World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI

Cross Ref DOI: 10.30574/wjarr

Journal homepage: https://wjarr.com/

(Research Article)

Check for updates

Influence of Banana Trunk Powder Incorporation on the Mechanical Properties of Stabilized Compressed Earth Blocks (SCEB) for Production at the National Laboratory of Building and Public Works of Côte d'Ivoire

Sylvestre DAGO [1, *], Konin Athanase [2], Koffi Morofie Justin KOUAME [1] and Koffi David AKAKI [1]

[1] *Nutrition and Food Technology Laboratory, Institut National Polytechnique Félix Houphouët-Boigny (INP-HB), BP 1093 Yamoussoukro.*

[2] *Département de formation et de recherche en infrastructures et transport, Laboratoire du Génie Civil, des Géosciences et Sciences géographiques, Institut National Polytechnique Félix Houphouët-Boigny, Yamoussoukro, Côte d'Ivoire.*

World Journal of Advanced Research and Reviews, 2025, 26(03), 153–173

Publication history: Received on 20 April 2025; revised on 28 May 2025; accepted on 31 May 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.26.3.2104

Abstract

In the context of climate change and the urgent need to reduce the carbon footprint of the construction sector, this study focuses on Stabilized Compressed Earth Blocks (SCEB) reinforced with banana trunk powder (BTP), as an alternative to cement, to improve their mechanical performance while promoting local resources. The main objective is to assess the effect of these additives on the flexural and compressive strength of the SCEB in order to determine optimal formulations. The methodology consisted of mechanical tests comparing two distinct formulations—earth + sand + BTP and earth + sand + cement—with additive dosages ranging from 2% to 10% and water content between 9% and 14%. The results revealed that a formulation with 2% BTP and 13% water produced the best mechanical performance, with flexural strength reaching 0.82 ± 0.10 MPa and compressive strength 3.91 ± 0.58 MPa, representing a significant improvement compared to the unstabilized control (0.55 ± 0.28 MPa in flexion and 2 ± 0.31 MPa in compression). However, higher BTP concentrations led to a marked decline in these properties. Conversely, the cement-stabilized formulation showed a linear improvement in performance, reaching 2.59 ± 0.31 MPa in flexion and 12.32 ± 0.66 MPa in compression for a 10% cement dosage with 13% water. The study concludes that the optimal formulation for SCEB combining mechanical efficiency and environmental sustainability is a mixture with 2% BTP and 13% water, paving the way for the development of innovative and eco-friendly construction materials.

Keywords: Stabilized Compressed Earth Blocks; Banana Trunk Powder; Cement; Mechanical Properties; Sustainable Construction

1. Introduction

Climate change, marked by a global rise in temperatures, is a major challenge for modern societies, particularly in Côte d'Ivoire where its effects are increasingly pronounced. These climatic changes threaten ecosystems and biodiversity, affecting productivity and living conditions (Doffou et al., 2021). The increase in temperature and the intensification of extreme weather events—well documented in recent studies (Coulibaly et al., 2024; Fofana, 2023)—are largely attributed to CO_2 emissions, with the cement industry being a significant contributor (Dionne and Lefebvre, 2022). This sector, both a greenhouse gas emitter and vulnerable to climate variation, contributes to deteriorating housing conditions, leading to increased air-conditioning use and, consequently, greater energy consumption and emissions (Egah, 2021).

* Corresponding author: Sylvestre DAGO.

To address these issues, sustainable solutions such as Stabilized Compressed Earth Blocks (SCEB) are gaining ground. These materials, composed of soil and natural binders, reduce the carbon footprint of buildings (Tobias et al., 2023). The incorporation of agricultural waste such as banana trunk powder (BTP) valorizes local resources while enhancing the mechanical properties of SCEBs. BTP, rich in natural fibers, improves compressive strength (Petit et al., 2020) and offers lower thermal conductivity than cement, thus reducing cooling needs (Adjacou et al., 2022). Additionally, decomposing banana trunks emit methane (CH_4) and carbon dioxide (CO_2) when burned, contributing to greenhouse gas emissions (Nougtara et al., 2021). The increased porosity of SCEBs also improves resistance to moisture and erosion—critical in tropical regions (Ruf, 2022).

In Côte d'Ivoire, where annual banana production reaches approximately 1.7 million tons, valorizing banana trunks presents both an economic opportunity for farmers and aligns with circular economy principles (Takpa et al., 2022). In summary, incorporating BTP into SCEBs illustrates the synergy between technological innovation and sustainable development. This approach addresses climate change challenges while enhancing quality of life through more comfortable and environmentally friendly housing. The aim of this study is to demonstrate how valorizing plantain banana trunk waste as a binder in SCEBs can reduce thermal flow, provide good mechanical strength, and contribute to more sustainable and context-adapted construction practices.

2. Matériel et method

2.1. Study Site

The study was conducted in the Autonomous District of Abidjan, specifically in the commune of Cocody, within the Palmeraie neighborhood bordered by Riviera, Angré, Cocody Centre, and II-Plateaux. Additional activities took place in the Lagunes District, particularly in the Agnéby-Tiassa region, which includes Tiassalé (120 km from Abidjan, ~60,000 inhabitants, coordinates: 5°53' N, 4°49' W), N'Douci (between Tiassalé and Agboville, ~40,000 inhabitants, coordinates: 6°03' N, 5°01' W), and Agboville (north of Tiassalé, ~120,000 inhabitants, coordinates: 5°56' N, 4°13' W). These locations, interconnected by strategic road networks, play a key economic and cultural role in their respective regions.

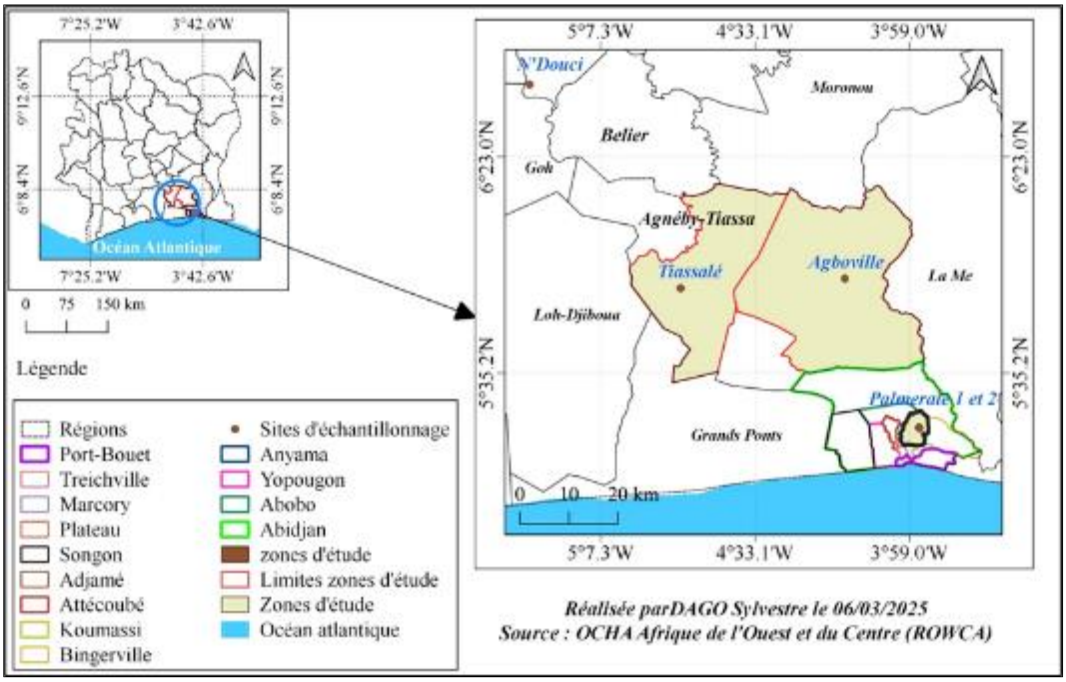


Figure 1 Location of the Study Areas

2.2. Study Materials

The study focused on soil samples and plantain banana trunks collected from four major locations: Cocody Palmeraie, Agboville, Tiassalé, and N'douci. Sample collection was conducted between March 2024 and February 2025.

Figure 2 Photographs of Soil and Banana Trunk Samples

2.3. Technical Equipment

Figure 3 Illustrations of Some Technical Equipment Used

The technical equipment used in this study includes a precision balance and a measuring cup to accurately determine the masses of the samples, as well as a sieve and an oven essential for particle size analysis by sieving, allowing the separation of particles by size and the removal of residual moisture. For sedimentation particle size analysis, water, a hydrometer, an electric stirrer, a pipette, a stopwatch, and a thermometer are used to determine the distribution of fine particles in suspension by measuring their sedimentation rate and controlling experimental conditions.

To determine the California Bearing Ratio (CBR), a CBR rammer is used to prepare and compact samples according to strict standards, while a CBR press measures penetration resistance, thus assessing the load-bearing capacity of the material.

