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Article

Contribution of earth bricks reinforced with African locust bean pod powder (Parkia biglobosa) to sustainable construction in Togo: Characterization, formulation, mechanical performance, and recommendations

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Abstract: In response to the challenges of climate change, this study explores the use of moringa pod powder as reinforcement in the manufacture of compressed earth bricks to promote sustainable building materials. The objective is to evaluate the impact of African locust bean pod powder on the mechanical properties of the bricks. Two types of soils from Togo were characterized according to geotechnical standards. Mixtures containing 8% African locust bean pod powder at various particle sizes (0.08 mm, 2 mm, and between 2 and 5 mm) were formulated and tested for compression and tensile strength. The results show that the addition of African locust bean pod reduces the mechanical strength of the bricks compared to the control sample without pods, with strengths ranging from 0.697 to 0.767 MPa, compared to 0.967 to 1.060 MPa for the control. However, the best performances for the mixtures were obtained with a fineness of less than 2 mm. This decrease in performance is attributed to several factors, including inadequate water content and suboptimal preparation and compaction methods. Optimizing formulation parameters is necessary to maximize the effectiveness of African locust bean pods. This work highlights the valorization of agro-industrial waste, paving the way for a better understanding of bio-based materials and future research for sustainable construction.

Keywords: African locust bean pods; grinding fineness; mechanical strength; bio-based materials; compressed earth bricks

1. Introduction

The world is experiencing significant changes, particularly global warming, a real and major environmental problem requiring immediate attention (Aykut and Maertens, 2021; Ebekozien et al., 2024). This warming is primarily caused by human activities, such as burning fossil fuels, deforestation, and the construction sector, which release greenhouse gases (GHGs) into the atmosphere, trapping the sun’s heat (Khiratkar et al., 2022). Unfortunately, this phenomenon has several harmful effects on the planet, such as more intense and frequent heat waves and more severe weather events (Chamasemani et al., 2024). As the rate of urbanization increases, so does the demand for infrastructure and housing (Tleuberdinova et al., 2024). The construction sector contributes significantly to this problem due to its energy consumption (Gan et al., 2018). Indeed, during the production of building materials, the transportation of workers and materials to construction sites, and the operation of construction equipment, the energy consumed releases GHGs into the atmosphere (Cavalliere et al., 2019). Moreover, the production of building materials such as cement, lime, steel, and fired bricks generates substantial GHG emissions (Cavalieri et al., 2023; Chong et al., 2021) Consequently, buildings consume 40% of global energy and contribute to about one-third of global GHG emissions (Environment, 2010).

Over the past decades, the consequences of climate change have raised increasing awareness due to the continued impact of human activities on the planet (Archbold and Bonifacio, 2024). As a result, several international initiatives have been implemented, such as the Paris Agreement (Horowitz, 2016), aimed at combating climate change by addressing key sectors, including construction (Archbold and Bonifacio, 2024). This has created an urgent need for a paradigm shift in building design (Nina et al., 2023). This shift requires adopting new approaches, favoring construction solutions that are efficient, sustainable, and economically viable to reduce environmental impact.

The scientific community has adopted several strategies in light of this growing awareness. Among these is the development of bio-based materials focused on utilizing by-products from various production chains, including readily renewable lignocellulosic resources and their use in composite materials (Bledzki and Gassan, 1999; Elfaleh et al., 2023; Guo et al., 2023). Thus, studies explore the use of forest residues and agricultural by-products, such as wood chips (Guo et al., 2023; Liu et al., 2022), sawdust (Batool et al., 2021), corn stalks (Kouto, 2024), wheat straw (Jiang et al., 2021), rice bran (Ayite et al., 2011), and African locust bean pods (Banakinao et al., 2017), to formulate composite materials that can enhance the properties of basic materials. These bio-based materials offer highly relevant solutions and represent a tremendous opportunity to limit GHG emissions and store large amounts of carbon (Dejeant et al., 2021). Indeed, using bio-based materials in the construction sector helps reduce dependence on fossil resources. Their production requires less energy than conventional materials (Verspieren, 2024). Moreover, these materials can capture and store CO_2 during their growth through photosynthesis (Lecompte, 2024). Consequently, their use in construction actively contributes to combating climate change.

One of the potential bio-based materials in Africa comes from the production of African locust bean. African locust bean, also known as Parkia biglobosa or Parkia clappertoniana, is a perennial tropical legume from the Fabaceae family found in the tropical forests of Togo, Benin, Burkina Faso, Ivory Coast, Cameroon, Nigeria, and Mali (Bothon et al., 2023). It is a plant that can reach up to 30 meters in height, with reddish globular inflorescences and flat pods bearing seeds (Balogun et al., 2018; Paradis, 2009). Its roots, leaves, and bark are known for their medicinal properties (Balogun et al., 2018), while its seeds are valued for their food qualities, commonly called tchotu in Togo, afitin in Benin (Azokpota et al., 2006), and soumbala in Burkina Faso (Compaoré et al., 2020). The fruit pulp, particularly appreciated for its high nutritional value (carbohydrates, proteins, minerals) (Ahodegnon et al., 2018), is consumed. Meanwhile, extracts from its pods find an unexpected use in the construction sector. It is used as a natural binder to improve adhesion between clay tiles and the ground and more broadly to enhance the durability of earthen constructions in West Africa (Aguwa et al., 2016; Banakinao et al., 2016).

