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Enhancing the Value of Clay Soils in Ebolowa (Cameroon) for the Sustainable Production of Cement-Stabilised Earth Bricks

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ABSTRACT

This study investigates the valorisation potential of clay soils from MVAM ESSAKO and LO'O-BIYENG (Ebolowa, Cameroon) for cement-stabilised earth bricks (CSEBs). Two representative soils were characterised using geotechnical tests, mechanical testing and FTIR analysis after stabilisation with 2%–8% Portland cement (28 days curing). The soils exhibit moderate plasticity (IP: 20.6%–22.4%) with methylene blue values of 2.43–2.80. Cement addition significantly improves performance: At 8% cement, compressive strength reaches 5.68–5.81 MPa (exceeding the 5 MPa requirement for structural masonry), flexural strength is 0.81–1.06 MPa and water absorption decreases to <20%. FTIR analysis reveals spectral changes consistent with mineralogical transformations associated with stabilisation: decreasing intensity of kaolinite-related bands at 3695 cm^{-1} (suggestive of dehydroxylation) and increasing intensity of bands in the $1000\text{--}1100\text{ cm}^{-1}$ region (consistent with the formation of cementitious silicate phases). The integrated approach demonstrates that Ebolowa clay soils are suitable for producing CSEBs, offering a potential local alternative for sustainable masonry in humid tropical environments. These two representative soils show promising results, but further studies are needed to confirm extrapolation to the wider range of soils in the Ebolowa region.

1 | Introduction

Cameroon, like many developing African countries, is experiencing rapid population growth, which is driving strong demand for housing and infrastructure [1]. The city of Ebolowa, newly established as a university hub, illustrates this dynamic through rapid urbanisation. However, the construction sector still relies heavily on imported materials such as cement, iron

and sheet metal, the production and transport of which generate high costs and a significant carbon footprint [2, 3].

In this context, promoting the use of local materials with low environmental impact appears to be a strategic solution for promoting sustainable construction and reducing dependence on industrialised materials [4–6]. Among these resources, earth is an abundant, recyclable local material with low

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embodied energy, particularly suited to tropical areas [7–9]. It also offers significant environmental and socioeconomic benefits: reduced energy consumption for cooking, improved thermal comfort and promotion of the circular economy [10, 11]. These qualities are in line with the United Nations' sustainable development goals and decarbonisation strategies for the building sector [1, 12].

However, despite its advantages, unstabilised raw earth has major limitations: low mechanical strength, sensitivity to water and a tendency to crack [13]. Cement stabilisation is a proven approach to improving these properties by strengthening the cohesion, strength and durability of bricks [14–18].

In Cameroon, few studies have focused on the integrated characterisation of local soils, particularly in humid climate zones. The work of Ndjigui et al. [19] highlighted the mineralogical and geotechnical variability of lateritic soils in the south, while Fadil-Djenabou et al. [20] demonstrated the potential of these soils in the north for the production of compressed earth bricks. However, studies in the south are limited to the locality of Ngog-Lituba, which is insufficient to represent the regional topographical and geological diversity. However, recent work [21] has demonstrated that cement stabilisation of Cameroonian soils simultaneously improves mechanical and thermal performance, confirming the value of localised research to better adapt formulations to the specific conditions of each area.

With this in mind, an in-depth study of the clay soils of Ebolowa is necessary to assess their suitability for the manufacture of cement-stabilised earth bricks (CSEBs) and to propose local sustainable construction solutions. The present study, therefore, is aimed at characterising the physical, mechanical and mineralogical properties of these soils in order to optimise their stabilisation with cement. The study is based on standardised geotechnical tests (grain size distribution, Atterberg limits and methylene blue value [MBV]), physical and mechanical tests (density, water absorption, compressive and flexural strength) and Fourier transform infrared (FTIR) mineralogical analysis to identify the structural transformations induced by stabilisation [14, 22].

Similar research conducted in other tropical areas [14–16, 22–26] has focused on the characteristics of stabilised soils and their applications, and certain studies have shown that cement contents of between 4% and 10% and a curing period of 28 days enable strengths to be achieved that comply with international standards. Drawing inspiration from these methodological approaches, this study is aimed at evaluating the suitability of clay soils from the Ebolowa region for the production of CSEBs. The research combines geotechnical characterisation, physical and mechanical testing and mineralogical analysis using FTIR spectroscopy.

While several studies in West Africa have investigated the mechanical behaviour of stabilised earth materials [22, 27, 28], few have explored the microstructural mechanisms linking mineralogical transformations to macroscopic mechanical performance, particularly in humid tropical environments.

The novelty of this work therefore lies in the integrated approach combining geotechnical, mechanical and FTIR analyses to (i) establish quantitative correlations between cement content and mechanical performance, (ii) identify spectroscopic markers of stabilisation and (iii) propose mechanistic explanations linking mineralogical evolution to macroscopic property improvements.

