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Experimental Study of the Effect of Palm Fiber Orientation on the Mechanical Properties of Compressed Earth Bricks Made From Pobè Clay

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Abstract

This study analyzes the influence of palm fiber orientation on the mechanical properties of compressed earth bricks (CEB) made from clay from Pobè (Benin), with a view to promoting sustainable local materials. Prismatic test specimens (40 × 40 × 160 mm) were prepared with fiber contents of 0%, 0.30%, and 0.40% of dry mass, with a length of 3 cm, in three orientations: horizontal, vertical, and random. The samples were subjected to simple compression tests (NF EN 13286-41) and three-point bending tests (NBN EN 1015-11) after 14 and 28 days of curing. The results show that incorporating fibers significantly improves the mechanical performance of BTCs. The optimal configuration corresponds to a dosage of 0.30% randomly oriented fibers, with a compressive strength of 12.5 MPa and a flexural strength of 5.5 MPa at 28 days. These results suggest that random orientation allows for better fiber mobilization and increased mechanical isotropy, thus offering a suitable solution for the production of sustainable building materials in a local context.

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Keywords

Palm fibers, clay, compressed earth bricks, mechanical strength, fiber orientation.

Introduction

The issue of sustainable development, combining economic growth and environmental protection, deserves careful consideration in all sectors of human activity, particularly in building and transport infrastructure. Infrastructure development (buildings, roads, and civil engineering structures), along with rapid advances in industrial technology, necessitates the intensive exploitation of natural resources and an increasing reliance on synthetic and chemical products in the search for higher-performance materials. This dynamic, while generating technological progress, leads to significant environmental impacts through the modification and degradation of natural ecosystems (1).

Access to decent housing is a fundamental right, but it remains a major challenge in many developing countries, such as Benin. A large portion of the population still struggles to find decent housing due to the high cost of modern building materials like cement and steel. This situation is largely due to dependence on imported materials, the lack of competitive local production, and the continued price increases linked to energy scarcity.

Only a minority with higher incomes can afford the systematic use of cement in construction. (2) which exacerbates inequalities in access to housing (3) (4).

The growing demand for housing, fueled by strong population growth, is increasing reliance on Portland cement. This material, although widely used, is a major source of pollution: the cement industry is responsible for 7 to 8% of global CO_2 emissions. (5) (6), which is approximately one tonne of CO_2 released into the atmosphere for every tonne of cement produced (7). While industrialized countries seek to reduce their cement consumption, developing countries are instead seeing their demand grow rapidly, which exacerbates the environmental and economic consequences.

In this context, it becomes imperative to explore local, economical, and ecological alternatives. Earthen construction, used for centuries in many parts of the world, appears as a relevant solution. Earth is a widely available, inexpensive material with a low carbon footprint, and possesses interesting properties in terms of thermal insulation and humidity regulation. (8) (9) In West Africa, and particularly in Benin, this resource remains abundant but still under-exploited. Its development could help reduce dependence on imported materials, while promoting more sustainable construction practices.

However, earthen constructions have certain limitations: they are prone to cracking due to shrinkage, vulnerable to water, and often exhibit mechanical resistance lower than modern standards. (10) To overcome these weaknesses, various approaches have been proposed, including chemical stabilization through the addition of cement or lime. (11) (12) and physical stabilization through reinforcement with natural fibers (13)

The second, which utilizes local resources such as sisal, jute, coconut, or palm fibers, represents a promising alternative. (14) It improves ductility and limits crack propagation. (15) and strengthens the flexural strength of the BTC (16) (17). Hejazi *et al.,* (2012) confirm in a comprehensive review that random reinforcement with natural fibers significantly improves the mechanical properties of soils, validating the traditional empirical approach with modern predictive models (18) . Natural fibers have indeed long been used as an additive in the manufacture of earthen materials. (19) (20) allowing for a reduction in shrinkage cracking and improved mechanical strength (21) (22) (9) Several studies have also demonstrated that the presence of fibers has a positive effect on the mechanical behavior of the composite, increasing its ductility compared to the brittle behavior of the matrix alone. (23) (24) (25) (26). Quagliarini and Lenci (2010) showed that adding straw and coarse sand to Roman adobes significantly improves mechanical strength and modifies the mode of failure, validating the ancestral empirical approach. (27). In the specific case of Benin, palm fibers constitute an abundant, renewable, and still largely untapped resource. Their integration into the production of compressed earth blocks (CEBs) offers a dual opportunity: improving the mechanical performance of local materials and reducing the ecological footprint of construction. (28) However, the performance achieved is highly dependent on parameters such as fiber length, dosage, and orientation within the matrix. Optimizing these parameters is therefore necessary to define reliable, reproducible processes adapted to the needs of local populations.