For the Proctor test, a mold and a Proctor rammer are used to compact the samples in successive layers, and an oven determines the optimum moisture content and maximum dry density, ensuring reproducible and accurate compaction conditions.

Finally, for the formulation of the Compressed Stabilized Earth Blocks (CSEB), a mixer ensures homogeneous blending of materials, and a mold is used to shape the blocks as desired.

These pieces of equipment are essential for ensuring the reliability of results and optimizing the mechanical properties of the materials.

2.4. Selection of Zones and Sampling Sites

The sites selected for producing Compressed Stabilized Earth Blocks (CSEB) and for collecting soil and plantain banana trunk samples are located in four Ivorian localities: Cocody-Palmeraie, Agboville, Tiassalé, and N'Douci. These areas were chosen based on their geographical characteristics, soil quality, and agricultural potential, especially for plantain banana cultivation.

Although Cocody-Palmeraie is urban, it contains agricultural pockets suitable for such cultivation. Agboville, known for its fertile soils and favorable climate, is a major production hub. Tiassalé, characterized by hydromorphic soils and the presence of rivers, offers a consistently humid environment. N'Douci, with its rich soils and humid climate, is also a prime zone.

This pedoclimatic diversity enables the study of the influence of soil and climate on CSEBs and the mechanical properties of plantain banana materials, ensuring results that are both representative and scalable to other regions. Furthermore, these areas are well connected by road infrastructure, facilitating the transport of samples to laboratories and reinforcing the study's feasibility.

2.5. Sample Collection

A single sampling site was selected per study zone. At each site, soil plots were chosen for sample collection. In total, four soil samples and four plantain banana trunk samples were randomly collected and packaged in new market-purchased bags. Three sampling campaigns were conducted over eleven months, from March 2024 to February 2025, resulting in a total of 30 composite samples. This methodology ensures a structured and representative data collection process.

2.6. Processing of Plantain Banana Trunks Collected from the Study Sites

Following the collection of plantain banana trunks from the study sites, a rigorous treatment process was conducted to ensure the reliability of subsequent analyses. Fibers were first extracted, thoroughly cleaned, and cut into homogeneous fragments to facilitate the following steps.

These fragments were dried in an oven at 105 °C to eliminate residual moisture, preventing degradation that could affect analytical results. Once dried, the samples were ground using a mill to obtain a fine, homogeneous powder—essential for reproducibility. The resulting powder was then carefully stored in airtight bags to preserve its physicochemical properties before being used in various analyses.

2.7. Grain Size Analysis by Sieving

The grain size analysis by sieving of the soil samples was carried out in accordance with ISO 17892-4, Geotechnical Investigation and Testing — Laboratory Testing of Soil. This standardized method assesses particle distribution by separating them into size classes using a series of sieves.

Samples, dried at 105 °C to remove moisture, were gently crushed to disaggregate clumps without altering the particles. Sieving was performed using a stack of sieves with decreasing mesh sizes (from 80 mm to 0.063 mm). The sample was placed at the top of the stack and mechanically shaken for 10 to 15 minutes.

Each retained fraction was then weighed, enabling the calculation of relative proportions and the plotting of a grain size curve—essential for characterizing the soil's particle distribution.

2.8. Grain Size Analysis by Hydrometer

Grain size analysis by hydrometer was also performed according to ISO 17892-4. This method determines the distribution of fine particles (< 80 µm) by sedimentation.

Samples, dried at 105 °C and sieved at 2 mm, were dispersed in an aqueous suspension containing sodium hexametaphosphate, then mechanically agitated. The suspension was transferred into a graduated cylinder, and sedimentation was monitored using a hydrometer at specific time intervals (from 30 seconds to 24 hours).

The collected data were used to plot a grain size distribution curve, essential for identifying soil texture (clay, silt) and assessing its suitability for construction.

2.9. California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) was determined in accordance with standard NF P94-078 (1997), to evaluate the load-bearing capacity and mechanical resistance of soil-based materials stabilized with plantain trunk fiber powder (PTFP), under immediate and post-immersion conditions—critical for humid environments.

Samples were prepared under optimal moisture and compaction conditions. The soil-PTFP mixture was compacted in three layers in a standardized cylindrical mold, with a specified number of hammers blows per layer.

The immediate CBR test assessed the material's bearing capacity in its original state after compaction. For the soaked CBR test, samples were immersed for 96 hours (4 days) to simulate prolonged exposure to moisture before measuring penetration resistance.

The CBR was calculated by comparing the penetration resistance of the sample to that of a reference material, with results expressed as percentages. Higher values indicate better bearing capacity, confirming the material's performance under real-world conditions.

2.10. Proctor Compaction Test

The compaction properties of soil and plantain trunk fiber powder (PTFP)-based materials were evaluated using the Proctor test, following standard NF P94-093 (1997). This standard includes two methods: the Standard Proctor and Modified Proctor tests, used to determine the maximum dry density and optimal moisture content of the material.

Samples were compacted in standardized molds in successive layers, each subjected to a defined number of hammer blows.

For the Standard Proctor test, a moderate compaction energy was used, suitable for typical field conditions, while the Modified Proctor applied a higher energy level to simulate more rigorous compaction scenarios.

Results were presented as moisture-density curves, identifying optimal parameters to maximize strength and stability, ensuring mechanical performance suited to sustainable construction requirements.

2.10.1. Mixing Design

To design and optimize the material mixtures, the Design-Expert 3 software was used to generate a rigorous and efficient experimental plan.

Recognized for its capability in formulation optimization, this software defined 30 tests for each mixture, totaling 60 tests plus 6 control tests.

The two mixtures studied were

- Mixture 1: Plantain banana trunk powder + sand + soil
- Mixture 2: Soil + sand + cement

This methodological approach, based on optimized experimental design, enables evaluation of composite material properties and identification of optimal proportions that meet the specific requirements of the construction project.

Table 1 Mixing plan for the control material (100% soil)

Test	Component 1 A: Clay + Sand %	Component 2 C: Water %	Component 1 A: Clay + Sand %	Component 2 C: Water %
1	13,5	1.215	100%	9%
1	1350	121.5	1350	121.5
2	13,5	1.35	100%	10%
2	1350	135	1350	135
3	13,5	1.465	100%	11%
3	1350	146.5	1350	146.5
4	13,5	1.62	100%	12%
4	1350	162	1350	162
5	13,5	1.755	100%	13%
5	1350	175.5	1350	175.5
6	13,5	1.89	100%	14%
6	1350	189	1350	189

Table 2 Mixing plan for the material with cement

Test	Component 1 A: Clay + Sand %	Component 2 B:Cement %	Component 3 C: Water %	Component 1 A: Clay + Sand %	Component 2 B:Cement %	Component 3 C: Water %	Test	Component 1 A: Clay + Sand %	Component 2 B:Cement %	Component 3 C: Water %	Component 1 A: Clay + Sand %	Component 2 B:Cement %	Component 3 C: Water %
1	13,5	0.27	1.215	100%	2%	9%	16	13.5	0.81	1.62	100%	6%	12%
1	1350	27	121.5	1350	27	121.5	16	1350	81	162	1350	81	162
2	13,5	0.27	1.35	100%	2%	10%	17	13.5	0.81	1.755	100%	6%	13%
2	1350	27	135	1350	27	135	17	1350	81	175.5	1350	81	175.5
3	13,5	0.27	1.465	100%	2%	11%	18	13.5	0.81	1.89	100%	6%	14%
3	1350	27	146.5	1350	27	146.5	18	1350	81	189	1350	81	189
4	13,5	0.27	1.62	100%	2%	12%	19	13.5	1.08	1.215	100%	8%	9%
4	1350	27	162	1350	27	162	19	1350	108	121.5	1350	108	121.5
5	13,5	0.27	1.755	100%	2%	13%	20	13.5	1.08	1.35	100%	8%	10%
5	1350	27	175.5	1350	27	175.5	20	1350	108	135	1350	108	135
6	13,5	0.27	1.89	100%	2%	14%	21	13,5	1.08	1.465	100%	8%	11%
6	1350	27	189	1350	27	189	21	1350	108	146.5	1350	108	148.5
7	13,5	0.54	1.215	100%	4%	9%	22	13.5	1.08	1.62	100%	8%	12%
7	1350	54	121.5	1350	54	121.5	22	1350	108	162	1350	108	162
8	13,5	0.54	1.35	100%	4%	10%	23	13.5	1.08	1.755	100%	8%	13%
8	1350	54	135	1350	54	135	23	1350	108	175.5	1350	108	175.5
9	13,5	0.54	1.465	100%	4%	11%	24	13.5	1.08	1.89	100%	8%	14%
9	1350	54	146.5	1350	54	148.5	24	1350	108	189	1350	108	189
10	13,5	0.54	1.62	100%	4%	12%	25	13.5	1.35	1.215	100%	10%	9%
10	1350	54	162	1350	54	162	25	1350	135	121.5	1350	135	121.5
11	13,5	0.54	1.755	100%	4%	13%	26	13.5	1.35	1.35	100%	10%	10%
11	1350	54	175.5	1350	54	175.5	26	1350	135	135	1350	135	135