In Togo, particularly in the northern regions, tannin extracted from African locust bean pods was commonly used in villages long before the widespread use of concrete. African locust bean pods, soaked in water at room temperature, produced a decoction after a few days of infusion. This decoction was used to coat walls to protect them from the elements and to create terraces as durable as those made of concrete (Noukpakou et al., 2020).

Unfortunately, this practice is gradually being abandoned, leading to the loss of ancestral knowledge in favor of the widespread use of concrete and its derivatives. Yet, these materials are energy-intensive, emit significant amounts of GHGs, and create thermal discomfort, particularly high heat (Tossim et al., 2024), resulting in a negative environmental impact. In the face of climate change, it is crucial to reconnect with traditional knowledge by promoting the use of local and ecological materials to contribute to sustainable urban development.

This study aims to use African locust bean pods to manufacture bricks, employing a different implementation technique. So far, methods used primarily involved the decoction of tannins. Therefore, what using African locust bean pod powder, without infusion, and experimenting with different grinding fineness levels can achieve?

The main objective is to examine the use of African locust bean pod powder as a reinforcing material in the production of compressed earth bricks, evaluating its impact on the mechanical properties of the bricks to contribute to improved construction practices for sustainable urban development. Specifically, this involves: (i) Determining the properties of soil and African locust bean pods, focusing on the soil's compatibility for compressed earth brick production and the influence of different African locust bean pod powder fineness levels; (ii) developing different formulations of compressed earth bricks by incorporating African locust bean pod powder of varying grinding fineness; and (iii) evaluating the mechanical performance of the formulated bricks through compression and tensile tests.

2. Materials and methods

2.1. Materials

The materials used for this study come from two regions in Togo. The soil was collected in Tsévié (in the Maritime region in southern Togo) and Soumdina (located in the Kara region in northern Togo). The African locust bean pods were sourced from the Kara region north of Togo. Additionally, tap water produced by Togolaise Des Eaux (TDE) was used for this study. African locust bean pod powderis produced via a process involving cutting and grinding in a RETSCH knife mill, followed by sieving to achieve the desired particle size distribution. The tests were conducted in several laboratories, namely: The Mechanics Laboratory of the Polytechnic School of Lomé (EPL) for compression tests, the Soil Mechanics Laboratory of the Training Center for Road Maintenance (CERFER) for identification, classification, and formulation tests, and the National Building and Public Works Laboratory (LNBTP) for tensile tests. **Figure 1** provides an overview of the various materials used in this study.

(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Figure 1. The materials used, **(a)** African locust bean tree and pods; **(b)** African locust bean pod powder passing 2 mm; **(c)** African locust bean pod powder, passing 0.08 mm; **(d)** African locust bean pod powder with a diameter between 2 mm and 5 mm; **(e)** soil from Tsévié; **(f)** soil from Soumdina.

2.1.1. Soil characterization

Two soil samples were collected from two locations in Togo, the details of which are provided in **Table 1**.

Table 1. Sample collection locations.

Sample Number	Collection Location	GPS Coordinates	Region
1	Tsévié (Tse)	6°25′13.9″ N 1°13′20.3″ E	Maritime
2	Soumdina (Sda)	9°38′07.6″ N 1°16′00.6″ E	Kara

The tests performed to characterize the collected soils aim to determine their nature and geotechnical performance. These tests are carried out according to the following standards: Grain size analysis (NF P 94–056), Atterberg limits (NF P 94–051), Proctor (NF P 94–093), and simple compression and tensile strength tests (NF P 18–411). The equipment used for the various tests includes AFNOR series sieves, an electronic balance, a Casagrande cup, an oven, a dryer, a smooth marble plate, Proctor molds, a modified Proctor rammer, graduated cylinders, and a hydraulic press made in Togo.

Determination of the Water Content of Materials Using the Oven-Drying Method

Water content is a crucial parameter in determining certain mechanical characteristics of soil, especially its consistency, particularly for fine soils. The test, conducted following the NF P 94–050 standard, measures the water content of a soil sample by weight. To do this, a wet soil sample (mh) was dried in an oven at 105 ℃ for 24 h. The obtained dry mass (ms) is then used to calculate the water content (W) using the equation:

$$\mathrm{W} = ((\mathrm{mh} - \mathrm{ms})/\mathrm{ms}) \times 100 \tag{1}$$

Grain size analysis using the dry sieving method after washing

The purpose of this test is to determine the mass distribution of grains based on their size and to represent the different diameters of their masses graphically. Conducted according to the NF P 94–056 standard (Vandenbossche Maréchal, 1998), this test involves separating and fractionating a compacted soil into several categories of decreasing grain sizes using a series of sieves. A quantity of wet material (mh) is first soaked in water, and the elements are manually dispersed. The mixture is then passed through an 80 µm sieve, with a tray placed below to collect fine particles for subsequent sedimentation analysis. The remaining elements on the sieve are dried at 105 ℃ for 24 h. The dried material is then poured onto the top of a column of sieves, with increasing mesh sizes from bottom to top. **Figure 2** shows the washing test in **a**) and the sieving with the AFNOR sieve series in **b**). After sieving, the accumulated residue (Rc) on each sieve is weighed, and the percentage of cumulative passing (P%) is calculated using the equation:

$$\mathrm{P}(\%) = 100 - (\mathrm{Rc}/\mathrm{Ms}) \times 100 \tag{2}$$

where: P (%) is the cumulative passing percentage. Rc is the accumulated residue on each sieve. Ms is the dry mass of the sample soaked in water.