This study aims to answer the following question:

To what extent does the orientation of palm fibers influence the mechanical properties of compressed earth bricks made from Pobè clay?

The research hypothesis is that fiber orientation is a determining factor in the mechanical behavior of compressed earth blocks (CEBs). In particular, a random orientation would promote better stress distribution and more effective crack bridging, leading to an overall improvement in mechanical performance compared to controlled orientations. Furthermore, the use of local materials and the absence of hydraulic binders reduce the embodied energy of construction. The use of earth as a building material thus contributes to reducing greenhouse gas emissions and mitigating the risks associated with climate change.

Materials and Methods

Material

The final product to be tested is composed of two materials: clay and palm fiber.

Clay

The clay used in this study comes from the locality of Issaba, located in the commune of Pobè, in the Republic of Benin. The samples were taken at a depth of between 1.50 and 3.35 m, at latitude 7° 04' 52" North and longitude 2° 39' 00" East.

Physical characterization tests revealed a particle size of 92.12% passing through a 63 µm sieve and a plasticity index of 38.5%. According to the GTR classification, this is a highly plastic clay soil (Class F3). (29) This is also an inorganic soil with an organic matter content of 0.574%. This type of soil is representative of the clay formations found in several regions of Benin, notably in Zalimé in the commune of Zogbodomey, where previous studies have also highlighted similar behaviors in terms of swelling and compressibility (30) .

Figure 2 illustrates the macroscopic appearance of the Pobè clay in its dry state. Its color and fine texture indicate a particle size distribution dominated by clay particles, confirmed by the results obtained during the geotechnical characterization.

Palm fiber

The fibers used in this study were obtained in the locality of Igana, in Pobè. They have a length of 3 cm and were incorporated at rates of 0.30% and 0.40% of the dry mass. The 3 cm length was chosen based on previous work on compressed earth blocks (CEBs) reinforced with plant fibers. (31) These results show that a length between 2 and 4 cm represents an optimal compromise between crack bridging efficiency and ease of application during compaction. Fibers that are too short offer insufficient anchoring surface area in the matrix, while fibers that are too long tend to become entangled and disrupt the homogeneity of the mixture. (32) .

Dosages of 0.30% and 0.40% of dry mass were selected with reference to the range of contents commonly studied in the literature for natural fibers in compressed earth blocks (CEBs). (10) (31) (33) This places the critical reinforcement threshold between 0.25% and 0.75%, depending on the nature of the fiber and matrix. These two values define the optimal dosage and allow for precise identification of the threshold beyond which excess fibers degrade the compactness of the clay matrix.

Figures 3 and 4 show the palm fibers used, respectively in their raw state and after cutting to the chosen length of 3 cm.

Mechanical characterization tests

Three mechanical characterization tests were performed. Dry density was first determined using the standard Proctor test, in accordance with standard NF P 94-093. The flexural strength of the compressed earth blocks (CEBs) was then measured using the three-point bending test, according to standard NBN EN 1015-11. Finally, compressive strength was evaluated using the simple compression test, in accordance with standard NF EN 13286-41. These tests made it possible to assess the suitability of the material for manufacturing the samples and to characterize the influence of fiber orientation on the mechanical properties of the CEBs.

Methodology

Different formulations of compressed earth bricks based on clay and palm fibers were developed. The fiber contents (0%, 0.30%, and 0.40%) were chosen based on previous studies. (10) (31) The manufacturing protocol is summarized in Table 1. The fabrication of the BTCs (Bio-Construction Techniques) relies on the production of 35 prismatic specimens measuring 40 × 40 × 160 mm.

The setup includes 5 control specimens, devoid of fibers (0%), serving as a reference, as well as 30 reinforced specimens. The latter are prepared according to two dosage levels (0.30% and 0.40%) and three fiber orientation configurations, resulting in 6 experimental conditions, each tested on five specimens. The value retained for analysis is the arithmetic mean of the measurements. This experimental setup guarantees satisfactory repeatability of the measurements and statistical robustness of the results, in accordance with the requirements of standard NF EN 13286-41. Following this protocol, a two-layer approach was implemented: the prismatic mold was filled in two successive layers of equivalent volume, each compacted before the deposition of the next. Two fiber incorporation protocols were applied depending on the desired orientation:

- Controlled orientation (horizontal or vertical): after compacting the first layer, the fibers were manually placed in the mold according to the chosen orientation, respecting the prescribed dosage. The second layer of soil was then added and compacted.
- Random orientation: the palm fibers, previously cut to the chosen length, were incorporated directly into the clay matrix before molding. The homogenized mixture was then introduced into the mold in two successive layers, each being compacted.