12	13,5	0.54	1.89	100%	4%	14%	27	13.5	1.35	1.465	100%	10%	11%
12	1350	54	189	1350	54	189	27	1350	135	146.5	1350	135	148.5
13	13,5	0.81	1.215	100%	6%	9%	28	13.5	1.35	1.62	100%	10%	12%
13	1350	81	121.5	1350	81	121.5	28	1350	135	162	1350	135	162
14	13,5	0.81	1.35	100%	6%	10%	29	13.5	1.35	1.755	100%	10%	13%
14	1350	81	135	1350	81	135	29	1350	135	175.5	1350	135	175.5
15	13,5	0.81	1.465	100%	6%	11%	30	13.5	1.35	1.89	100%	10%	14%
15	1350	81	146.5	1350	81	148.5	30	1350	135	189	1350	135	189

Table 3 Mixing plan for the material with plantain banana trunk powder

Test	Component 1 A: Clay + Sand %	Component 2 B: Plantain banana trunk powder %	Component 3 C: Water %	Component 1 A: Clay + Sand %	Component 2 B: Plantain banana trunk powder %	Component 3 C: Water %	Test	Component 1 A: Clay + Sand %	Component 2 B: Plantain banana trunk powder %	Component 3 C: Water %	Component 1 A: Clay + Sand %	Component 2 B: Plantain banana trunk powder %	Component 3 C: Water %
1	13.5	0.27	1.215	100%	2%	9%	16	13.5	0.81	1.62	100%	6%	12%
1	1350	27	121.5	1350	27	121.5	16	1350	81	162	1350	81	162
2	13.5	0.27	1.35	100%	2%	10%	17	13.5	0.81	1.755	100%	6%	13%
2	1350	27	135	1350	27	135	17	1350	81	175.5	1350	81	175.5
3	13.5	0.27	1.465	100%	2%	11%	18	13.5	0.81	1.89	100%	6%	14%
3	1350	27	146.5	1350	27	146.5	18	1350	81	189	1350	81	189
4	13.5	0.27	1.62	100%	2%	12%	19	13.5	1.08	1.215	100%	8%	9%
4	1350	27	162	1350	27	162	19	1350	108	121.5	1350	108	121.5
5	13.5	0.27	1.755	100%	2%	13%	20	13.5	1.08	1.35	100%	8%	10%
5	1350	27	175.5	1350	27	175.5	20	1350	108	135	1350	108	135

6	13.5	0.27	1.89	100%	2%	14%	21	13.5	1.08	1.465	100%	8%	11%
6	1350	27	189	1350	27	189	21	1350	108	146.5	1350	108	148.5
7	13.5	0.54	1.215	100%	4%	9%	22	13.5	1.08	1.62	100%	8%	12%
7	1350	54	121.5	1350	54	121.5	22	1350	108	162	1350	108	162
8	13.5	0.54	1.35	100%	4%	10%	23	13.5	1.08	1.755	100%	8%	13%
8	1350	54	135	1350	54	135	23	1350	108	175.5	1350	108	175.5
9	13.5	0.54	1.465	100%	4%	11%	24	13.5	1.08	1.89	100%	8%	14%
9	1350	54	146.5	1350	54	148.5	24	1350	108	189	1350	108	189
10	13.5	0.54	1.62	100%	4%	12%	25	13.5	1.35	1.215	100%	10%	9%
10	1350	54	162	1350	54	162	25	1350	135	121.5	1350	135	121.5
11	13.5	0.54	1.755	100%	4%	13%	26	13.5	1.35	1.35	100%	10%	10%
11	1350	54	175.5	1350	54	175.5	26	1350	135	135	1350	135	135
12	13.5	0.54	1.89	100%	4%	14%	27	13.5	1.35	1.465	100%	10%	11%
12	1350	54	189	1350	54	189	27	1350	135	146.5	1350	135	148.5
13	13.5	0.81	1.215	100%	6%	9%	28	13.5	1.35	1.62	100%	10%	12%
13	1350	81	121.5	1350	81	121.5	28	1350	135	162	1350	135	162
14	13.5	0.81	1.35	100%	6%	10%	29	13.5	1.35	1.755	100%	10%	13%
14	1350	81	135	1350	81	135	29	1350	135	175.5	1350	135	175.5
15	13.5	0.81	1.465	100%	6%	11%	30	13.5	1.35	1.89	100%	10%	14%
15	1350	81	146.5	1350	81	148.5	30	1350	135	189	1350	135	189

2.10.2. Methods for Determining Formulations

The formulation method is based on the preparation of a 1350 g material, carefully weighed, homogenized, and molded into specific shapes to ensure uniform distribution and standardized dimensions. The samples are then placed in a climatic chamber, where they are exposed to controlled temperature and humidity conditions for a defined period of 28 days.

This step simulates the curing process and the evolution of the material's mechanical properties in a stabilized environment. After each curing period, flexural and compressive strength tests are performed to measure the mechanical resistance of the samples. These tests provide essential data on the material's capacity to withstand bending stresses and compressive forces, thereby evaluating both tensile behavior and resistance to crushing.

This methodical and rigorous approach ensures accurate and reliable characterization of the material's mechanical performance.

3. Results and discussion

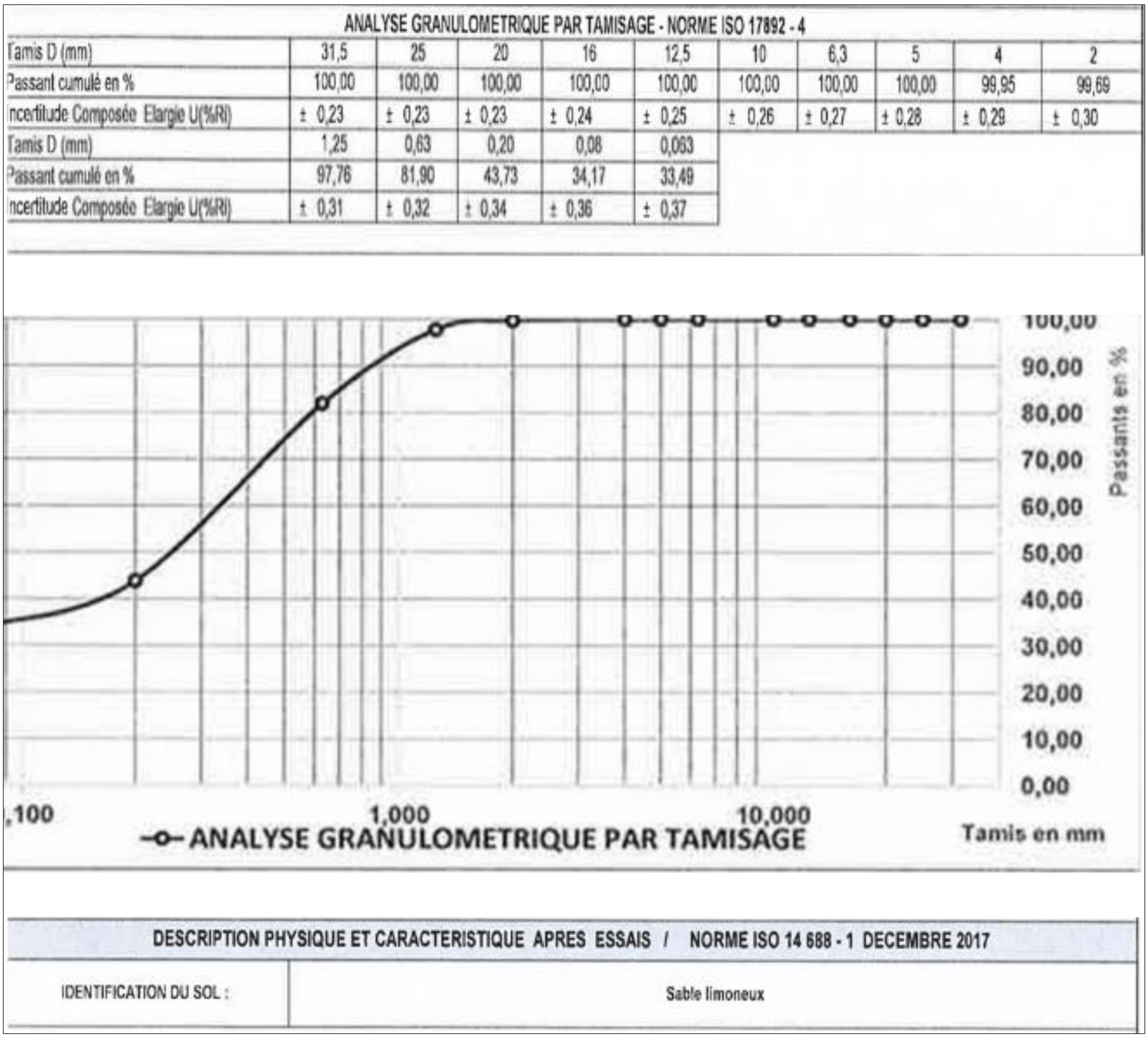
This study analyzes the physical and mechanical properties of Compressed Stabilized Earth Blocks (CSEBs) composed of soil and plantain banana trunks subjected to various treatments. The results reveal significant variations depending on the applied treatments, highlighting the impact of compositional parameters on the strength and durability of CSEBs. These findings offer promising perspectives for optimizing eco-friendly construction materials.