(a) **(b)**

Figure 2. Granulometric analysis by sieving after dry washing, **(a)** soil washing; **(b)** sieving with the AFNOR sieve series.

Granulometric analysis by sedimentation method

This test complements the granulometric analysis by sieving. It becomes necessary when, after sieving, the percentage of particles passing through the 80 µm sieve exceeds 10%. The material obtained from the 80 µm sieve, along with the washing water from the soil sample, is collected in a container, siphoned, and then dried in an oven at 105 °C. Once dry, the material is disaggregated using a pestle in a mortar and then homogenized. A sample of 80 g ± 10 g is then taken, prepared by the NF P 94–057 standard (Bazus et al., 1991), and placed in a solution in a 2000 cm^3 test tube. Using a densimeter and a thermometer, the evolution of the solution's density, the immersion depth of the densimeter, and the solution's temperature are measured over time. These data are then used to determine the percentage (P) and the diameter (D) of the precipitated grains at a given time (t).

Atterberg limit tests

The liquid limit and the plastic limit, known as Atterberg limits, are essential parameters for characterizing the nature of the soil and its consistency state (AFNOR EDITIONS, 1993). These tests are performed on soils that have passed through a 0.4 mm sieve, according to the NF P 94–051 standard (1993).

The liquid limit (WL) is the water content of a remolded soil at the transition between the liquid and plastic state. It is determined by using the Casagrande method and corresponds to the water content needed for a 1 cm closure after 25 blows.

The plastic limit (WP) is the water content of a remolded soil at the transition between the plastic and solid state, determined by the rolling method. It represents the water content needed for a manually formed soil thread, of a fixed size, to crack into 2 or 3 pieces when its diameter reaches 3 mm.

The plasticity index (Ip) is the range between the liquid and plastic states and is determined by the following equation: $Ip = Wl - Wp$. **Table 2** lists the soils according to their plasticity indices.

Table 2. Soil classification based on plasticity index (Verdeyen et al., 1971).

Ip	Plasticity
0	Non-plastic
1–5	Very slightly plastic
5–10	Slightly plastic
10–20	Moderately plastic
20–40	Plastic
> 40	Very plastic

Modified proctor test

The purpose of this test is to determine the optimal water content and dry density of a compacted soil sample, by the NF P 94–093 standard (NF P 94–093, 2014). The principle of the test is to moisten the soil with different water contents and then compact it following a standardized method and energy. For each water content, the dry bulk density of the soil is measured, and a curve of its variations is plotted against the water content. This bell-shaped curve shows an optimum known as the modified Proctor. (**Figure 3**).

Figure 3. Proctor compaction.

2.1.2. Physicochemical and mineralogical characterization of African locust bean pod

The residue of the African locust bean pod, remaining after the use of its fruit, is generally burned or discarded. It consists of two layers: A dark outer layer covering a fibrous inner layer. In this study, the powder derived from this residue will be used. To obtain this powder, the pod is first dried and then ground.

Mineralogical analysis (XRD)

Mineralogical analysis was performed using X-ray diffraction on the African locust bean pod powder. In this study, the samples were characterized using a Bruker D8 Advance diffractometer, equipped with a Ge (111) monochromator, which allows for distinguishing the Kα1 wavelength of copper (λ = 1.54056 Å). The sample is placed in a sample holder mounted on a rotating stage. This stage allows the sample holder to rotate on its axis, scanning the sample optimally, thereby improving the accuracy of the analysis. The beam is reflected each time Bragg's condition (Equation

(1)) is met and is then “counted” by a detector positioned at a 2θ angle relative to the incident beam.

Chemical analysis (XRF)

Chemical analysis by X-ray fluorescence spectroscopy determines both the nature of the chemical elements present in a sample and their mass concentration. The principle is based on exposing the sample to an X-ray beam. Under the influence of these rays, the atoms in the sample transition from their ground state to an excited state, emitting photons with wavelengths specific to the chemical elements being analyzed. This phenomenon, known as X-ray fluorescence, corresponds to the secondary emission of X-rays, characteristic of the atoms making up the sample.

Absorbance measurement

Absorbance is a commonly used measure in spectroscopy to evaluate the amount of light absorbed by a chemical substance at a given wavelength. Absorbance is measured using a spectrophotometer.

Lignin content

The lignin content refers to the amount of lignin present in plant material. Lignin is a complex and resistant polymer, primarily located in the cell walls of plants. It provides plants with rigidity and structural strength. The lignin content can vary significantly between plants, influencing its usage in various fields (Banakinao, 2016). In this study, lignin content was determined from absorbance using the following equation:

$$\text{Lignin Content} = \text{Absorbance} \times \text{Dilution Factor}/110 \tag{3}$$

2.2. Formulation of African locust bean pod-earth composite

For the formulation of the African locust bean Pod-Earth composite, a quantity of soil must be mixed with a percentage of African locust bean pod, homogenized, and then moistened with a quantity of water corresponding to the optimal Proctor water content, adding the amount of water absorbed by the African locust bean pod. The finenesses of the grinding considered in this study are particles passing through 0.08 mm, 2 mm, and between 2 mm and 5 mm sieves. The compositions of the mixtures are presented in **Table 3**.

Table 3. Composition of mixtures for specimen formulation.