After demolding, all test specimens were cured at a temperature of 20°C in the laboratory. The curing times considered were 14 and 28 days, in order to monitor the progressive evolution of mechanical performance.

Figure 5 illustrates the three-point bending test setup used in accordance with NBN EN 1015-11. The prismatic specimen (40 × 40 × 160 mm) is placed on two supports 100 mm apart, and a load is applied at its center at a constant rate until failure. The bending strength Rf is calculated using the formula: $Rf = 1.5 \times F \times L / (b \times h^2)$ (1), where F is the breaking load (N), L the span (mm), b the width and h the height of the section (mm).

Figure 6 shows the simple compression test setup carried out in accordance with standard NF EN 13286-41. The half-specimens from the bending test are subjected to an increasing uniaxial load until failure. The compressive strength $RC = F / (b \times h)$ (2) where F is the failure load at the cross-section of the specimen (40 × 40 mm^2).

Results and Discussion

Normal Proctor Test

The Proctor curve obtained indicates a maximum dry density of 1.57 t/m^3 for an optimal water content of 19.3%. These parameters were used for preparing the test specimens. It should be noted that this characterization was performed on the base clay. The influence of fiber incorporation on compaction parameters was not specifically studied in this work and constitutes a potential avenue for further investigation. Obtaining a high dry density at this water content confirms the good compactability of the Pobè clay, characteristic of highly plastic clay soils of type F3ts. This high dry density is directly linked to the good mechanical performance obtained: a more compact matrix offers a better fiber-matrix contact surface and reduces interstitial porosity, two factors favorable to the transfer of forces between the composite constituents. (23) (34) The incorporation of palm fibers does not significantly alter the Proctor parameters, indicating good physical compatibility between the two constituents.

Analysis of the evolution of mechanical performance between 14 and 28 days of curing reveals a significant improvement for the control compressed earth blocks (CEBs). Compressive strength increases from 3.1 MPa to 5.5 MPa (+78%), while flexural strength doubles, from 1.1 MPa to 2.2 MPa (+100%). This evolution reflects the progressive consolidation of the clay matrix during drying: water loss leads to a tightening of the clay layers and an increase in intercrystalline cohesion, a well-documented phenomenon for raw earth materials. (8) (23) Fiber-reinforced BTCs follow the same trend, with even more pronounced gains, demonstrating a synergy between matrix maturation and the progressive development of fiber-matrix adhesion during drying.

Fiber-matrix interaction mechanism

When a crack initiates under load, the fibers that cross the fracture plane resist its opening: they absorb some of the tensile stresses that the matrix alone cannot bear. This crack bridging mechanism is all the more effective when the fibers are well anchored and oriented in the direction of the principal stresses. The fiber-matrix interface also determines the quality of force transfer. Sufficient adhesion between fiber and matrix allows loads to be redistributed to the fibers before overall damage occurs, which explains the joint improvement in compressive and flexural strength documented here, consistent with the results of previous work. (35) (36) .Moreover Tang *et al.,* (2006) showed by scanning electron microscopy (SEM) that bond strength and interfacial friction dominate the benefits of fiber reinforcement in clay soils, with distinct behaviors depending on the cementation (37)

When a crack develops in the clay matrix, the fibers that cross the fracture plane ensure stress transfer through bridging. This mechanism limits crack opening, improves the material's ductility, and delays brittle fracture.

Three-point bending test

The results highlight a significant influence of fiber orientation on flexural strength. Random orientation exhibits the best performance, followed by horizontal and then vertical orientations. A clear hierarchy emerges: random orientation > horizontal > vertical.

This behavior can be explained by the crack bridging mechanism. In bending, tensile stresses develop in the tension zone of the specimen. A random orientation allows for a multidirectional distribution of fibers, ensuring that some of them are always favorably oriented to intercept cracks, regardless of their direction of propagation.

This mechanism is consistent with Taallah's observations (23). Conversely, controlled orientations induce anisotropic behavior, limiting the effectiveness of the reinforcement when the fibers are not aligned with the principal loading directions. This result confirms the directional dependence of fiber reinforcement, a well-established point in the literature on earth-fiber composites. (35) (36) Furthermore, the 0.30% dosage proves superior to 0.40% in bending: with random orientation, the increase from 0.30% to 0.40% results in a drop in bending strength. (38) From 5.5 MPa to 5.0 MPa, confirming the existence of a critical threshold beyond which excess fiber degrades matrix compactness. This observation has been made by other researchers for various plant fibers. (13).