3.1. Grain Size Analysis by Sieving

The grain size analysis of the soil samples shows a predominance of fine particles, characteristic of silty or clayey soils, which are well-suited for the formulation of Compressed Stabilized Earth Blocks (CSEBs). The presence of clay enhances the cohesion and stability of CSEBs, both of which are crucial for their long-term durability (Muntohar et al., 2020; Ilboudo et al., 2023).

However, excessive clay content can lead to shrinkage and cracking, reducing the performance of the materials (Obonyo et al., 2023). Clay soils, thanks to their water retention capacity, are ideal for construction, but they require an optimal balance to avoid environmental sensitivity.

Recent studies emphasize the importance of particle size characteristics for resistance to extreme weather conditions (Ouédraogo et al., 2023). A rigorous approach is therefore essential to formulate durable CSEBs, taking into account the specific properties of local soils. Future research should focus on adapting formulations to regional grain size distributions to maximize their structural effectiveness.



ANALYSE GRANULOMETRIQUE PAR TAMISAGE - NORME ISO 17892 - 4

Tamis D (mm)	31,5	25	20	16	12,5	10	6,3	5	4	2
Passant cumulé en %	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	99,95	99,69
ncertitude Composée Elargie U(%Ri)	± 0,23	± 0,23	± 0,23	± 0,24	± 0,25	± 0,26	± 0,27	± 0,28	± 0,29	± 0,30
Tamis D (mm)	1,25	0,63	0,20	0,08	0,063					
Passant cumulé en %	97,76	81,90	43,73	34,17	33,49					
ncertitude Composée Elargie U(%Ri)	± 0,31	± 0,32	± 0,34	± 0,36	± 0,37					

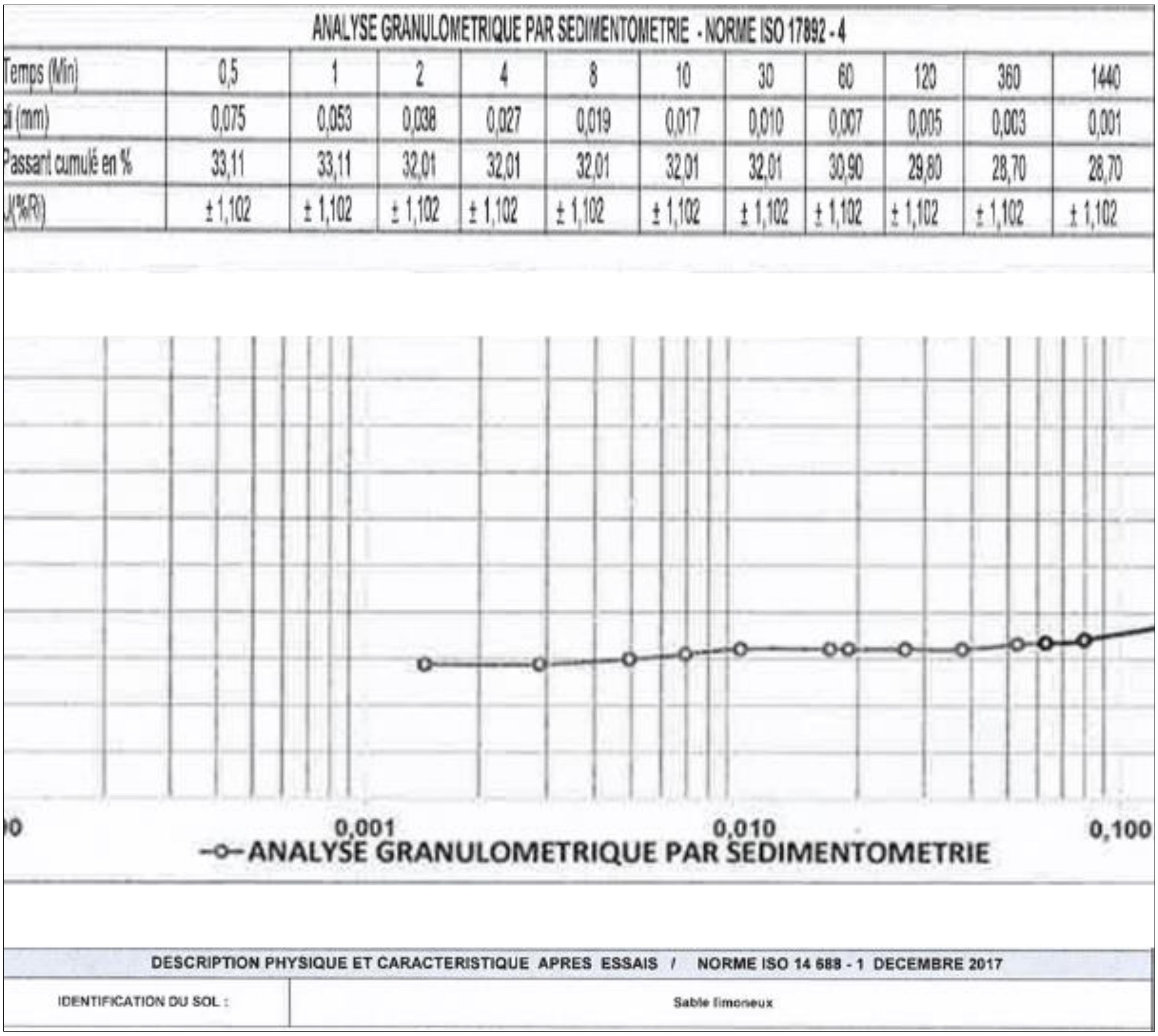
DESCRIPTION PHYSIQUE ET CARACTERISTIQUE APRES ESSAIS / NORME ISO 14 688 - 1 DECEMBRE 2017	
IDENTIFICATION DU SOL :	Sable limoneux

Figure 4 Grain Size Analysis by Sieving

3.2. Grain Size Analysis by Hydrometer

The hydrometer-based particle size analysis confirms the predominance of fine particles in the studied soils, classifying them as silty or clayey. This composition directly influences their physical properties, particularly water absorption and nutrient availability (Adingo et al., 2021; Cao et al., 2023). However, an excess of clay can lead to shrinkage and cracking risks, thereby compromising the durability of Compressed Stabilized Earth Blocks (CSEBs) (Balkıs et al., 2023).

Studies have emphasized that optimizing CSEBs requires a thorough understanding of local granulometric characteristics (Cao et al., 2022). An optimal balance of fine particles enhances both water infiltration and retention—critical factors for long-term stability (Ueda et al., 2022; Deng et al., 2023). Thus, the hydrometer analysis reinforces the importance of tailoring formulations to local soil profiles in order to ensure the performance and durability of CSEBs (Adingo et al., 2021; Kaur and Fanourakis, 2018).



ANALYSE GRANULOMETRIQUE PAR SEDIMENTOMETRIE - NORME ISO 17892-4

Temps (Min)	0,5	1	2	4	8	10	30	60	120	360	1440
di (mm)	0,075	0,053	0,038	0,027	0,019	0,017	0,010	0,007	0,005	0,003	0,001
Passant cumulé en %	33,11	33,11	32,01	32,01	32,01	32,01	32,01	30,90	29,80	28,70	28,70
U(%R)	± 1,102	± 1,102	± 1,102	± 1,102	± 1,102	± 1,102	± 1,102	± 1,102	± 1,102	± 1,102	± 1,102

Figure 5 Sedimentation Grain Size Analysis

3.3. CBR and PROCTOR Analysis

The Proctor test revealed an optimal moisture content of 7.45% and a dry bulk density of 1.98 t/m^3—key parameters for optimizing Compressed Stabilized Earth Blocks (CSEBs) (Nshimiyimana et al., 2020; Bailly et al., 2024). These indicators are essential for assessing material performance under load and for reinforcing their suitability in sustainable construction applications (Belayali et al., 2022).