Quantity of the components	**M0 (100% T + 11% E)**	**M1: Cne < 2 mm (92% T + 8% Cne + 11% E)**	**M2: Cne < 0.08mm (92% T + 8% Cne + 11% E)**	**M3: 2mm < Cne < 5 mm (92% T + 8% Cne + 11% E)**
Soil (Tse-1)	100	92	92	92
African locust bean pods (Cne)	0	8	8	8
Water (E)	11	11	11	11

2.2.1. Equipment

The materials used include, among others: Cylindrical molds with a diameter of 10 cm and height of 10 cm to mold the material, a metal plate for leveling, an electronic scale to weigh the different materials, a bowl to scoop the material, release oil, a thermometer, and other tools (containers, graduated cylinders, spatula, wooden ruler, trowel).

2.2.2. Specimen fabrication

For this study, four (4) mixtures were prepared: 0% pod and 8% pod for each of the three grinding finenesses. To prepare the mixture, the required amount of soil is first dried in an oven at 105 °C until it reaches a constant weight. Once dried, the soil is placed in a container. The specified percentage of African locust bean pod powder is then added to the soil, along with the determined amount of water. The mixture is manually mixed until it becomes thoroughly homogeneous. Before filling the molds, they are coated with a layer of oil to facilitate the removal of the specimens. The mold is placed on the work surface and filled completely with the mixture using a spatula. The mixture is then compacted at a pressure of 10 KN. Finally, the specimen is carefully removed from the mold. **Figure 4** shows the appearance of the mix and specimens produced.

(a) **(b)**

Figure 4. Specimen fabrication. **(a)** aspect of the mixture; **(b)** aspects of the specimens.

The test tubes are dried and stored in a chamber at room temperature for 28 days for some and 90 days for others.

2.3. Measurement of mechanical strength

For the measurement of mechanical strength in **Figure 5**, uniaxial compression strength tests were conducted on each dried sample based on the guidelines of the standards (NF EN 13286–41) (all samples were dried in the shade). These tests were performed using an electronic universal press, which allows applying load at a rate of 0.2 kn/s with load and displacement sensors. The cylindrical sample was monitored for the maximum force applied before a crack appeared. Each sample was subjected to a constant loading speed of 2 mm/min during the loading process. The tensile strength test was performed using the same universal testing machine according to the standard (NF EN 13286–42). As illustrated in **Figure 5**, the cylindrical samples were placed between two flat loading plates, to apply a diametral linear load along the entire length of the sample. For each test, three samples were tested. A computer is connected to the press to record the desired results (sample dimensions, maximum load, obtained strength).

(a) **(b)**

(c) **(d)**

Figure 5. Simple compression tests and splitting tensile test. **(a)** before compression; **(b)** after compression; **(c)** before splitting tensile; **(d)** after splitting tensile.

2.4. Statistical analysis

The statistical analysis was performed using the software R 4.4.1. It is a two-way analysis of variance (two-way ANOVA) where factor A is the type of mixture (M0, M1, M2, M3) and factor B is time (28 days, 90 days) for the compression tests. For the tensile tests, a one-way ANOVA was conducted with the mixture type as the quantitative variable and tensile strength as the qualitative variable.

3. Results

3.1. Results of identification tests

The identification was carried out according to the procedures described in paragraph 2.1.1.

3.1.1. Soil identification

Particle size distribution test

The results of the particle size distribution test conducted on the two (2) soils are presented in **Figure 6**.

The analysis of these curves shows that the percentage passing through the 2 mm sieve is 33.01% for Soumdina soil and 31.15% for Tsévié soil.

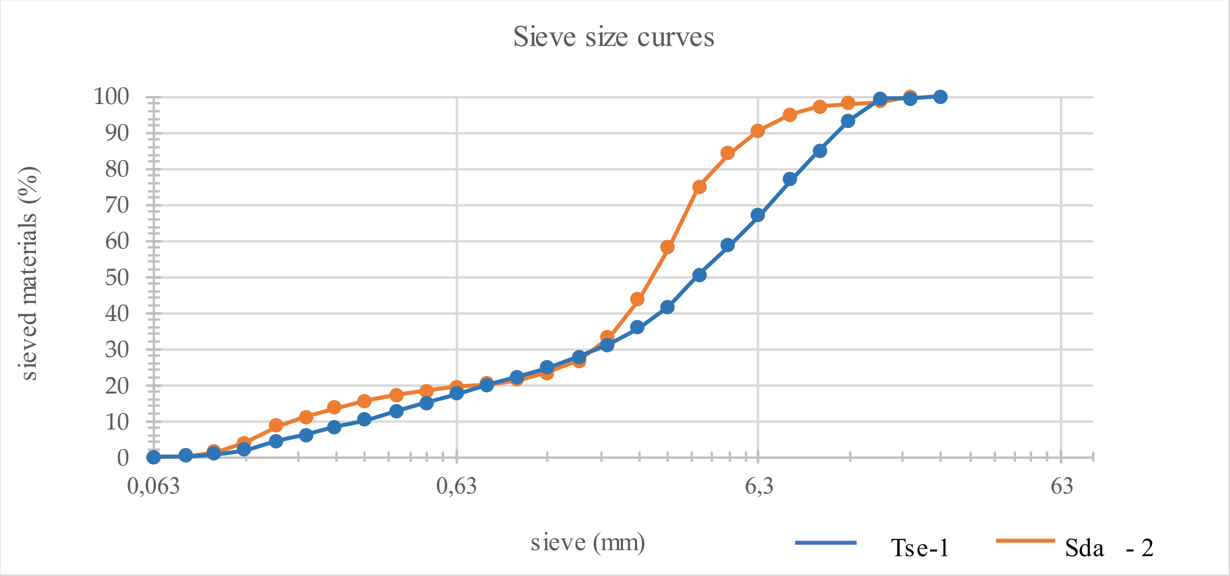


Figure 6. Results of particle size analyses.