Figure 10 illustrates the evolution of compressive strength at 14 days according to fiber orientation. At this stage, random orientation already leads to the best performance (≈ 11 MPa), followed by vertical and then horizontal orientations. The increase from 0.30% to 0.40% results in a slight decrease, attributable to fiber agglomeration which locally reduces the matrix compactness.

This figure confirms the percolation ceiling at 0.30%, where the optimal fiber distribution maximizes stress transfer, thus validating the chosen experimental design. Randomization excels due to its omnidirectional ability to accommodate microcracks under compression.

Simple compression test at 28 days

Figure 11 shows the compressive strength at 28 days as a function of fiber orientation. The improvement is clear: 5.5 MPa for the control BTCs, 8.9 MPa for the horizontal orientation at 0.30%, 10.15 MPa for the vertical orientation at 0.30%, and 12.5 MPa for the random orientation at 0.30%, representing a gain of 127% compared to the BTCs without fibers. Binici *et al.,* (2005) confirm these gains with straw fibers in mud bricks, where the fiber-matrix interface layers optimize stress transfer and meet ASTM requirements (39) These results exceed those obtained by Koffi & Konin (2024) on compressed earth blocks (CEBs) reinforced with fan palm (Borassus aethiopum Mart.) fibers in Côte d'Ivoire, ranging from 5.97 to 6.61 MPa for dosages of 0.2 to 0.8%. This difference can be attributed to the higher plasticity of the Pobè clay (IP = 38.5%) compared to the soil, resulting in a more cohesive base matrix that is more conducive to fiber-matrix anchorage. (24).

The superiority of vertical over horizontal orientation in compression requires explanation. Fibers arranged vertically along the compression axis effectively resist lateral matrix expansion and delay the initiation of oblique crack planes. Horizontal fibers are minimally mobilized in this loading configuration. Random orientation combines both effects and remains the most efficient, simultaneously mobilizing fibers in all directions. The 0.30% dosage confirms its optimal nature: at 0.40% and random orientation, the compressive strength drops to 10.6 MPa, a decrease of 15%. This existence of a limiting dosage beyond which the fibers degrade the matrix compactness is corroborated by Koffi & Konin (2024), who, for the African fan palm, also observed a decrease in compressive strength at just 0.4% fibers, regardless of their length, confirming that this threshold behavior is inherent to the African palm fiber family in clay matrices. (24) An excess of fibers creates weak interfaces and discontinuity zones within the matrix, decreasing its overall cohesion.

This critical threshold behavior, by Taallah (35) For date palm fibers, the results confirm that a low proportion of properly dispersed fibers promotes better compactness and optimal fiber-matrix adhesion. The results suggest that a fiber content of 0.30% constitutes, under the experimental conditions of this study, an optimal level for improving the mechanical performance of compressed earth blocks (CEBs). Beyond this value, particularly at 0.40%, a decrease in performance is observed, likely due to a degradation of matrix compactness and poor fiber dispersion. This increase in compressive strength has also been observed by other researchers for other plant fibers in the literature. (23) (40) (48) (41).

The orientation of the fibers directly influences the mechanical behavior of the composite. Random orientation ensures better mechanical isotropy, while controlled orientations induce anisotropic behavior dependent on the direction of loading.

The mold is filled in two successive layers, each being compacted. The incorporation of fibers can be carried out either in a controlled manner between the layers or randomly within the matrix.

Limitations of the study and perspectives on sustainability

The results obtained under laboratory conditions are encouraging, but the long-term durability of palm fiber-reinforced compressed earth blocks (CEBs) remains an open question. The clayey nature of the matrix gives the material an inherent sensitivity to water: in the presence of moisture, the clay layers tend to rehydrate and separate, which can lead to a progressive degradation of mechanical strength and differential wall swelling. (23).

Table.1 Manufacturing protocol for palm fiber-reinforced compressed earth blocks (CEBs)

Stage	Description	Settings
1	Materials preparation	Drying and sieving of the Pobè clay; cutting of the palm fibers to the desired length. Clay: F3ts, IP = 38.5%; Fibers: L = 3 cm
2	Dosage and mixing	Weighing of constituents; incorporation of fibers into the clay matrix according to the chosen protocol (guided or random). Dosages: 0%, 0.30%, 0.40% of dry mass
3	Compaction	The prismatic mold is filled in two successive layers; each layer is compacted. Mold dimensions: 40 × 40 × 160 mm; two-layer approach
4	Unmolding and curing	Immediate demolding after compaction; laboratory storage at a constant temperature: 20°C; Shelf life: 14 and 28 days
5	Mechanical tests	Measurement of resistance to simple compression and flexure at three points NF EN 13286-41; NBN EN 1015-11.

