Archives of Current Research International

Volume 25, Issue 8, Page 19-31, 2025; Article no.ACRI.140403
ISSN: 2454-7077

Effect of a 90-day Curing Time on the Mechanical Properties of Stabilized Compressed Earth Blocks Reinforced with Banana Trunk Powder

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/acri/2025/v25i81391

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/140403

Original Research Article

Received: 24/05/2025
Published: 28/07/2025

ABSTRACT

In the context of combating climate change and reducing the carbon footprint of the construction sector, this study focuses on the evaluation of the mechanical performance of Stabilized Compressed Earth Blocks (SCEB) incorporating banana trunk powder (BTP) as a partial alternative to cement. The main objective is to analyze the impact of an extended curing time of 90 days on the mechanical strength of laboratory-made SCEBs. Two formulations were studied: earth + sand +

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***Cite as:** DAGO, Sylvestre, Konin Athanas, Koffi Morofie Justin KOUAME, and Koffi David AKAKI. 2025. "Effect of a 90-Day Curing Time on the Mechanical Properties of Stabilized Compressed Earth Blocks Reinforced With Banana Trunk Powder". Archives of Current Research International 25 (8):19-31. https://doi.org/10.9734/acri/2025/v25i81391.*

BTP and earth + sand + cement, with stabilizer dosages ranging from 2% to 10% and a water content between 9% and 14%. The results show that the formulation with 2% BTP and 13% water offers the best mechanical performances after 90 days of curing, reaching 1.89 ± 0.01 MPa in flexion and 6.84 ± 0.12 MPa in compression, a significant improvement compared to the performances observed at 28 days (0.82 ± 0.10 MPa in flexion and 3.91 ± 0.58 MPa in compression). On the other hand, an increase in the BTP rate beyond 2% leads to a significant decrease in strength. Conversely, cement-based formulations exhibit a linear performance evolution, reaching 4.02 ± 0.07 MPa in flexure and 18.77 ± 0.36 MPa in compression at 10% cement and 13% water, compared to 2.59 ± 0.31 MPa and 12.32 ± 0.66 MPa respectively at 28 days. This study demonstrates that the use of 2% BTP with a 90-day curing time is an optimal solution, combining mechanical efficiency, low environmental impact and the recovery of agricultural waste, thus contributing to the promotion of sustainable and ecological construction materials.

Keywords: SCEB; BTP; mechanical resistance; curing time.

1. INTRODUCTION

In a global context marked by the climate emergency and the need to reduce the carbon footprint of the construction sector, compressed and stabilized earth blocks (CSEBs) are emerging as a sustainable, ecological and economical alternative, effectively valorizing local resources and agricultural waste such as banana trunk powder (Arduin et al*.,* 2022). These materials are fully in line with sustainable construction approaches, making it possible to limit the use of conventional materials with high carbon emissions while offering a second life to agricultural waste (Jaafar et al*.,* 2023). Indeed, the integration of SCEB responds to the environmental challenges linked to rapid urbanization and contributes to the reduction of environmental impacts (Droutsa et al*.,* 2023). However, the mechanical performance and durability of these materials are highly dependent on the curing time, a key parameter that determines the effectiveness of stabilization reactions, the reduction of porosity and, consequently, the improvement of mechanical resistance (Arairo et al*.,* 2023). Several studies have demonstrated that a prolonged curing time, particularly 90 days, significantly improves compressive and flexural strength, making these materials more suitable for the structural requirements of modern constructions (Abouhelal et al*.,* 2023; Ait et al*.,* 2023). This observation highlights the importance of controlling the duration of treatment to guarantee the performance of SCEB (Iwuanyanwu et al*.,* 2024). The problem of this study is therefore based on understanding the impact of a 90-day curing time on the evolution of the mechanical properties of SCEB, in order to maximize their durability and structural reliability. The general objective is to evaluate the influence of a prolonged curing time on the mechanical performance of SCEB designed in the laboratory, and the specific objective aims to precisely analyze the evolution of compressive and flexural strength as a function of this duration, in order to propose optimized, sustainable construction solutions that comply with eco-responsible construction standards.