Atterberg limit test

Table 4 records the results of the Atterberg limit tests conducted on the two (2) soils.

Table 4. Results of atterberg limits.

Source	Liquid Limit (Wl)	Plastic Limit (Wp)	Plasticity Index (Ip)
Tse-1	32.5	18.37	14.13
Sda-2	29	17.86	11.14

The values of the limits allow the classification of both soils as moderately plastic.

Proctor test

The results of the modified Proctor test allowed the drawing of the Proctor curves shown in **Figure 7**:

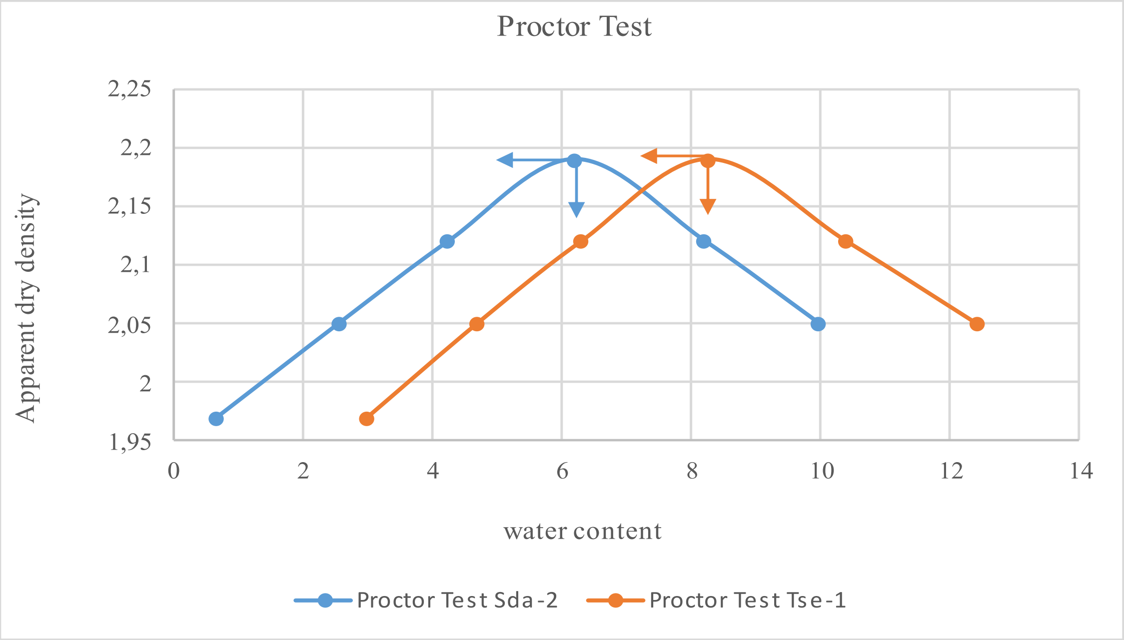


Figure 7. Results of the proctor test.

The values of the proctor optimums are:

(Tse-1): Optimum water content = 8.27%; optimum density = 2.19 g/cm³

(Sda-2): Optimum water content = 6.19%; optimum density = 2.19 g/cm³.

The Proctor tests carried out on these two soils allowed for the determination of an optimal water content corresponding to a maximum dry density for each soil. Subsequently, the soil from Tsévié (Tsé-1) was selected for the formulation of the earth-African locust bean pod composite. This formulation took into account the water content of 2.19% obtained during this test.

According to the classification by the American Association of State Highway and Transportation Officials (AASTHO) and the Central Laboratory of Bridges and Highways (LCPC), both soils are moderately (slightly) plastic clayey sands. **Table 5** shows the results of this classification.

Table 5. Classification according to AASTHO and LCPC of the soils.

Soil	% passing at 2 mm	Ip	Wl	LCPC Classification	AASHTO Classification	Type
Tse-1	31.15 < 35	14.13 > 11	32.5 < 40	B4	A2–6	slightly plastic clayey sands
Sda-2	33.01 < 35	11.14 > 11	29 < 40	B4	A2–6	slightly plastic clayey sands

As a result of the tests, the soil from Tsévié (Tsé-1) was selected for the formulation of the earth-African locust bean pod composite due to the proximity of its extraction site to the formulation location. The water content of 2.19%, obtained during the tests, was integrated into the formulation process.

3.1.2. Results of the physicochemical and mineralogical characterization of the African locust bean pod

Table 6 shows a low mineral content of 2.90% and a very low lipid content of 0.9%. Although the African locust bean is a legume, its protein content is low, around 4.69%. Additionally, there is a high content of cellulose (49.76%), lignin (32.95%), and hemicellulose (22.52%). This good lignin content is associated with the presence of tannins in the African locust bean pod.

Table 6. Chemical composition (Nenonene et al., 2014).