Table.2 Summary table of compressive and flexural strengths at 14 days and 28 days of fiber-free BTC

Property	**At 14 days**	**At 28 days**
Unconfined compressive strength (MPa)	3.1	5.5
Three-point bending strength (MPa)	1.1	2.2

Figure.1 Location of clay sampling (Source: Agbelele *et al.,* 2025)

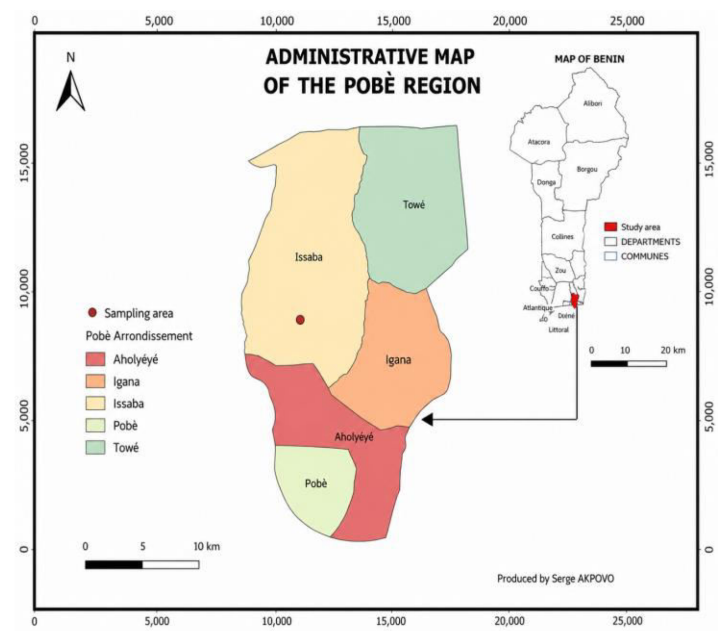


Figure.2 Sample of dry clay (AGBELELE, 2025)

Figure.3 Palm fibers (Source: Agbelele *et al.,* 2025)

Figure.4 Palm fibers of 3 cm (Source: Agbelele *et al.,* 2025)

Figure.5 Three-point bending test (Source: NBN EN 1015-11)

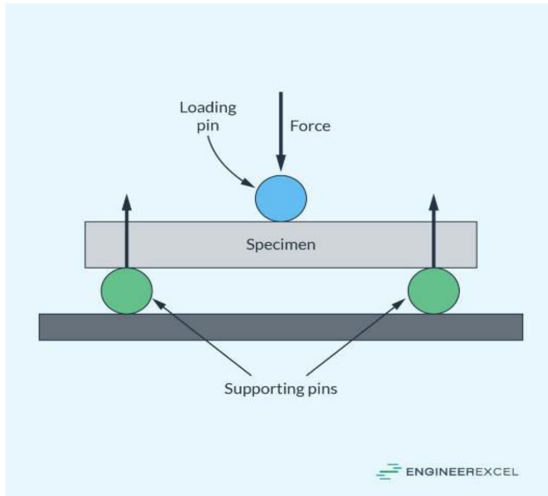


Figure.6 Compression test (Source: NF EN 13286-41)

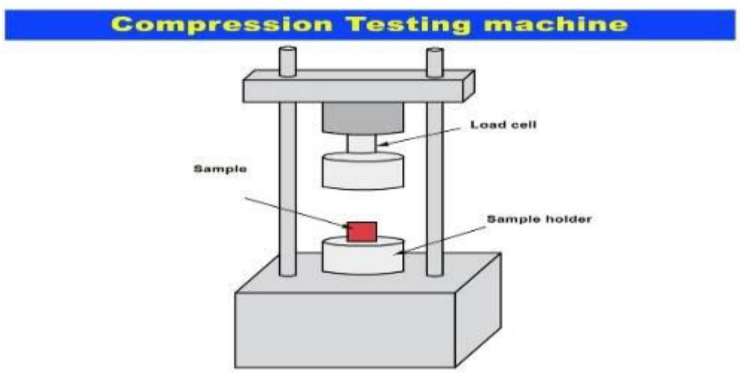


Figure.7 Proctor curve (Source: Agbelele *et al.,* 2025)