2. MATERIALS AND METHODS

2.1 Study Site

The work was carried out in the autonomous district of Abidjan, more precisely in the commune of Cocody, particularly in the Palmeraie district, bordered by the zones of Riviera, Angré, Cocody Centre and II-Plateaux. The study also extended to the Lagunes district, in the Agnéby-Tiassa region, covering the localities of Tiassalé, located 120 km from Abidjan with approximately 60,000 inhabitants (coordinates: 5°53' N, 4°49' W), N'Douci, positioned between Tiassalé and Agboville, with nearly 40,000 inhabitants (coordinates: 6°03' N, 5°01' W), and Agboville, north of Tiassalé, with a population of approximately 120,000 inhabitants (coordinates: 5°56' N, 4°13' W). These areas, easily accessible thanks to a well-developed road network, are of major strategic interest on the economic, agricultural and cultural levels, which justifies their selection for the realization of this study.

2.2 Study Materials

The study involved samples of soil and plantain trunks from four major localities: Cocody palm grove, Agboville, Tiassalé, and N'douci. Sample collection took place from March 2024 to February 2025.

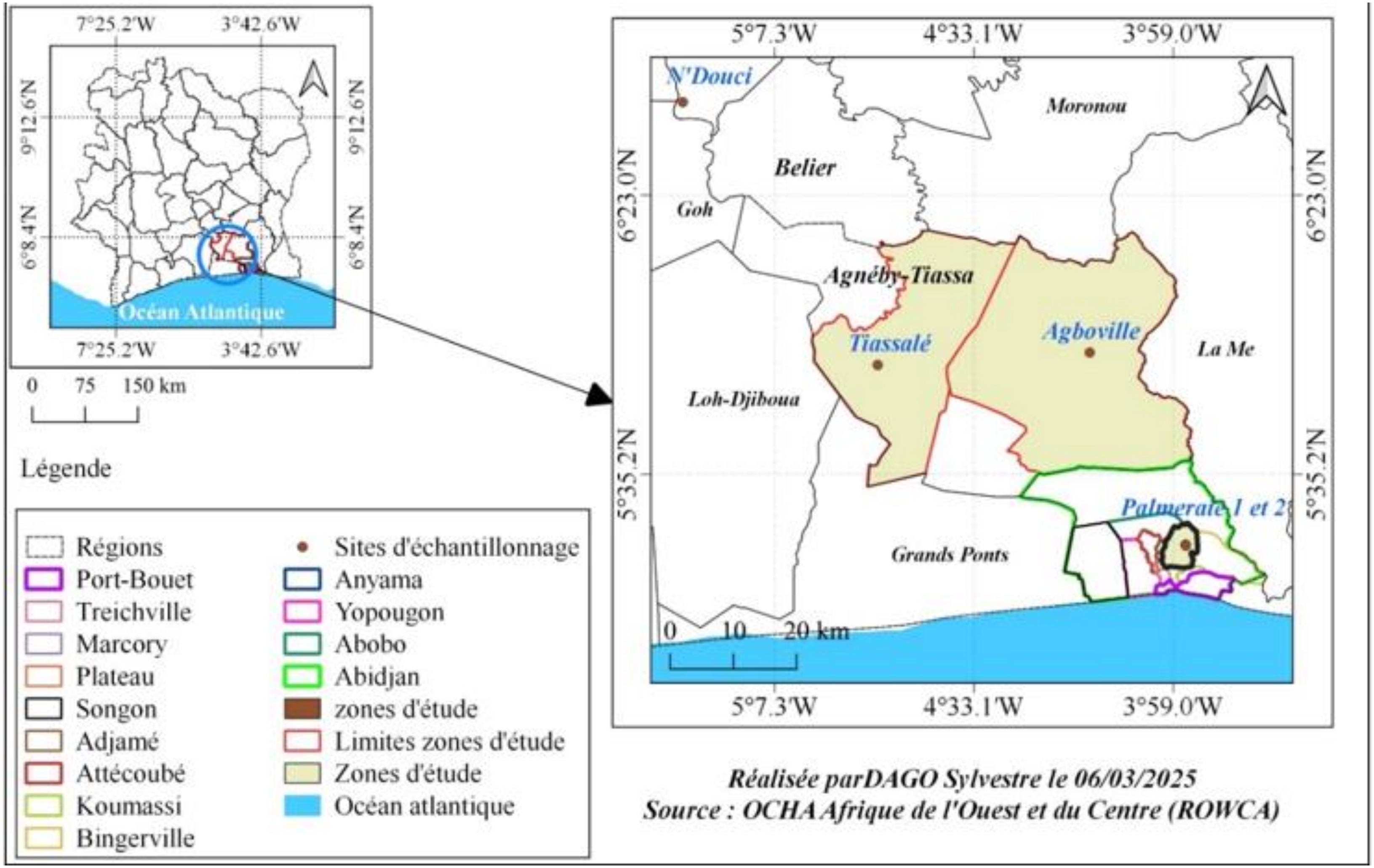

Fig. 1. Location of study areas

Fig. 2. Photographs of soil samples, banana trunk and SCEB

Fig. 3. Some illustrations of the technical equipment used

2.3 Technical Equipment

SCEB production relies on a set of specialized equipment that guarantees the quality and precision of the tests. For sample production, a mixer ensures the homogeneity of the mixes, while a SCEB mold is used to obtain blocks with standardized dimensions. The flexural press and the hydraulic compression press, equipped with load sensors, are used to evaluate the flexural and compressive strength respectively. Proctor and CBR tests require specific molds, compaction rams, and a CBR press to measure the bearing capacity of the materials. An oven is essential for drying and determining the optimal humidity, supplemented by a precision balance for mass control. Measuring instruments such as a caliper, a thermometer, and a hygrometer ensure control of dimensions and ambient conditions, while simple tools such as a wheelbarrow facilitate material logistics on the construction site. All of this equipment ensures the reliability, reproducibility, and performance of the manufactured SCEB.

2.4 Choice of Sampling Areas and Sites

The sites were selected for their soil quality, pedoclimatic diversity, and strong agricultural potential, particularly for plantain cultivation. Cocody-Palmeraie, despite its urban character, has suitable agricultural pockets, while Agboville stands out for its fertile soils and favorable climate. Tiassalé, with its hydromorphic soils and streams, benefits from constant humidity, and N'Douci has rich soils associated with a humid climate. This diversity helps ensure representative samples, while taking into account the influence of soil types and climatic conditions on the performance of SCEB. Finally, the good road accessibility of these sites facilitates transport to the laboratories and ensures the rigor of the study.