In line with the findings of Donkor et al. (2021), the incorporation of natural fibers enhances both the strength and durability of CSEBs while positively influencing flexural strength and reducing environmental impact (Nshimiyimana et al., 2020). The production of CSEBs using different formulations enables a systematic comparison of mechanical and physical performance, thereby validating their structural properties (Kougoum et al., 2023; Oti and Kinuthia, 2020). These findings are critical to aligning CSEB performance with the evolving requirements of durability and efficiency in the construction industry (López-Rebollo et al., 2024; Char, 2024).

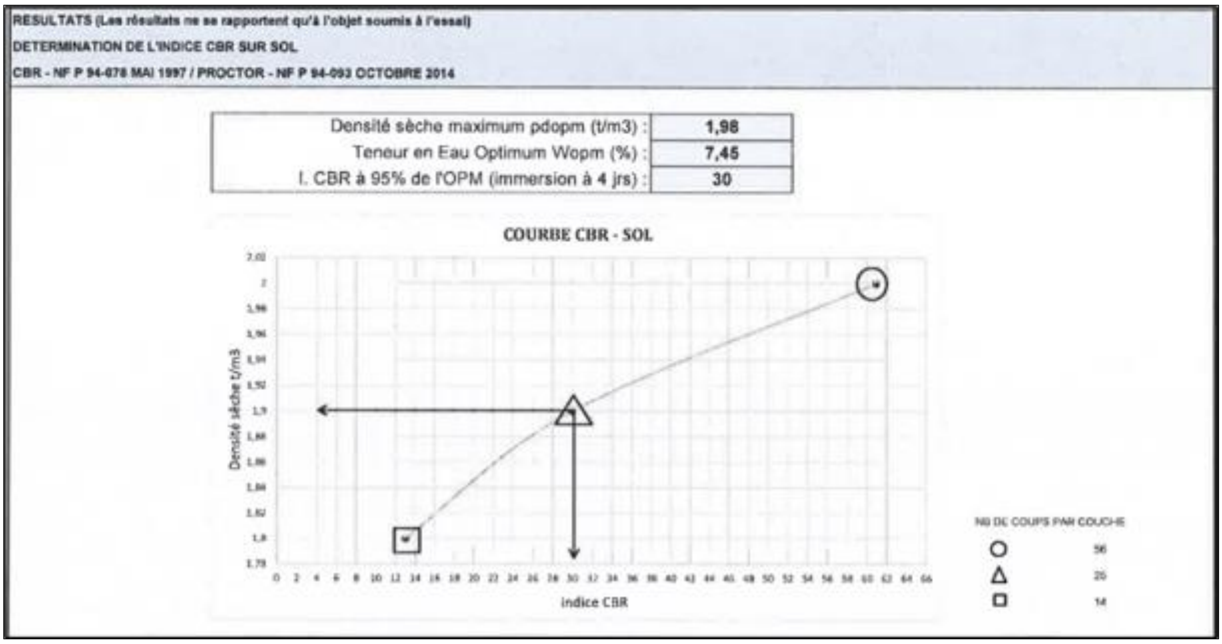


Figure 6 Determination of the CBR Index on Soil

3.4. Formulation Determination at 28 Days

Mechanical tests reveal that the unstabilized control sample exhibits values of 0.55 ± 0.28 MPa in flexural strength and 2 ± 0.31 MPa in compressive strength. The analysis of the mixtures composed of soil + sand + banana trunk powder (BTP) and soil + sand + cement shows contrasting behaviors depending on the additive proportions.

For BTP, three tests were conducted at a 2% dosage, with test No. 5 yielding the best results based on the median principle, reaching 0.82 ± 0.10 MPa in flexion and 3.91 ± 0.58 MPa in compression. Conversely, at 10% dosage (test No. 25), values significantly dropped to 0.22 ± 0.00 MPa and 0.62 ± 0.02 MPa respectively, indicating structural degradation at high concentrations (Belaribi et al., 2024). These findings corroborate previous studies showing that natural fibers like BTP enhance mechanical performance at low dosages but become counterproductive when used in excess (Serifou et al., 2020; Naceri and Vautrin, 2010). BTP thus acts as an optimal binder at low concentrations (Guettala and Mezghiche, 2011).

In contrast, cement-based mixtures demonstrated a linear improvement in performance as the dosage increased, reaching 2.59 ± 0.31 MPa in flexion and 12.32 ± 0.66 MPa in compression at 10% dosage (test No. 29), confirming its effectiveness as a high-strength binder (Helson et al., 2020). However, this comes with a significant environmental cost due to greenhouse gas emissions (Lessard et al., 2019).

In conclusion, the combination of 2% BTP with 13% water offers the best compromise between mechanical performance and environmental sustainability, while a 10% cement dosage with 13% water provides maximum strength. These findings pave the way for the development of sustainable construction materials that meet contemporary environmental challenges (Hayek et al., 2020; Tiana et al., 2014).

Table 4 Results of Control Samples

Test Control Sample	**Component 1 A: Clay + Sand %**	**Component 3 B: water %**	**Total Mass (g)**	**FLEXURAL STRENGTH RESULT**				**COMPRESSIVE STRENGTH RESULT**						
				R1	R2	R3	Average	R1	R2	R3	R4	R5	R6	Average
1	100%	9%		0.07	0.17	0.25	0.16±0.09	0.75	0.78	0.79	0.8	0.82	0.86	0.80±0.04
1	1350	121.5	1472	0.07	0.17	0.25	0.16±0.09	0.75	0.78	0.79	0.8	0.82	0.86	0.80±0.04
2	100%	10%		0.15	0.24	0.32	0.24±0.09	0.65	0.85	0.95	0.97	1.1	1.3	0.97±0.22
2	1350	135	1485	0.15	0.24	0.32	0.24±0.09	0.65	0.85	0.95	0.97	1.1	1.3	0.97±0.22
3	100%	11%		0.2	0.35	0.47	0.34±0.14	1	1.15	1.25	1.29	1.45	1.6	1.29±0.21
3	1350	146.5	1497	0.2	0.35	0.47	0.34±0.14	1	1.15	1.25	1.29	1.45	1.6	1.29±0.21
4	100%	12%		0.25	0.48	0.68	0.47±0.22	0.7	1.1	1.4	1.48	1.8	2.4	1.48±0.58
4	1350	162	1512	0.25	0.48	0.68	0.47±0.22	0.7	1.1	1.4	1.48	1.8	2.4	1.48±0.58
5	100%	13%		0.26	0.55	0.8	0.54±0.27	1.2	1.4	1.7	1.78	2.1	2.5	1.78±0.47
5	1350	175.5	1526	0.26	0.55	0.8	0.54±0.27	1.2	1.4	1.7	1.78	2.1	2.5	1.78±0.47
6	100%	14%		0.28	0.58	0.79	0.55±0.26	1.6	1.75	1.95	2	2.25	2.45	2.00±0.31
6	1350	189	1539	0.28	0.58	0.79	0.55±0.26	1.6	1.75	1.95	2	2.25	2.45	2.00±0.31

Table 5 Results of the Mixture Design with Banana Trunk Powder

Test	**Component 1 A: Clay + Sand %**	**Component 2 B: Plantain banana trunk powder %**	**Component 3 C: water %**	**Total Mass (g)**	**FLEXURAL STRENGTH RESULT**				**COMPRESSIVE STRENGTH RESULT**						
					R1	R2	R3	**Average**	R1	R2	R3	R4	R5	R6	**Average**
1	100%	2%	9%		0.59	0.7	0.69	**0.66±0.06**	2.88	2.98	3.1	3.21	3.21	3.31	**3.12±0.16**
1	1350	27	121.5	1498.5	0.59	0.7	0.69	**0.66±0.06**	2.88	2.98	3.1	3.21	3.21	3.31	**3.12±0.16**
2	100%	2%	10%		0.67	0.7	0.73	**0.70±0.03**	3.14	3.21	3.28	3.31	3.48	3.45	**3.31±0.13**