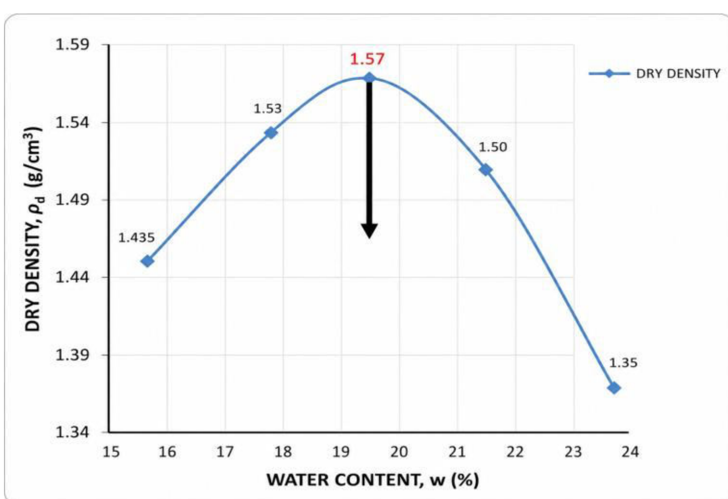
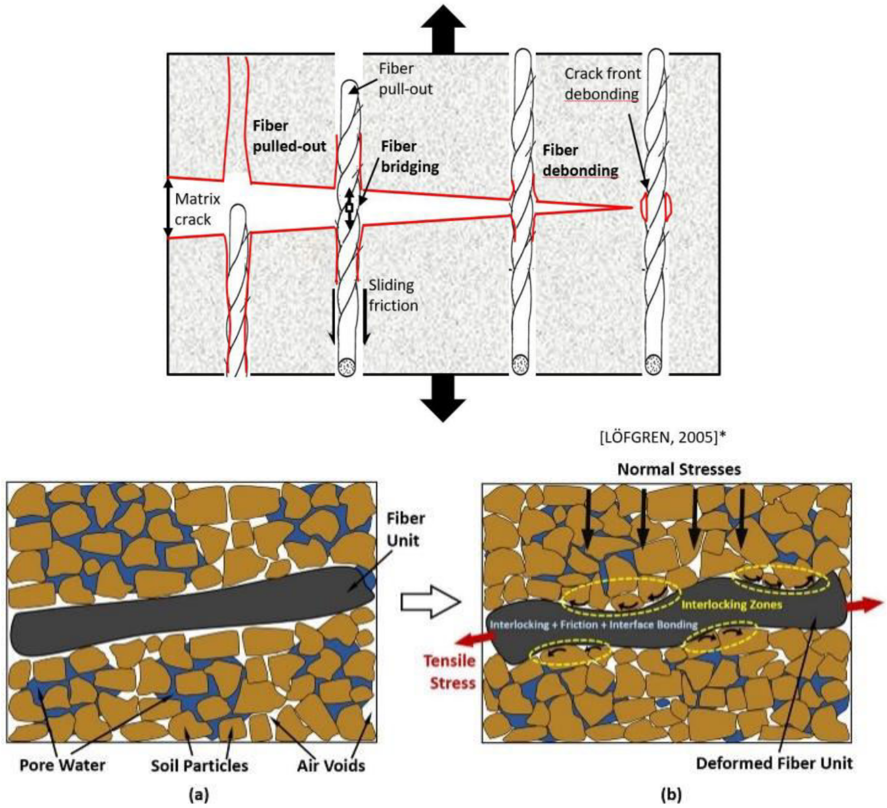


Figure.8 Crack bridging mechanism by fibers in the clay matrix**.**



(a) Adapted from Löfgren, 2005.
(b) Adapted from Gowthaman *et al.,* 2018, based on Millogo *et al.,* 2014.)

Figure.8 Flexural strength of BTCs with respect to fiber orientation (Source: Agbelele *et al.,* 2025)

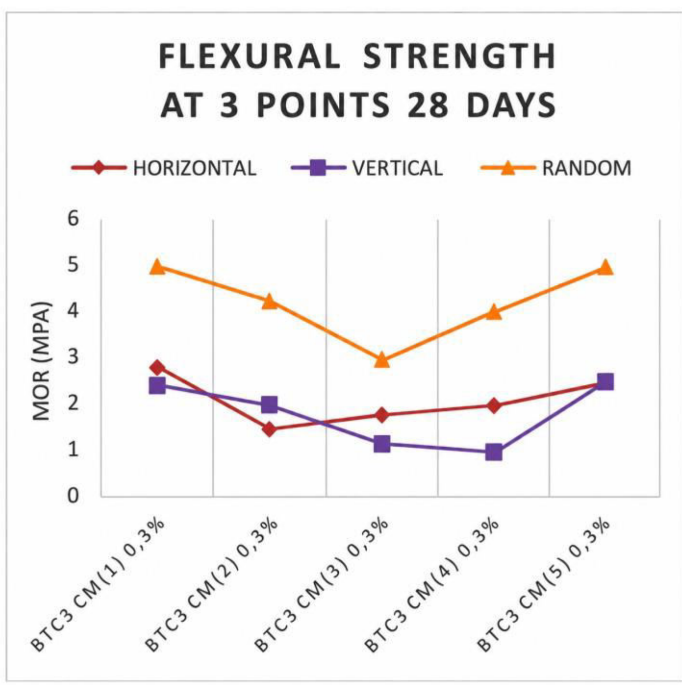


Figure.9 Compression resistance at 14 days with respect to fiber orientation (Source: Agbelele *et al.,* 2025)