2.5 Sample Collection

Sampling was carried out at one site per study area, with a targeted selection of specific plots. At each site, four 100 kg soil samples and four 3.3 kg samples of dry fiber extracted from banana trunks were randomly collected. All samples were carefully packaged in new bags and labeled to ensure rigorous traceability. Three sampling campaigns were conducted over an eleven-month period, from March 2024 to February 2025, resulting in the collection of a total of 30 composite samples, representing 1200 kg of soil and 396 kg of dry fiber. All samples were then transported to the Cocody-Palmeraie site for processing, and then to the LBTB laboratory for analysis.

2.6 Process of Processing Banana Trunks Collected from the Study Sites

After collecting the banana trunks from the study sites, rigorous processing was carried out to ensure the quality of subsequent analyses. The fibers were first extracted, carefully cleaned, and then cut into homogeneous fragments to facilitate the following steps. These samples were then dried in an oven at 105 °C to remove any residual moisture, thus avoiding any alteration that could compromise the analytical results. Once dried, the fibers were ground using a laboratory grinder until a fine and homogeneous powder was obtained, totaling 300 kg of banana trunk powder, essential for the reproducibility of the analyses. The powder obtained was carefully packaged in airtight bags to preserve its physicochemical properties for the various planned analyses.

2.7 Choice of Mixing Plan

The mixing plan was developed using the factorial design of experiments method, in accordance with ISO 16269-8, to optimize binder proportions. Design-Expert 3 software was used to generate a rigorous plan comprising 30 tests per mix, i.e. 60 tests. Two formulations were studied: earth + sand + banana trunk powder and earth + sand + cement. This experimental strategy makes it possible to determine the optimal compositions, by evaluating the mechanical performance of the composites, to meet the requirements of durability and quality in construction.

2.8 Production Stage

The production of stabilized compressed earth blocks (SCEBs) follows a rigorous protocol starting with the preparation of 1350 g batches, weighed according to ISO 11464, then homogenized in accordance with ISO 17892-2 before molding into standardized shapes. The samples are then subjected to controlled curing in a climatic cabinet, under precise temperature and humidity conditions, for 28 and 90 days according to ISO 12571, simulating the progressive hardening of the material. At the end of each period, mechanical bending and compression tests, carried out according to ISO 679, make it possible to evaluate the capacity of the SCEB to withstand mechanical stress, thus guaranteeing the reliability and durability of the materials obtained.