Analyzed constituents	Content (%) per 100 g of dry matter
Dry matter rate	91.68
Mineral matter	2.90
Lipids	0.90
Crude protein	4.69
Cellulose	49.76
Hemicellulose	22.52
Lignin	32.95

Further chemical analyses reveal the dominance of sugars such as galacturonic acid (37.74%) and galactose (23.95%). The total bulk density, grinding fineness, and hygroscopic power are recorded in **Table 7**.

Table 7. Physical test results (Banakinao, 2016).

Parameters	Values
Grain diameter	Lower limit
0.08 mm	39%
0.1 mm	90%
0.125 mm	95%
0.2 mm	99%
0.4 mm	100%
0.5 mm	100%
1.00 mm	100%
Total bulk density	0.69 g/cm³
Absorption rate	0.44 ml/g

3.2. Formulation results

The soil sampled from Tsévié was used for the mixture formulation. Based on the results of the mixes conducted by Banakinao (2016), the optimal dosages for African locust bean pod were identified as follows:

(1) 8 to 10% for clays, sandy clay, and low-to-medium plasticity gravelly clays;
(2) 10 to 12% for silts, sandy silts, and non-plastic gravelly silts;
(3) 7 to 9% for clays, sandy clay, and plastic gravelly clays.

Since the Tsévié soil (Tse-1) falls into the first category, 8% of the African locust bean pod was used. The water content of 11% corresponds to the optimum Proctor moisture content. This results in 1900 g soil + 152 g African locust bean pod + 209 g water.

3.3. Measurement of mechanical strength

The drying of the test specimens after formulation was done in a chamber at room temperature. Three (3) specimens were produced per mixture to obtain a range of values, with the average serving as the final retained value.

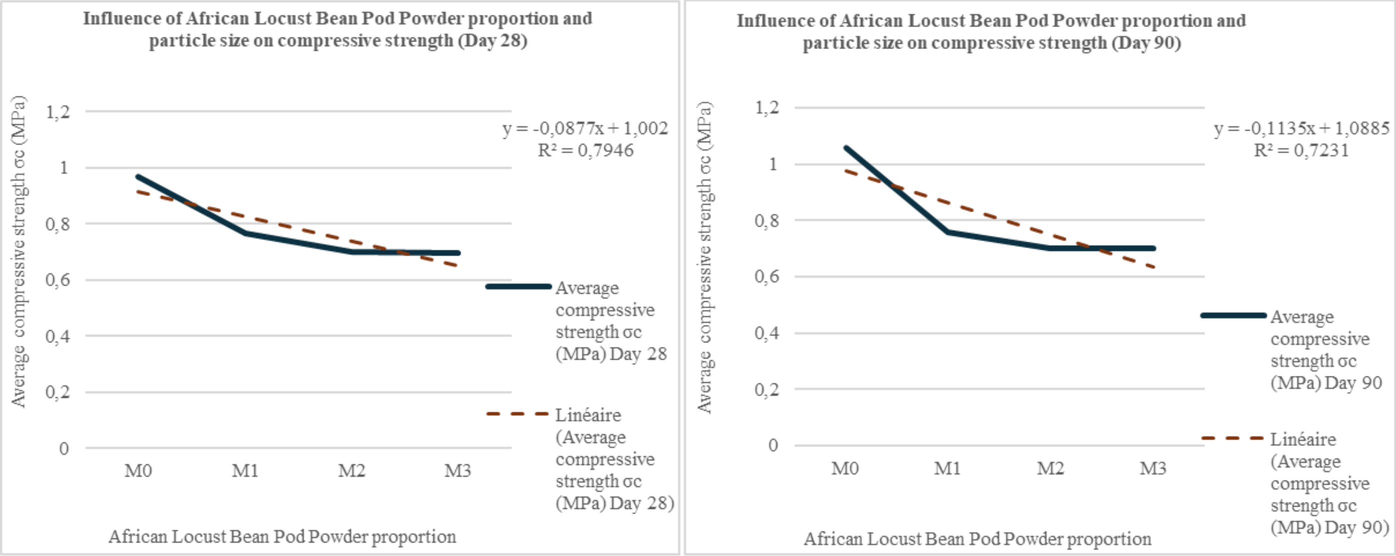
3.3.1. Simple compression test results

Table 8 shows the results of the compression tests on the formulated specimens. Compression test results.

Table 8. Compression test results.

Mixes	Average compressive strength σc (MPa) Day 28	Average compressive strength σc (MPa) Day 90
M0 (100% T+11% E)	0.967	1.060
M1: Cne < 2 mm (92% T + 8% Cne + 11% E)	0.767	0.758
M2: Cne < 0.08 mm (92% T + 8% Cne + 11% E)	0.700	0.700
M3: 2 mm < Cne < 5 mm (92% T + 8% Cne + 11% E)	0.697	0.701

Figure 8 shows the influence of African locust bean pod powder proportion and particle size on compressive strength.



(a) **(b)**

Figure 8. Influence of African Locust Bean Pod Powder proportion and particle size on compressive strength. **(a)** day 28; **(b)** day 90.

The ANOVA results show that the type of mix (with or without pods, and pod size) has a significant impact on compressive strength with a *p*-value of 0.01472, which is below 0.05. However, for mixes M1, M2, and M3, the time factor (28 days or 90 days) has no significant effect on compressive strength, with a *p*-value of 0.36418. The *p*-value associated with the interaction of “mix type: Time” is also greater than 0.05 (0.95109), indicating that the effect of the mix type does not depend on time.