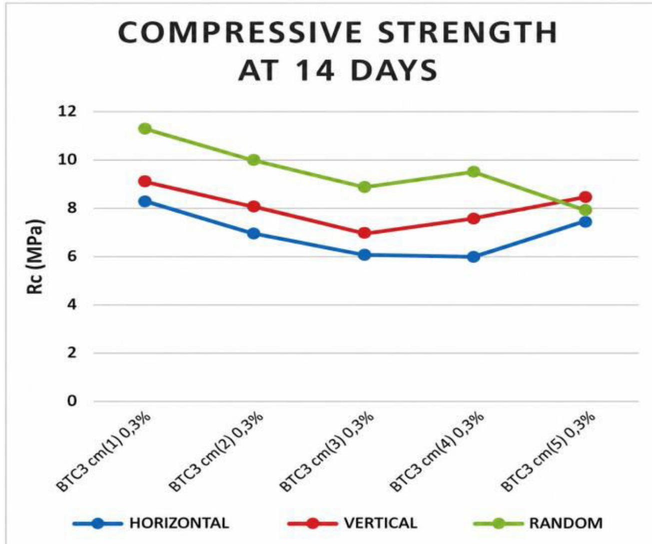


Figure.10 Compressive strength at 28 days with respect to fiber orientation (Source: Agbelele *et al.,* 2025)

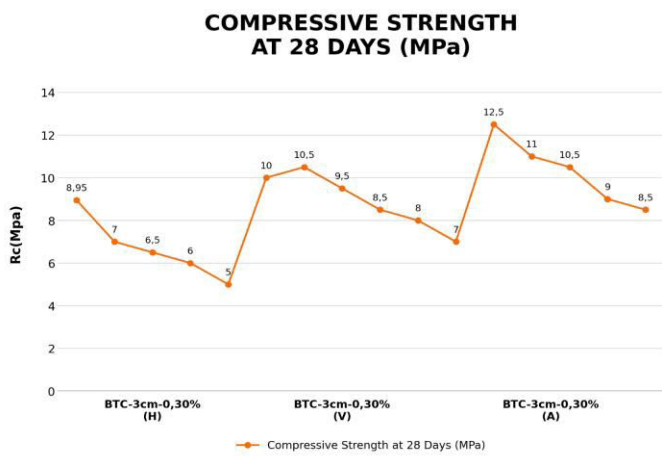


Figure.11 Fiber orientation configurations in BTCs: (a) horizontal, (b) vertical, (c) random (Source: adapted from Tavşanoğlu, 2014)

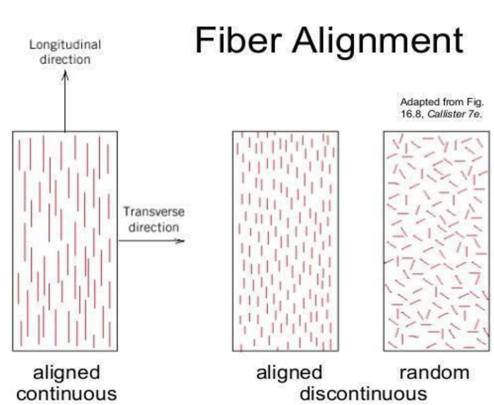


Figure.12 Manufacturing process for reinforced compressed earth blocks (two-layer approach) (Source: adapted from Open Source Ecology, 2024)