2 | Materials and Methods

2.1 | Study Area and Environmental Characteristics

The study area is located in southern Cameroon, specifically in the city of Ebolowa, which is characterised by a humid equatorial climate with four seasons (two rainy seasons and two dry seasons). Average annual rainfall exceeds 1600 mm, and temperatures vary between 23°C and 25°C, as shown in Table 1. The terrain consists of rounded hills resting on Precambrian geological formations composed of granite and gneiss. The predominant soils are ferrallitic, rich in kaolinite, iron and aluminium oxyhydroxides, and locally clayey in low-lying areas. These characteristics favour the availability of earthy materials suitable for stabilisation.

In the city of Ebolowa, the sampling sites (EBL2 and EBM1) are shown in Figure 1, with their geographical coordinates listed in Table 2.

2.2 | Materials

2.2.1 | Soils Studied

Two representative samples were taken manually from wells approximately 1 m deep, labelled EBM1 and EBL2 for soils taken at MVAM ESSAKO and LO'O-BIYENG, respectively. These soils have a fine texture, a reddish-brown colour and a high clay and silt content. They were chosen because of their abundance and their use in local brick production.

To ensure that the sampling areas were representative, four samples weighing 50 kg/ha were taken. Each 50-kg sample was obtained by mixing approximately 2–3 kg of soil collected from a distribution of 20 points randomly selected within the subareas. This quantity was required by the MIPROMALO laboratory and the LOBOGEC laboratory of the Ministry of Public Works (MINTP) in Yaoundé. Figure 2 shows a sample being taken in situ.

TABLE 1 | Average climate parameters for the Ebolowa region (2011–2021).

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
P (mm)	25	59	130	180	225	151	80	100	260	300	120	30
T (°C)	24.5	25	24.7	24	24	23	23	23.4	23.6	24	24.2	24.0

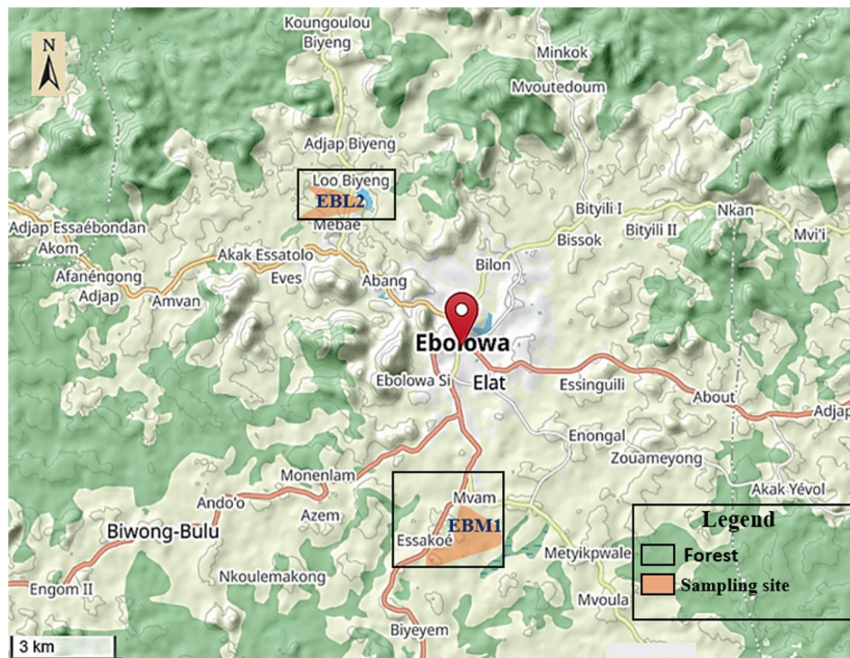


FIGURE 1 | Geographical location of sampling sites (MVAM ESSAKO [EBM1] and LO'O-BIYENG [EBL2], Ebolowa).

TABLE 2 | Geographical coordinates of sampling points.

Location	Site	Shaft	Site code	Geographical coordinates
Ebolowa	MVAM ESSAKOE	1	EBM1	2°57',51.8 N
				11°07',15.8 E
	LO'O-BIYENG	2	EBL2	2°52',47.7 N
				11°10',28.9 E

2.2.2 | Stabiliser

The cement used is Portland Composite Cement (CPI 42.5), compliant with NF EN 197-1 standards. The cement contents investigated in this study (0%, 2%, 4%, 6% and 8% by dry weight of soil) were selected based on recommendations reported in previous studies on stabilised earth materials in tropical regions, where optimal cement contents typically range between 4% and 10% [18, 23, 27].

This range was chosen in order to evaluate the minimum cement content required to achieve sufficient mechanical performance while limiting binder consumption, thereby reducing both environmental impact and production costs.

2.3 | Experimental Methods

2.3.1 | Geotechnical Identification Tests

Tests carried out in accordance with French standards NF P 94-051 and NF P 94-056 were used to determine the particle size distribution by sieving and sedimentometry, the Atterberg limits (plasticity and liquidity) and the MBV to estimate the active clay mineral content. Table 3 summarises the geotechnical tests and standards used. Additional basic properties were determined: natural water content (NF P 94-050), specific gravity (NF P

94-054) and modified Proctor compaction characteristics (NF P 94-093). These results are presented in Table 4.