2	1350	27	135	1512	0.67	0.7	0.73	**0.70±0.03**	3.14	3.21	3.28	3.31	3.48	3.45	**3.31±0.13**
3	100%	2%	11%		0.84	0.78	0.6	**0.74±0.12**	3.1	3.3	3.48	3.6	3.75	3.84	**3.51±0.28**
3	1350	27	146.5	1523.5	0.84	0.78	0.6	**0.74±0.12**	3.1	3.3	3.48	3.6	3.75	3.84	**3.51±0.28**
4	100%	2%	12%		0.78	0.74	0.82	**0.78±0.04**	3.4	3.51	3.69	3.85	3.9	3.9	**3.71±0.21**
4	1350	27	162	1539	0.78	0.74	0.82	**0.78±0.04**	3.4	3.51	3.69	3.85	3.9	3.9	**3.71±0.21**
5	100%	2%	13%		0.89	0.7	0.87	**0.82±0.10**	3.1	3.4	3.82	4.13	4.45	4.55	**3.91±0.58**
5	1350	27	175.5	1552.5	0.89	0.7	0.87	**0.82±0.10**	3.1	3.4	3.82	4.15	4.45	4.55	**3.91±0.58**
6	100%	2%	14%		0.7	1.02	0.86	**0.86±0.16**	3.1	3.2	4.15	4.9	5	6.15	**4.42±1.17**
6	1350	27	189	1566	0.7	1.02	0.86	**0.86±0.16**	3.1	3.2	4.15	4.9	5	6.15	**4.42±1.17**
7	100%	4%	9%		0.6	0.58	0.62	**0.60±0.02**	2.1	2.2	2.35	2.47	2.55	2.52	**2.37±0.18**
7	1350	54	121.5	1525.5	0.6	0.58	0.62	**0.60±0.02**	2.1	2.2	2.35	2.47	2.55	2.52	**2.37±0.18**
8	100%	4%	10%		0.64	0.61	0.67	**0.64±0.03**	1.9	2.1	2.35	2.6	2.75	2.83	**2.42±0.37**
8	1350	54	135	1539	0.64	0.61	0.67	**0.64±0.03**	1.9	2.1	2.35	2.6	2.75	2.83	**2.42±0.37**
9	100%	4%	11%		0.68	0.64	0.71	**0.68±0.04**	2.2	2.45	2.35	2.55	2.63	2.64	**2.47±0.17**
9	1350	54	148.5	1552.5	0.68	0.64	0.71	**0.68±0.04**	2.2	2.45	2.35	2.55	2.63	2.64	**2.47±0.17**
10	100%	4%	12%		0.8	0.7	0.66	**0.72±0.07**	2.35	2.2	2.5	2.65	2.73	2.67	**2.52±0.21**
10	1350	54	162	1566	0.8	0.7	0.66	**0.72±0.07**	2.35	2.2	2.5	2.65	2.73	2.67	**2.52±0.21**
11	100%	4%	13%		0.73	0.76	0.85	**0.78±0.06**	2.6	2.58	2.57	2.05	3.09	2.54	**2.57±0.33**
11	1350	54	175.5	1579.5	0.73	0.76	0.85	**0.78±0.06**	2.6	2.58	2.57	2.05	2.09	2.54	**2.41±0.26**
12	100%	4%	14%		0.75	0.85	0.8	**0.80±0.05**	2	2.35	2.5	2.8	2.95	3.1	**2.62±0.41**
12	1350	54	189	1593	0.75	0.85	0.8	**0.80±0.05**	2	2.35	2.5	2.8	2.95	3.1	**2.62±0.41**
13	100%	6%	9%		0.48	0.5	0.46	**0.48±0.02**	1.2	1.35	1.47	1.55	1.62	1.64	**1.47±0.17**
13	1350	81	121.5	1552.5	0.48	0.5	0.46	**0.48±0.02**	1.2	1.35	1.47	1.55	1.62	1.64	**1.47±0.17**
14	100%	6%	10%		0.52	0.49	0.55	**0.52±0.03**	1.4	1.45	1.5	1.52	1.55	1.58	**1.50±0.07**
14	1350	81	135	1566	0.52	0.49	0.55	**0.52±0.03**	1.4	1.45	1.5	1.52	1.55	1.58	**1.50±0.07**
15	100%	6%	11%		0.56	0.53	0.59	**0.56±0.03**	1.2	1.35	1.5	1.62	1.8	1.7	**1.53±0.22**

15	1350	81	148.5	1579.5	0.56	0.53	0.59	**0.56±0.03**	1.2	1.35	1.5	1.62	1.8	1.7	**1.53±0.22**
Test	**Component 1 A: Clay + Sand %**	**Component 2 B: Plantain banana trunk powder %**	**Component 3 C:water %**	**Total Mass (g)**	**FLEXURAL STRENGTH RESULT**				**COMPRESSIVE STRENGTH RESULT**						
					R1	R2	R3	**Average**	R1	R2	R3	R4	R5	R6	**Average**
16	100%	6%	12%		0.6	0.53	0.67	**0.60±0.07**	1.5	1.5	1.56	1.5	1.7	1.6	**1.56±0.08**
16	1350	81	162	1593	0.6	0.53	0.67	**0.60±0.07**	1.5	1.5	1.56	1.5	1.7	1.6	**1.56±0.08**
17	100%	6%	13%		0.69	0.64	0.59	**0.64±0.05**	1.54	1.58	1.5	1.6	1.63	1.69	**1.59±0.07**
17	1350	81	175.5	1606.5	0.69	0.64	0.59	**0.64±0.05**	1.54	1.58	1.5	1.6	1.63	1.69	**1.59±0.07**
18	100%	6%	14%		0.68	0.71	0.65	**0.68±0.03**	1.25	1.6	1.4	1.75	1.9	1.8	**1.62±0.25**
18	1350	81	189	1620	0.68	0.71	0.65	**0.68±0.03**	1.25	1.6	1.4	1.75	1.9	18	**1.62±0.25**
19	100%	8%	9%		0.35	0.33	0.37	**0.35±0.02**	0.55	0.65	0.72	0.78	0.8	0.8	**0.72±0.10**
19	1350	108	121.5	1579.5	0.35	0.33	0.37	**0.35±0.02**	0.55	0.65	0.72	0.78	0.8	0.8	**0.72±0.10**
20	100%	8%	10%		0.39	0.3	0.48	**0.39±0.09**	0.65	0.55	0.75	0.82	0.85	0.88	**0.75±0.13**
20	1350	108	135	1593	0.39	0.3	0.48	**0.39±0.09**	0.65	0.55	0.75	0.82	0.85	0.88	**0.75±0.13**
21	100%	8%	11%		0.43	0.39	0.47	**0.43±0.04**	0.5	0.55	0.7	0.85	0.95	1.1	**0.78±0.23**
21	1350	108	148.5	1606.5	0.43	0.39	0.47	**0.43±0.04**	0.5	0.55	0.7	0.85	0.95	1.1	**0.78±0.23**
22	100%	8%	12%		0.47	0.5	0.44	**0.47±0.03**	0.7	0.6	0.9	0.78	0.95	0.92	**0.81±0.14**
22	1350	108	162	1620	0.47	0.5	0.44	**0.47±0.03**	0.7	0.6	0.9	0.78	0.95	0.92	**0.81±0.14**
23	100%	8%	13%		0.51	0.55	0.47	**0.51±0.04**	0.55	0.6	0.75	0.9	1	1.25	**0.84±0.26**
23	1350	108	175,5	1633.5	0.51	0.55	0.47	**0.51±0.04**	0.55	0.6	0.75	0.9	1	1.25	**0.84±0.26**
24	100%	8%	14%		0.55	0.54	0.56	**0.55±0.01**	0.7	0.78	0.85	0.9	0.95	1.01	**0.87±0.11**
24	1350	108	189	1647	0.55	0.54	0.56	**0.55±0.01**	0.7	0.78	0.85	0.9	0.95	1.01	**0.87±0.11**
25	100%	10%	9%		0.22	0.22	0.22	**0.22±0.00**	0.65	0.63	0.62	0.6	0.64	0.59	**0.62±0.02**
25	1350	135	121.5	1606.5	0.22	0.22	0.22	**0.22±0.00**	0.65	0.63	0.62	0.6	0.64	0.59	**0.62±0.02**
26	100%	10%	10%		0.26	0.25	0.27	**0.26±0.01**	0.55	0.58	0.65	0.7	0.75	0.67	**0.65±0.07**
26	1350	135	135	1620	0.26	0.25	0.27	**0.26±0.01**	0.55	0.58	0.65	0.7	0.75	0.67	**0.65±0.07**

27	100%	10%	11%		0.3	0.28	0.32	**0.30±0.02**	0.5	0.6	0.68	0.72	0.77	0.8	**0.68±0.11**
27	1350	135	148.5	1633.5	0.3	0.28	0.32	**0.30±0.02**	0.5	0.6	0.68	0.72	0.77	0.8	**0.68±0.11**
28	100%	10%	12%		0.34	0.37	0.31	**0.34±0.03**	0.68	0.71	0.75	0.68	0.73	0.78	**0.72±0.04**
28	1350	135	162	1647	0.34	0.37	0.31	**0.34±0.03**	0.68	0.71	0.75	0.68	0.73	0.78	**0.72±0.04**
29	100%	10%	13%		0.38	0.46	0.3	**0.38±0.08**	0.55	0.63	0.8	0.72	0.9	0.9	**0.75±0.14**
29	1350	135	175.5	1660.5	0.38	0.46	0.3	**0.38±0.08**	0.55	0.63	0.8	0.72	0.9	0.9	**0.75±0.14**
30	100%	10%	14%		0.42	0.38	0.46	**0.42±0.04**	0.6	0.6	0.7	0.96	1.06	0.7	**0.77±0.19**
30	1350	135	189	1674	0.42	0.38	0.46	**0.42±0.04**	0.6	0.6	0.7	0.96	1.06	0.7	**0.77±0.19**