Fig. 4. Banana trunk powder production flow chart

Table 1. Mixing plan for material with 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

Table 2. Mixing plan for 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

3. RESULTS AND DISCUSSION

The results of the 90-day curing tests show that the mechanical strength of SCEB increases significantly with maturation time. The addition of banana trunk powder improves compressive and flexural strength at low dosages, while enhancing durability against climatic aggressions. This development confirms that curing time is a determining parameter for optimizing the mechanical and environmental performance of SCEB, promoting their use as a sustainable alternative to conventional materials.

3.1 Results

3.1.1 90-day formulations with added banana trunk powder fiber

Analysis of the mechanical performance of SCEB formulated with soil, sand and banana trunk powder (BTP) shows that the curing time strongly influences the strength. At 2% BTP, the mixture shows the best performance, reaching 1.89 ± 0.01 MPa in bending and 6.84 ± 0.12 MPa in compression after 90 days of curing, compared to 0.82 ± 0.10 MPa in bending and 3.91 ± 0.58 MPa in compression at 28 days, i.e. a near doubling of the strengths. In contrast, increasing the BTP content to 10% results in a significant deterioration in properties, with strengths reduced to 0.35 ± 0.02 MPa in bending and 0.27 ± 0.01 MPa in compression at 90 days, compared to 0.22 ± 0.00 MPa in bending and 0.62 ± 0.02 MPa in compression at 28 days. This drop reflects a negative effect of fiber overload on the long-term cohesion of the material. These results demonstrate that the combination of an optimal dosage of 2% BTB and a curing time of 90 days significantly improves the mechanical performance of SCEB, while excessive dosages impair their durability.

