a crucial role in the development of the material's final characteristics.

Finally, the results of this experimental study demonstrate that the valorization of wood biomass ash as a partial substitute for silty-clay soil represents a promising solution for brick production. This approach offers an excellent compromise between thermal performance, shrinkage control, economics, and environmental considerations. It is perfectly in line with a sustainable construction approach, combining the use of industrial waste with the improvement of the properties of construction materials. This research thus contributes to the advancement of knowledge in the field of ecological building materials, while proposing a concrete solution for the recovery of biomass waste.

REFERENCES

[1] Rivera J, Coelho J, Silva R, Miranda T, Castro, Cristelo N. (2021). Compressed earth blocks stabilized with glass waste and fly ash activated with a recycled alkaline cleaning solution. Journal of Cleaner Production. 284, 124783.

[2] Mansour M.B, Jelidi A, Cherif A.S, Jabrallah S.B. (2016). Optimizing thermal and mechanical performance of compressed earth blocks (CEB). Construction and Building Materials, 104, 44-51.

[3] Balasubramaniam T, Sharan Karthik P.M, Sureshkumar S, Bharath M, Arun M. (2021). Effectiveness of industrial waste materials used as ingredients in fly ash brick manufacturing. Materials Today: Proceedings, 45, 7850-7858.

[4] Omar Sore S, Messan A, Prud'homme E, Escadeillas G, Tsobnang F. (2018). Stabilization of compressed earth blocks (CEBs) by geopolymer binder based on local materials from Burkina Faso. Construction and Building Materials. 165, 333-345

[5] Felipe - Sesé M. A, Pérez - Villarejo L, Castro E, Eliche - Quesada D. (2020). Wood bottom ash and GeoSilex: a by - product of the acetylene industry as alternative raw materials in calcium silicate units. Materials. 13, 489.

[6] Eliche - Quesada D, Felipe – Sesé M. A, Fuentes - Sánchez M. J. (2021). Biomass bottom ash waste and by - products of the acetylene industry as raw materials for unfired bricks. Journal of Building Engineering. 38, 102191.

[7] Çiçek T, Çinçin Y. (2015). Use of fly ash in production of light - weight building bricks. Construction and Building Materials. 94, 521-527.

[8] Eliche - Quesada D, Sandalio - Pérez J. A, Martínez - Martínez S, Pérez - Villarejo L, Sánchez - Soto P. J. (2018), Investigation of use of coal fly ash in eco - friendly construction materials: fired clay bricks and silica - calcareous non fired bricks. Ceramics International. 44, 4400-4412.

[9] D. Nagrockiene, A. Dauge, Investigation into the properties of concrete modified with biomass combustion fly ash. Constr. Build. Mater. 174 (2018) 369-375.

[10] S. Siddiqua, P.N.M. Barreto, Chemical stabilization of rammed earth using calcium carbide residue and fly ash. Constr. Build. Mater. 169 (2018) 364-371.

[11] Carrasco B, Cruz N, Terrados J, Corpas F.A, Pérez L. (2014). An evaluation of bottom ash from plant biomass as a replacement for cement in building blocks. Fuel. 118, 272-280.

[12] Khoudja D, Taallah B, Izemmouren O, Aggoun S, Herihiri O, Guettala A. (2021). Mechanical and thermophysical properties of raw earth bricks incorporating date palm waste. Construction and Building Materials. 270, 121824.

[13] AFNOR XP P13-901. (2001). Compressed Earth Blocks for Walls and Partitions: Definitions - Specifications - Test Methods - Acceptance Conditions. Saint-Denis La Plaine Cedex: AFNOR.

[14] AFNOR NF P 94-051. (1993). Soils: recognition and testing – Determination of Atterberg limits – Cup liquidity limit – Roll plasticity limit.

[15] AFNOR NF P 18-592. (1990). Aggregates - Methylene blue test - Stain method.

[16] Hany E. Fouad N. Abdel-Wahab M. Sadek E. (2021). Investigating the mechanical and thermal properties of compressed earth bricks made by eco-friendly stabilization materials as partial or full replacement of cement. Construction and Building Materials, 281, 122535.

[17] Arezki S., Chelouah N., Tahakourt A. (2016). The effect of the addition of ground olive stones on the physical and mechanical properties of clay bricks. Materiales de Construcción 66 (322).

[18] N. Boussaa, F. Kheloui, N. Chelouah, Mechanical, thermal and durability investigation of compressed Earth bricks stabilized with wood biomass ash. Constr. Build. Mater. 364 (2023)129874.

[19] Espuelas S, Omer J, Marcelino S, Echeverría A. M, Seco A. (2017), Magnesium oxide as alternative binder for unfired clay bricks manufacturing. Applied Clay Science. 146, 23-26.

[20] T. Miranda, R.A. Silva, D.V. Oliveira, D. Leitão, N. Cristelo, J. Oliveira, E. Soares, ICEBs stabilised with alkali-activated fly ash as a renewed approach for green building: Exploitation of the masonry mechanical performance. Constr. Build. Mater, 155 (2017) 65-78.

[21] Nagaraj, H. B., Sravan, M. V., Arun, T. G., & Jagadish, K. S. (2014). Role of lime with cement in long-term strength of Compressed Stabilized Earth Blocks. International Journal of Sustainable Built Environment, 3(1), 54-61.