Table 6 Results of the Mixture Design with Cement

Essai	**Component 1 A: Clay + Sand %**	**Component 2 B: Cement %**	**Component 3 C: water %**	**Total Mass (g)**	**FLEXURAL STRENGTH RESULT**				**COMPRESSIVE STRENGTH RESULT**						
					R1	**R2**	**R3**	**Average**	**R1**	**R2**	**R3**	**R4**	**R5**	**R6**	**Average**
1	100%	2%	9%		0.45	0.51	0.57	0.51±0.06	2.6	2.4	2	3	2.53	2.5	2.51±0.07
1	1350	27	121.5	1498.5	0.45	0.51	0.57	0.51±0.06	2.6	2.4	2	3	2.53	2.51	2.51±0.07
2	100%	2%	10%		0.52	0.6	0.5	0.54±0.02	2.49	2.67	3	3	2.67	2.85	2.66±0.13
2	1350	27	135	1512	0.52	0.6	0.5	0.54±0.02	2.49	2.67	3	3	2.67	2.85	2.66±0.13
3	100%	2%	11%		0.47	0.7	0.6	0.59±0.12	2.73	2.82	3	3	2.85	2.91	2.81±0.06
3	1350	27	146.5	1523.5	0.47	0.7	0.6	0.59±0.12	2.73	2.82	3	3	2.85	2.91	2.81±0.06
4	100%	2%	12%		0.65	0.6	0.7	0.64±0.01	2.95	2.97	3	3	2.93	3.11	2.97±0.08
4	1350	27	162	1539	0.65	0.6	0.7	0.64±0.01	2.95	2.97	3	3	2.93	3.11	2.97±0.08
5	100%	2%	13%		0.59	0.7	0.8	0.69±0.10	3	3	3	3	3.2	3.28	3.11±0.11
5	1350	27	175.5	1552.5	0.59	0.7	0.8	0.69±0.10	3	3	3	3	3.2	3.28	3.11±0.11
6	100%	2%	14%		0.68	0.8	0.7	0.74±0.06	3.25	3.27	3	4	3.29	3	3.27±0.18
6	1350	27	189	1566	0.68	0.8	0.7	0.74±0.06	3.25	3.27	3	4	3.28	3	3.27±0.18
7	100%	4%	9%		1.06	0.6	0.8	0.81±0.25	3.8	3.82	4	4	3.6	4.04	3.82±0.14

7	1350	54	121.5	1525.5	1.06	0.6	0.8	0.81±0.25	3.8	3.82	4	4	3.6	4.04	3.82±0.14
8	100%	4%	10%		0.85	0.8	0.9	0.84±0.01	3.6	3.92	4	4	4.29	4.62	4.07±0.35
8	1350	54	135	1539	0.86	0.8	0.9	0.84±0.01	3.6	3.92	4	4	4.29	4.62	4.07±0.35
9	100%	4%	11%		1.05	0.7	0.9	0.89±0.16	4.04	4.34	4	5	4.5	4.6	4.32±0.29
9	1350	54	148.5	1552.5	1.05	0.7	0.9	0.89±0.16	4.04	4.34	4	5	4.5	4.6	4.32±0.29
10	100%	4%	12%		0.95	0.9	0.9	0.94±0.01	3.54	4.88	4	5	4.77	5.07	4.57±0.57
10	1350	54	162	1566	0.95	0.9	0.9	0.94±0.01	3.54	4.88	4	5	4.77	5.07	4.57±0.57
11	100%	4%	13%		1.07	0.9	1	0.99±0.08	3.94	5.34	4	5	5.44	5.54	4.90±0.65
11	1350	54	175.5	1579.5	1.07	0.9	1	0.99±0.08	3.94	5.34	4	5	5.44	5.54	4.90±0.65
12	100%	4%	14%		1.14	0.9	1	1.04±0.10	4.48	5.68	5	5	5.37	5.57	5.19±0.44
12	1350	54	189	1593	1.14	0.9	1	1.04±0.10	4.48	5.68	5	5	5.37	5.57	5.19±0.44
13	100%	6%	9%		1.53	0.9	1.2	1.21±0.32	5.22	6.6	5	6	6.32	6.22	5.83±0.69
13	1350	81	121.5	1552.5	1.53	0.9	1.2	1.21±0.32	5.22	6.6	5	6	6.32	6.22	5.83±0.69
14	100%	6%	10%		1.33	12	1.2	1.24±0.09	6.23	5.1	7	5	6.94	6.57	6.17±0.76
14	1350	81	135	1566	1.33	1.2	1.2	1.24±0.09	6.23	5.1	7	5	6.94	6.57	6.17±0.76
15	100%	6%	11%		1.32	1.3	1.3	1.29±0.03	6.5	6.18	6	7	6.72	6.82	6.52±0.23
15	1350	81	148.5	1579.5	1.32	1.3	1.3	1.29±0.03	6.5	6.18	6	7	6.72	6.82	6.52±0.23

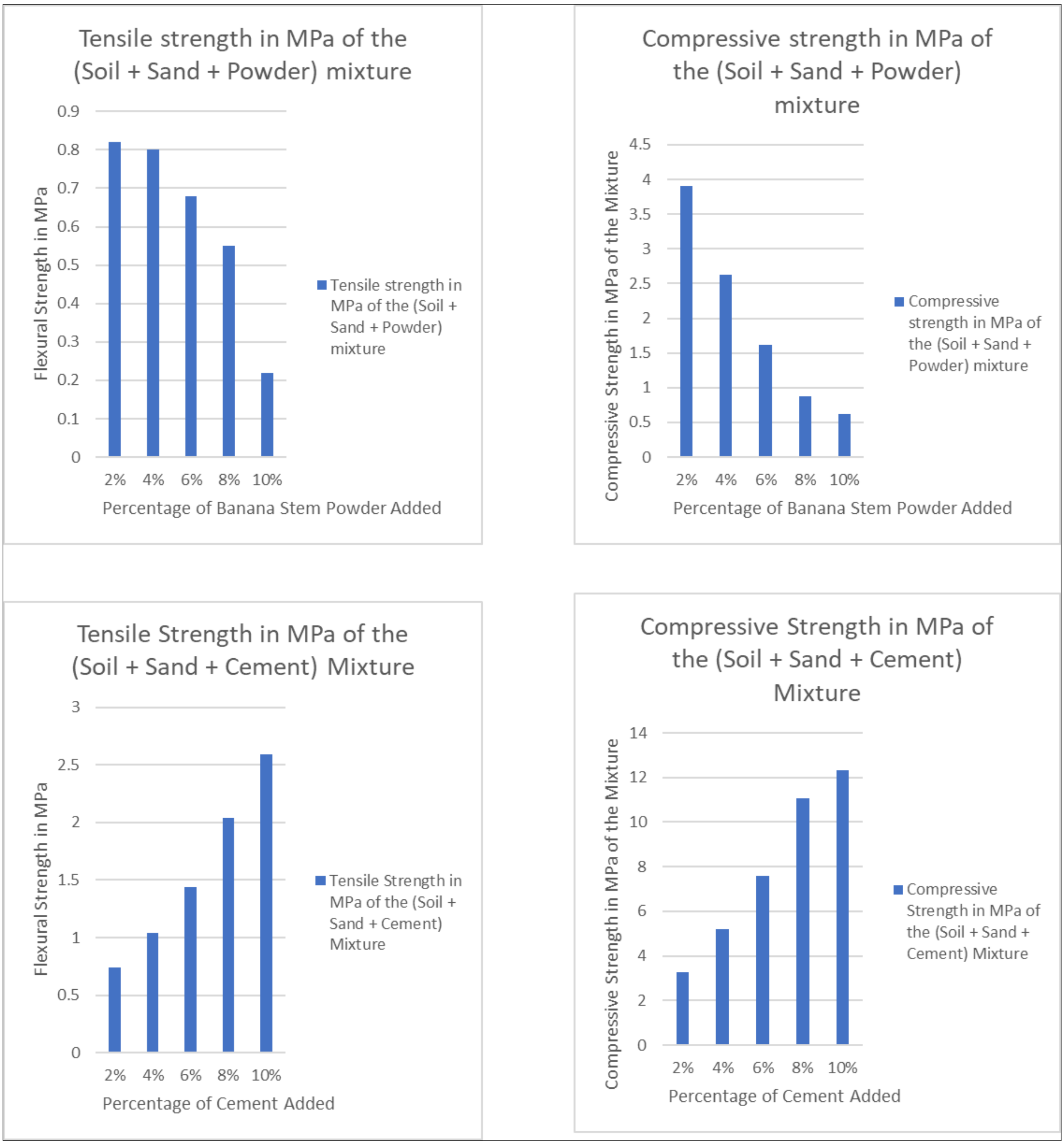


Figure 7 Flexural and Compressive Strength Values by Powder and Cement Percentage

4. Conclusion

This study demonstrates that incorporating a small proportion of banana trunk powder (BTP) can yield satisfactory mechanical properties in composite materials, achieving a balance between performance and sustainability while promoting the use of a local and renewable resource. However, at higher concentrations, its effectiveness declines, disrupting the cohesion of the material.