From **Table 8**, we can conclude that: The control mix M0, made only of soil and water, has better strength than the other mixes containing African locust bean pod of different grinding fineness. Its compressive strength increases significantly between 28 and 90 days, which is typical for clay soils.

The inclusion of African locust bean pod in mixes M1, M2, and M3 shows a reduction in their initial strength compared to the reference mix M0. However, this strength remains stable over time (between 28 and 90 days), indicating that age does not significantly affect the compressive strength of the earth-pod composites, regardless of the pod size.

Despite the decrease in strength observed for formulations with pod, mix M1 has better strength compared to M2 and M3. Thus, M1 > M2 > M3.

3.3.2. Splitting tensile test results

The results of the tensile tests on the formulated specimens are recorded in **Table 9**.

Table 9. Splitting tensile test results.

Mixes	Tensile Strength (MPa)
M0: Soil	0.098
M1: Soil + diameter of African locust bean pod < 2 mm	0.095
M2: Soil + diameter of African locust bean pod < 0.08 mm	0.061
M3: Soil + diameter of African locust bean pod 2 mm < x < 5 mm	0.065

Figure 9 shows the influence of African locust bean pod powder proportion and particle size on splitting tensile.

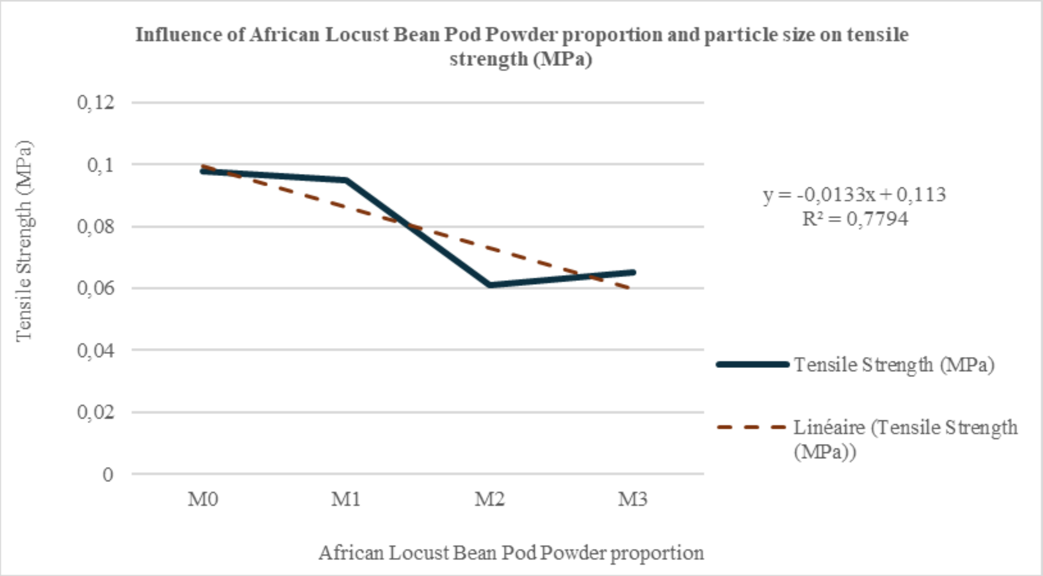


Figure 9. Influence of African locust bean pod powder proportion and particle size on splitting tensile.

The one-way ANOVA test revealed a *p*-value of less than 0.05 (0.01472), indicating a significant difference between the mixes in terms of tensile strength.

Table 9 shows that: M0, containing only soil, exhibits the greatest tensile strength (0.098), even though M1, with 0.095 MPa, is very close.

Adding an African locust bean pod reduces tensile strength, with the magnitude of this reduction depending on particle size. Finer particles (M2) significantly reduce tensile strength (0.061), while medium-sized particles (M3) also weaken the material, but less so than the finer particles (0.065). This suggests that finer and larger particles may disrupt the soil matrix more, leading to reduced tensile strength.

4. Discussion

The mechanical strength tests in this study aimed to assess the effect of adding African locust bean pod powder, ground to different fineness, on the properties of the soil. Traditionally, in West African construction systems, tannin extract from the African locust bean pod is used to coat buildings and compact soils, providing greater durability. The crucial element in the pod is its microstructure, which is responsible for strength. While research is still needed to explore extraction methods for these elements from the pod that could strengthen earth bricks, in this study, we used the powder form. Identification and classification tests were conducted on both the soil and the pod. After obtaining the results, the specimens were formulated, and compression and tensile tests were performed. Equipment for these tests came from different sources, some imported and others locally produced.

The results revealed that, regardless of grinding fineness, adding African locust bean pod powder reduced both compressive and tensile strength. However, particles passing through a 2 mm sieve provided better strength compared to other grindings. This result seems paradoxical because of previous studies that highlighted the strengthening properties of néré tannins. (Banakinao, 2016; Keita et al., 2014; Sorgho et al., 2014). Several factors may explain this difference. Firstly, the very nature of the pod powder, comparable to fine sand, could have disrupted the structure of the soil. In fact, by replacing part of the clay, which plays an essential role in soil cohesion, the néré powder would have reduced the plasticity of the mixture and thus diminished its resistance. It should be noted that the size of the powder particles seems to have an influence. Particles passing through a 2 mm sieve performed better than other particle sizes, suggesting that the presence of coarser particles could have a detrimental effect on the cohesion of the material. Poor cohesion between the soil matrix and the pod powder could be another reason. Indeed, (Dollente et al., 2023) found that ordinary geopolymer mortar exhibited higher strength than samples reinforced with fibers, which was attributed to voids created by the fibers that had not fully integrated during mixing (Dalvand and Mastali, 2016).