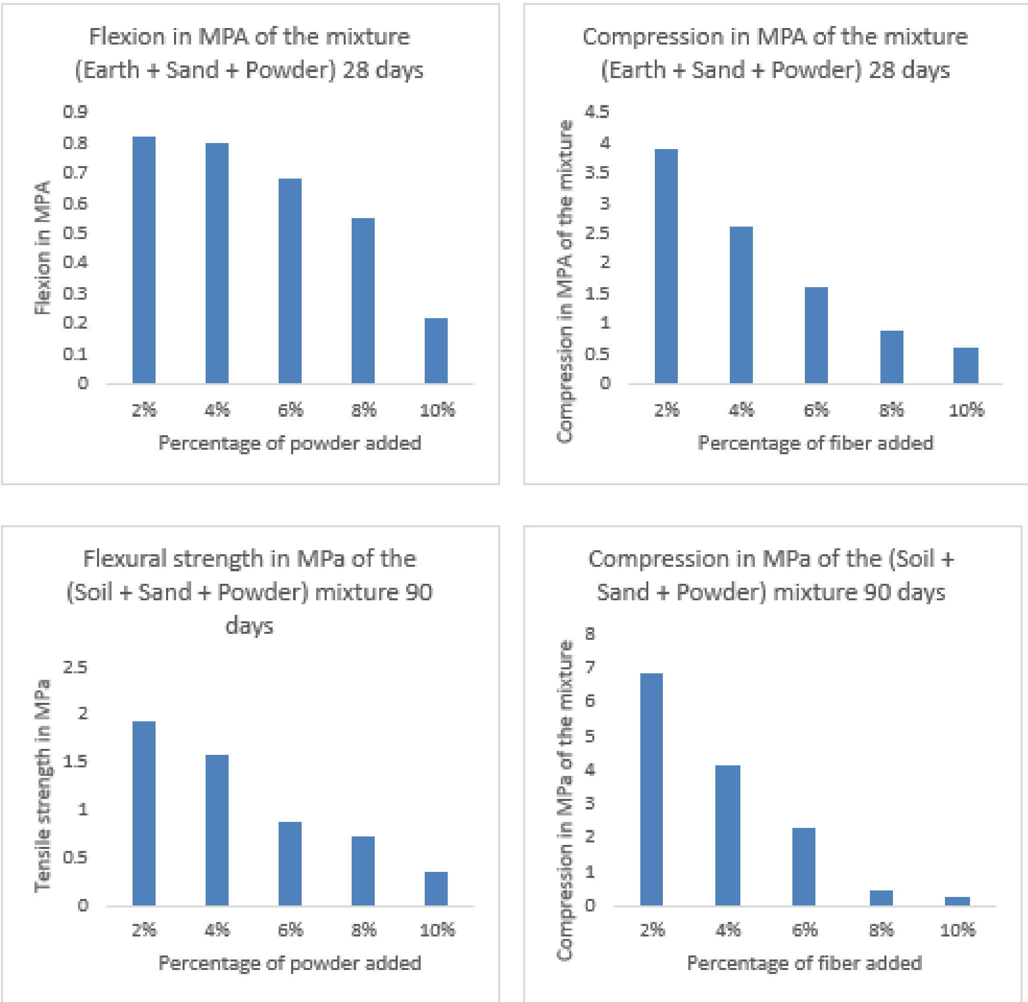

Fig. 5. Flexural and compression values of powder percentages 28 and 90 days of curing

3.1.2 Formulations with added banana trunk powder fiber

The performance analysis of SCEB based on earth, sand and cement shows a linear evolution of the mechanical resistance as a function of the cement content and the curing time. At 2% cement, the resistances increase from 0.51 ± 0.06 MPa in flexion and 2.51 ± 0.07 MPa in compression at 28 days, to 0.55 ± 0.04 MPa in flexion and 2.58 ± 0.12 MPa in compression at 90 days, i.e. a moderate progression. On the other hand, at 10% cement, the performances improve significantly, reaching 2.59 ± 0.31 MPa in flexion and 12.32 ± 0.66 MPa in compression at 28 days, then 4.02 ± 0.07 MPa in flexion and 18.77 ± 0.36 MPa in compression at 90 days, which represents a significant improvement over time. This regular progression confirms the effectiveness of cement as a hydraulic binder, particularly at high dosages, allowing the resistance of SCEB to be optimized over the long term. The extension of the curing time to 90 days thus considerably amplifies the mechanical performances, consolidating the essential role of cement in the formulation of stabilized materials.