Compared to cement which, when used intensively, results in high emissions and a significant carbon footprint—BTP presents an environmentally friendly and cost-effective alternative. While cement requires larger proportions to achieve optimal performance, its environmental impact limits its viability as a sustainable binder. Conversely, BTP, even at low dosages, helps reduce environmental impact while maintaining acceptable mechanical strength.

Therefore, the integration of low proportions of BTP into construction materials emerges as a sustainable and eco-responsible solution that addresses current climate challenges. This approach fosters greener construction practices and adds value to agricultural waste, opening new and innovative pathways for the future.

Compliance with ethical standards

Acknowledgments

We would like to express our thanks to all the participants who contributed to the completion of this study.

Disclosure of conflict of interest

Authors have declared that no competing interests exist.

Disclaimer (artificial intelligence)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

References

[1] Adingo, S., Yu, J., Liu, X., Jing, S., Li, X., and Xiaoning, Z. (2021). Land-use change influence soil quality parameters at an ecologically fragile area of Yongdeng County of Gansu Province, China. PeerJ, 9, e12246. https://doi.org/10.7717/peerj.12246

[2] Adjacou, D., Houéhanou, T., Gouwakinnou, G., and Natta, A. (2022). Ethnoecological knowledge of local Mangifera indica L. varieties in the Atacora region of Benin: uses, diversity, and perceptions of climate change. *Annales de l'Université de Parakou - Natural Sciences and Agronomy Series*, 12(1), 15–28. https://doi.org/10.56109/aup-sna.v12i1.107

[3] Belaribi, O., Safer, O., Belas, N., Belguesmia, K., and Sadok, R. (2024). Influence of perlite on mechanical behavior, capillary absorption, and thermal conductivity of mortars. *The Journal of Engineering and Exact Sciences*, 10(3), 18800. https://doi.org/10.18540/jcecvl10iss3pp18800

[4] Cao, D., Fayou, A., Li, Y., Yang, T., and Liao, Q. (2023). Characterization of the migration of soil particles in lateritic soils under the effect of rainfall. Applied Sciences, 13(22), 12292. https://doi.org/10.3390/app132212292

[5] Cao, Z., Sun, W., Xie, Q., Wu, Z., Fu, X., Fumagalli, A., … and Li, L. (2022). Fluid–solid coupled model for the internal erosion of gap-graded soil–rock mixtures with different fines contents: its verification and application. Hydrological Processes, 36(9). https://doi.org/10.1002/hyp.14677

[6] Coulibaly, K., N'Da, K., Sylla, D., Dibi-Anoh, P., and Goula, B. (2024). Persistence of rainfall sequences and flood risk in Côte d'Ivoire from 1971 to 2022. European Scientific Journal ESJ, 25. https://doi.org/10.19044/esipreprint.1.2024.p23

[7] Deng, Z., Chen, X., Jin, W., and Wang, G. (2023). Effect of gradation characteristics and particle morphology on internal erosion of sandy gravels: a large-scale experimental study. Water, 15(14), 2660. https://doi.org/10.3390/w15142660

[8] Dionne, L., and Lefebvre, I. (2022). Environmental and climate change education: support from international agreements for institutionalization. *Éducation Relative à l'Environnement*, 17(1). https://doi.org/10.4000/ere.8543

[9] Doffou, S., Kouadio, H., and Dibi, H. (2021). Predicted climate change effects by 2050 on the phytogeographic distribution of *Tieghemella heckelii* Pierre ex A. Chev. (Sapotaceae) in Côte d'Ivoire. International Journal of Biological and Chemical Sciences, 15(2), 679-694. https://doi.org/10.4314/ijbcs.v15i2.23

[10] Egah, J. (2021). Adapting agricultural financing models to climate change: the case of warrantage in Benin. *Tropicultura*, (4). https://doi.org/10.25518/2295-8010.1923

[11] Fofana, M. (2023). Human occupation practices in flood-prone urban areas: a case study of Abidjan (Côte d'Ivoire). *International Journal of Progressive Sciences and Technologies*, 38(2), 507. https://doi.org/10.52155/ijpsat.v38.2.5300

[12] Guettala, S., and Mezghiche, B. (2011). Effect of dune sand powder addition on the properties of concrete. European Journal of Environmental and Civil Engineering, 15(10), 1483-1507. https://doi.org/10.1080/19648189.2011.9723355

[13] Hayek, M., Salgues, M., Habouzit, F., Bayle, S., Souche, J., Weerdt, K., … and Pioch, S. (2020). Impact of carbonation on biocolonization of cement-based materials in marine environments. *Matériaux et Techniques*, 108(2), 202. https://doi.org/10.1051/mattech/2020020

[14] Helson, O., Eslami, J., Beaucour, A., Noumowé, A., and Gotteland, P. (2020). Parametric study of model materials: support for the design of underground works using soil–cement mixtures. *Revue Française de Géotechnique*, (162), 2. https://doi.org/10.1051/geotech/2020004

[15] Ilboudo, E., Kogou, A., and Yoda, A. (2023). Properties of clay for compressed earth block production in tropical regions. *International Journal of Sustainable Building Technology and Urban Development*, 14(1), 30-43. https://doi.org/10.1080/2093761X.2023.2237485

[16] Kaur, A., and Fanourakis, G. (2018). Effect of sodium carbonate concentration in calgon on hydrometer analysis results. Periodica Polytechnica Civil Engineering. https://doi.org/10.3311/ppci.9424

[17] Lessard, J., Habert, G., Tagnit-Hamou, A., and Amor, B. (2019). Climate change implications of sustainable development initiatives: focus on Portland cement. *Le Climatoscope*, (1), 46-53. https://doi.org/10.17118/11143/18889

[18] Muntohar, A. S., Hadi, S., Prabowo, A. H., and Sari, A. (2020). Granulometric analysis of local soil for compressed stabilized earth blocks. *Journal of Engineering Science and Technology*, 15(3), 1558-1570. https://doi.org/10.1016/j.jestch.2020.09.014

[19] Naceri, A., and Vautrin, A. (2010). Mechanical behavior of a composite (glass fabric/epoxy resin) under different hygrothermal aging periods. *Afrique Science International Journal of Science and Technology*, 2(2). https://doi.org/10.4314/afsci.v2i2.61146

[20] Nougtara, S., Kiema, A., Soudré, A., Guissou, L., and Berthe, T. (2021). Adaptation of cattle breeding in western Burkina Faso to recurring droughts. International Journal of Biological and Chemical Sciences, 15(4), 1648-1666. https://doi.org/10.4314/ijbcs.v15i4.27

[21] Obonyo, E. O., Otieno, A., and Were, J. (2023). Influence of clay content on the mechanical properties of stabilized earth blocks. *Construction* and Building Materials, 368, 130010. https://doi.org/10.1016/j.conbuildmat.2022.130010

[22] Ouédraogo, S., Wane, A. O., and Zongo, A. (2023). Role of soil particle size distribution in compressed earth block performance under extreme climates. *Environmental Earth Sciences*, 82(5), 17-29. https://doi.org/10.1007/s12665-023-10790

[23] Petit, S., Vergote, M., Castel, T., and Richard, Y. (2020). use of proxies to connect knowledge. *Natures Sciences Sociétés*, 28(1), 12-23. https://doi.org/10.1051/nss/2020016

[24] Ruf, F. (2022). Covid-19, decent income gaps, and declining cocoa farmer income in Côte d'Ivoire. *Cahiers Agricultures*,31, 25. https://doi.org/10.1051/cagri/2022022

[25] Serifou, M., Jolissaint, O., Kouassi, B., and Emeruwa, E. (2020). Physico-mechanical analysis of a rice straw/cement composite. *Matériaux et Techniques*, 108(2), 208. https://doi.org/10.1051/mattech/2020024

[26] Tiana, R., Ramamonjy, M., and Mandimby, T. (2014). Development of industrial ecology in Madagascar: utilization of fly ash in concrete construction. *Environnement Ingénierie et Développement*, No. 67 – June 2014. https://doi.org/10.4267/dechets-sciences-techniques.316

[27] Tobias, S., Siegrist, E., Bütikofer, L., Bürgi, M., Liechti, K., Reynard, E., … and Randin, C. (2023). +4 °C and beyond: Swiss landscapes facing climate change. https://doi.org/10.55419/wsl:35310

[28] Ueda, Y., Izumi, Y., Hirooka, Y., Watanabe, Y., and Iijima, M. (2022). Fine soil particle aggregation in ultra-fine bubble irrigated paddy fields. Water Science and Technology Water Supply, 22(11), 7972-7981. https://doi.org/10.2166/ws.2022.368