The work of (Benyahia et al., 2013; Nouri, 2020), suggests that the effectiveness of plant fibers in improving the mechanical strength of soils may be linked to their preparation methods. In the case of African locust bean husks, the extraction of tannins could concentrate the active compounds responsible for improving mechanical properties, unlike the use of raw powder, which, due to its more complex composition, could interfere with the homogeneity and cohesion of the composite material.

The quantity of water and the amount of néré powder in the mixtures, are essential parameters. In this study, the amount of water used for the formulation was set at 11% of the soil mass, according to the results of the Proctor test, while the proportion of African locust bean husk fibers incorporated was 8%. However, this water quantity did not account for the specific needs of the African locust bean husk's fineness, which might require adjustment either by adding more water or by reducing it. Previous research, such as that of (Kouto, 2024) on earth concretes incorporating corn fibers, showed that the composite material's mechanical strength is optimal with a water content of 18% for compression and 20% for tension when the fiber proportion is 20%. Conversely, a water content of 16% or inadequate fiber dosing leads to a significant drop in mechanical strength. The work of (Drovou et al., 2015) on kapok sawdust particleboard with tannin powder from African locust bean husk pods exhibits maximum mechanical strength only when a 15% dosage of tannin powder is reached. Similarly, the results of (Mahdy et al., 2023) indicate that an increase in rice straw fiber content to 0.75% decreases compressive strength by 4.2%. Other studies (Awal et al., 2021; Maglad et al., 2023; Majeed, 2024) also confirm the compressive and tensile strength decrease when the reinforcement dosage (fibers or ashes) is inadequate. These results highlight the importance of finding an optimal balance between water content and fiber proportion to improve the composite material's performance. For future research, it would be relevant to vary the amount of husk powder for all particle sizes.

The preservation method of base materials and composites is another key factor in material strength. Inappropriate storage conditions can alter the material's formulation and prevent achieving the desired mechanical properties. Research by (Camargo et al., 2020; Santos et al., 2017) shows that the moisture of plant fibers hurts the mechanical strength of reinforced materials. Additionally, Kouto (2024) demonstrated a decrease in strength when samples were not stored under appropriate conditions.

The reduction in strength observed in this study could also be related to the shape and pre-treatment of the fibers. The shape and orientation of plant fibers influence the mechanical properties of materials, as shown by Konečný et al. (2013) and Tlaiji et al. (2022) in their work on straw. The study (Kouto, 2024) also revealed a decrease in strength when untreated corn fibers were used compared to those that underwent pre-treatment.

Finally, Kouto (2024) highlighted the significant impact of the compaction method used during sample formulation on the material's final strength. These results indicate a 31.29% decrease in strength when switching from vibratory compaction to pegging compaction.

Nonetheless, it is important to emphasize the value of bio-based materials such as African locust bean husk in the creation of sustainable urban buildings. They are considered promising solutions for achieving decarbonization goals in the construction sector, as they act as a means of sequestering carbon while reducing reliance on other materials with high embodied energy (Koh and Kraniotis, 2020). Thanks to their pores and composition, they have low thermal conductivity, making them excellent thermal insulators (McCabe, 2018; Plazonić et al., 2016), which helps reduce energy consumption in buildings (Divsalar, 2011; Wesonga et al., 2023). The African locust bean husk, a natural plant-based stabilizer historically used to make surfaces shiny and harder, resistant to weathering and the test of time (Vissac et al., 2012), is a valuable resource that warrants further research. It is thus crucial to master the formulation and treatment parameters to optimize the mechanical performance of African locust bean husk-based composite materials.

5. Conclusion

This study explored the valorization of agricultural waste through the use of African locust bean husk powder (Parkia biglobosa) as a reinforcement material in the manufacture of compressed earth bricks, with a focus on the impact of different grinding fineness levels on the mechanical properties of the bricks. The results show that incorporating African locust bean husk powder into the soil leads to a 20% to 27% reduction in compressive strength and a 3% to 37% reduction in the tensile strength of the composite material, depending on the fiber size. However, in the case of adding husk powder, the best strengths are obtained with a fineness of less than 2mm. This reduction can be attributed to several factors, including poor adaptation of the water content to the husk's specific needs, inadequate storage conditions, the tannin content in the powder used, and the influence of the fibers' shape, orientation, and treatment. The results highlight the importance of mastering these parameters to optimize the mechanical properties of African locust bean husk-based composite materials.

The findings of this study contribute to the growing body of knowledge on the use of bio-based materials in construction. Documenting inconclusive results is important for building a more comprehensive collective understanding and avoiding publication bias, where only positive results are shared. This helps guide other researchers.

6. Perspectives

The results obtained open up several avenues for future research and improvement. It would be relevant to:

- Optimize treatment parameters by exploring different methods, such as chemical or thermal pretreatment, to improve adhesion between the fibers and the earthen matrix.
- Investigate the impact of different water content levels specifically adapted to the use of African locust bean husk.
- Conduct additional tests on all base materials and the resulting composite.
- Explore other African locust bean husk methods and consider combining it with other materials.
- Consider applications outside of construction.
- Research the interaction mechanisms between African locust bean husk fibers and the earthen matrix.

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