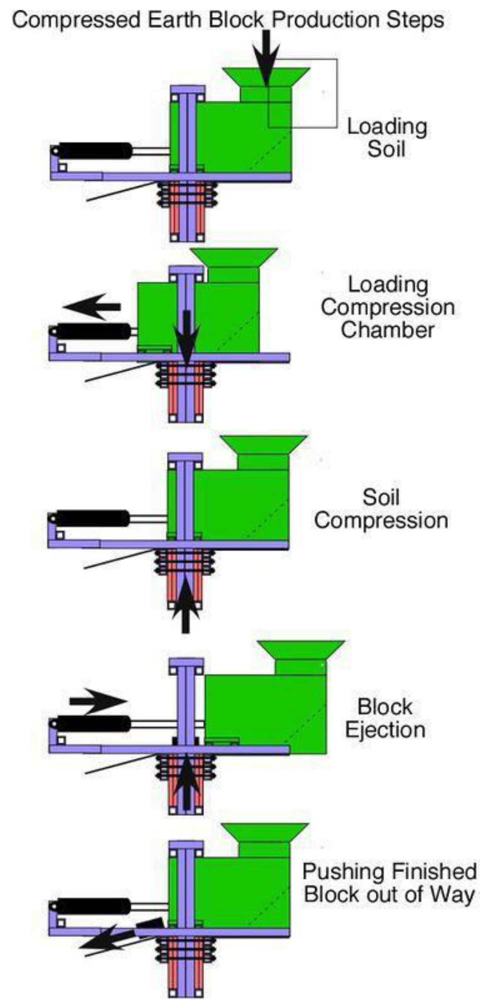
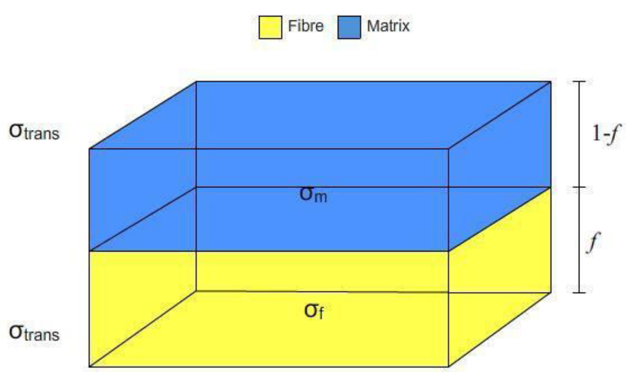


Figure.13 Interaction between fiber orientation and stress direction (Source: (adapted from DoITPoMS, University of Cambridge, 2025)



Several studies have documented this behavior for unstabilized BTC. Danso (16) It has been shown that immersion in water leads to a drop in compressive strength of up to 50 to 70% compared to dry measurements, depending on the clay's mineralogy. The Pobè clay, classified F3ts with a plasticity index of 38.5%, has a high content of swelling minerals, making it particularly vulnerable to this phenomenon.

Furthermore, the presence of untreated plant fibers can, over time, promote capillary absorption of water at the fiber-matrix interface and accelerate the composite's degradation. (35) (42) .

However, solutions exist to improve the water resistance of compressed earth blocks (CEBs). Taallah and Guettala (35) Studies have shown that alkaline treatment of date palm fibers improves fiber-matrix adhesion and reduces water absorption in the composite. Adding a small amount of hydraulic binder, such as lime or pozzolan, is another promising approach to stabilizing the clay matrix without compromising its carbon footprint. (8) These complementary approaches open up concrete prospects for the application of palm fiber-reinforced compressed earth blocks (CEBs) in exterior construction in Benin.

In conclusion, this study has highlighted the significant influence of palm fiber orientation on the mechanical behavior of compressed earth bricks made from Pobè clay in Benin.

The results show that incorporating fibers significantly improves mechanical performance, particularly at a content of 0.30% and random orientation, achieving a compressive strength of 12.5 MPa and a flexural strength of 5.5 MPa at 28 days. This represents respective gains of 127% and 150% compared to untreated BTC at 28 days of curing. The optimal dosage is established at 0.30% of the dry mass, for fibers with a length of 3 cm.

Random orientation appears to be the most relevant configuration due to its ability to efficiently mobilize fibers in all directions of stress, while also facilitating implementation. It combines excellent mechanical performance with ease of production, eliminating the need for manual fiber arrangement. This composite thus represents a viable alternative for infill walls in local construction, helping to reduce dependence on imported materials and the carbon footprint of the building sector. These results are part of a broader effort to valorize local clay soils in Benin, complementing previous work on soil stabilization in Zalimé (Zogbodomey), which also highlighted the importance of soil improvement techniques to ensure the durability of structures. (30) .

However, further investigations are needed to assess the material's durability, particularly with regard to water and wetting-drying cycles, as well as the effect of fiber treatments or mineral stabilizers. The tests were conducted under controlled laboratory conditions at a fixed curing temperature of 20°C, which does not necessarily reflect the actual climatic conditions in Benin. Furthermore, the material's sensitivity to water, inherent to the clayey nature of the matrix, is a limiting factor for its use in exterior construction without additional treatment.

In this perspective, future research could focus on: evaluating the durability of BTC under conditions of exposure to humidity and wetting-drying cycles; studying the effect of a low dosage hydraulic binder (lime or pozzolana); comparing performance with other locally available plant fibers, such as coconut or bamboo fibers; and evaluating the thermal and hygrometric properties of BTC for integrated application in sustainable construction.

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