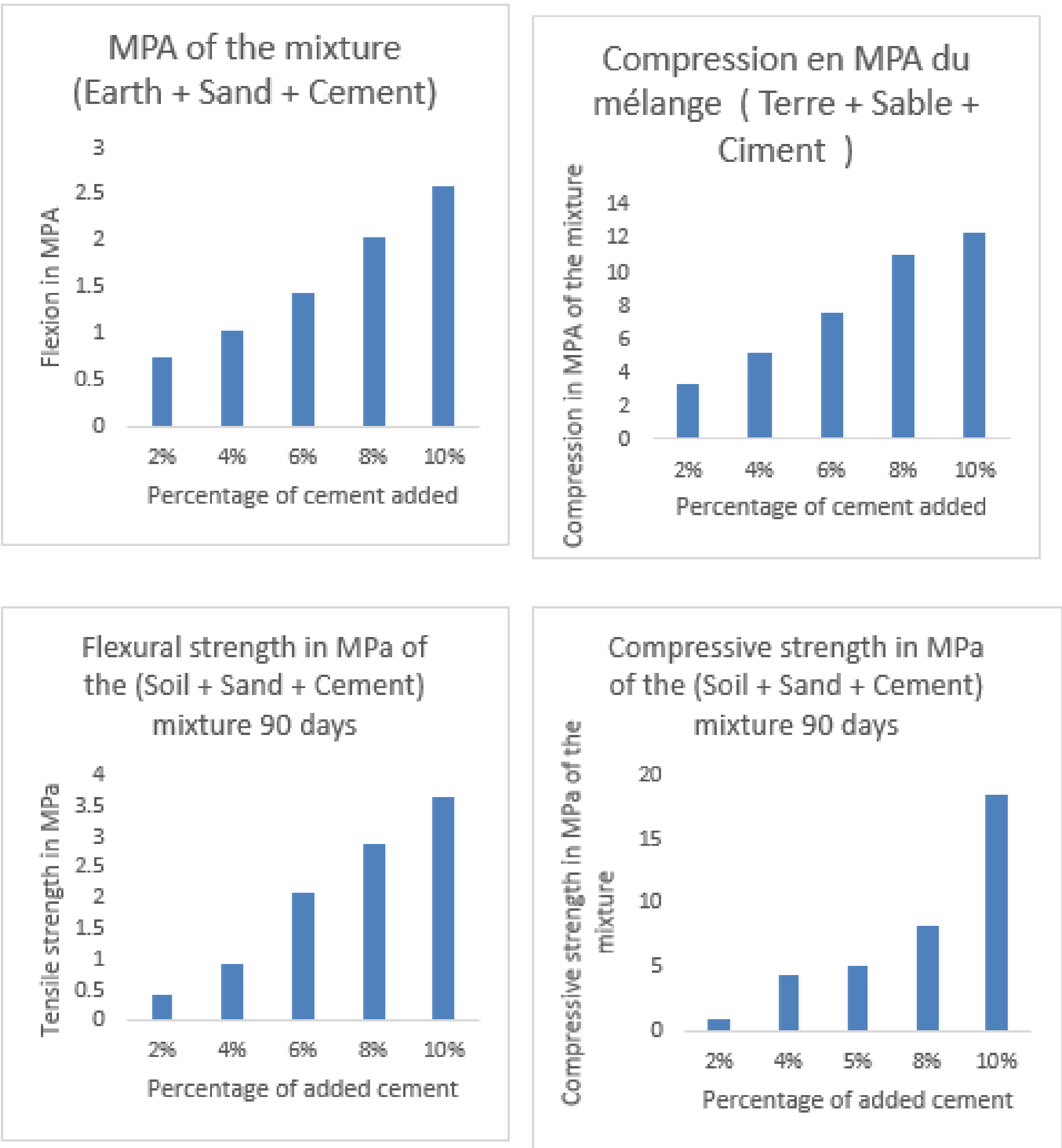

Fig. 6. Flexural and compressive values of cement percentages 28 and 90 days of curing

3.2 Discussion

Overall, the results clearly highlight the determining impact of the 90-day curing time on the mechanical performance of compressed and stabilized earth blocks (CSEBs), whether formulated with banana trunk powder (BTP) or cement. For CSEBs incorporating BTP, the results confirm that an optimal dosage of 2% coupled with prolonged curing significantly improves the flexural and compressive strength compared to the values recorded at 28 days. This improvement can be explained by the better internal cohesion and densification of the material under the effect of slow drying and stress redistribution, in agreement with several studies on bio-based composites, although there are variations in the results depending on the formulations used and the types of fibers (Soumaila et al*.,* 2022). However, beyond 2%, particularly at 10%, the fiber overload weakens the matrix, reduces compactness and leads to a significant deterioration in performance, a phenomenon also documented in the literature on the limits of incorporation of plant fibers (Guemidi et al*.,* 2024; Belaribi et al*.,* 2024). This highlights the importance of a strictly controlled dosage combined with sufficient curing time to ensure an optimal balance between mechanical strength and durability.

For cement-based SCEB, the performance evolution is linear and proportional to the cement content. At low levels (2%), the increase in strength between 28 and 90 days remains moderate, indicating that the hydration process is less efficient at low concentrations (Goutsaya et al*.,* 2022; Hall et al*.,* 2022). In contrast, at 10% cement, mechanical performance increases significantly, reaching 4.02 MPa in flexure and 18.77 MPa in compression after 90 days, compared to 2.59 MPa and 12.32 MPa at 28 days, respectively. This improvement is due to the continuation of hydration reactions that lead to the formation of CSH gels, the main contributors to the strength of the material, in accordance with current observations on cementitious materials (Achour et al*.,* 2024; Kushi, 2022). However, this increase in performance is potentially accompanied by an increased environmental impact, particularly in terms of CO_2 emissions and thermal conductivity, raising the question of the trade-off between mechanical resistance and ecological sustainability, a subject which is often discussed in the literature (Skałba, 2022; Morin, 2022).

4. CONCLUSION

Ultimately, the incorporation of banana trunk powder combined with a 90-day curing time significantly improves the mechanical strength of BTCS. The results indicate better internal cohesion and homogeneous dispersion of banana trunk powder in the earth-cement matrix. Comparative analysis of the two formulations shows that the extended 90-day curing optimizes the performance of SCEB, with maximum efficiency for 2% PTB, which offers a good balance between durability, strength and low environmental impact. Conversely, although high-content cement ensures superior mechanical performance, it remains penalized by its environmental effects. These results confirm the importance of combining a reasonable dosage of binders with an adequate curing time to promote sustainable and efficient construction materials, respectful of current climate issues.

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.

ACKNOWLEDGEMENTS

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

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
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