2.3.2 | Preparation and Manufacture of Bricks

The soil samples are first dried and crushed, then weighed and homogenised with the desired proportion of cement and an optimum water content determined by the modified Proctor test. The compaction pressure was approximately 15.3 MPa, calculated as $10,000 \text{ kg} \times 9.81 \text{ m/s}^2$ divided by the mould section (0.0064 m^2). This pressure is consistent with typical values for CEB production (CRATerre, 2019). The mixture was compacted in a metal mould measuring $160 \times 40 \times 40 \text{ mm}^3$ using a hydraulic press. The loading rate was set at 0.5 mm/min until the maximum load of 10 tonnes was reached. This maximum load was maintained for 30s before decompression to ensure adequate particle rearrangement and air evacuation. The applied load was controlled using a calibrated manometer connected to the press. After compaction, it was then removed from the mould and cured in a humid environment for 28 days in accordance with Cameroonian standard NC 102-114, 2002-2006, at room temperature (23°C – 25°C). Samples were cured for 28 days in a controlled environment at $23^\circ\text{C} \pm 2^\circ\text{C}$ and $95\% \pm 5\%$ relative humidity (RH). These conditions were maintained by storing specimens in sealed plastic containers with water reservoirs.



FIGURE 2 | Image of sampling in situ.

TABLE 3 | Standards used for geotechnical testing.

Geotechnical test	Norme
Particle size analysis	NF P 94-056
Sedimentation particle size analysis	NF P 94-057
Atterberg limits	NF P 94-051
Methylene blue test	NF P 94-068

Temperature and RH were continuously monitored using a data-logging hygrometer (recording every 2h) placed inside the curing chamber. Variations remained within the specified ranges throughout the curing period.

Figure 3 shows all the steps involved in manufacturing the samples in detail.

2.3.3 | Physical and Mechanical Tests

The stabilised earth bricks obtained were subjected to a series of physical and mechanical tests to assess their performance based on the stabilisation rate. The properties measured included bulk density, water absorption, dry compressive strength, flexural strength and water stability. The apparent density was determined in dry conditions in accordance with standard NF EN 771-1, enabling the density and compactness of the bricks to be estimated. The water absorption rate was measured by completely immersing the test specimens for 24h in order to assess the open porosity and susceptibility of the material to moisture. The dry compressive strength was determined after a 28-day curing period, in accordance with the protocols usually applied to stabilised earth bricks, in order to quantify the load-bearing capacity of the material.

The flexural strength (three-point bending test) was determined according to standard NF EN 12390-5. The test was performed on prismatic specimens ($160 \times 40 \times 40 \text{ mm}^3$) using a universal testing machine. The distance between the two bottom supports (span length) was 120mm. The load was applied at the mid-span at a constant displacement rate of 0.2 mm/min until failure. The flexural strength τ_f (in megapascals) was calculated using the standard formula (1):



$$\tau_f = \frac{3 \cdot F \cdot L}{2 \cdot b \cdot h^2}, \quad (1)$$

where F is the maximum load (newton), L is the span length (120 mm) and b and h are the width and height of the specimen (40 and 40 mm, respectively).

The water stability was assessed by comparing the compressive strength of dry and wet specimens, following the recommendations of CRATerre (2019) and standard NF P 94-102. For wet specimens, bricks were fully immersed in tap water at room temperature ($23^\circ\text{C} \pm 2^\circ\text{C}$) for 24 h. After immersion, the specimens were removed, lightly wiped to remove surface water and immediately tested in compression (same procedure as for dry compressive strength). Water stability is defined as the ratio $Sw = R_{c,wet} / R_{c,dry}$, where $R_{c,wet}$ is the compressive strength after immersion and $R_{c,dry}$ is the compressive strength of dry specimens. Three specimens were tested per formulation for both dry and wet conditions.

These tests provided an overall assessment of the effect of cement on the mechanical properties and durability of the earth bricks produced.

Table 5 summarises the various physical and mechanical tests carried out and the standards applied.

2.4 | Sample Formulation

The bricks were produced in 10 formulations: two soils (EBM1 and EBL2), each stabilised with five cement contents (0%, 2%, 4%, 6% and 8% by dry weight of soil). The 0% cement samples served as unstabilised controls for each soil. To ensure the reproducibility of the results, each formulation was prepared with three replicates ($n = 3$), resulting in 30 specimens for mechanical testing per test type. The reported values correspond to average results. Table 6 presents a summary of the physical treatment conditions.

2.5 | Mineralogical Analysis of Soils

FTIR spectroscopy was used to identify the main mineralogical phases and structural changes induced by cement stabilisation. The brick samples were first dried at 60°C for 24h, then finely

TABLE 4 | Geotechnical characteristics of soils EBM1 and EBL2.

Measured parameter	Symbol/unit	Method/reference standard	EBM1 (MVAM ESSAKO)	EBL2 (LO'O-BIYENG)	Geotechnical interpretation
Gravel fraction	%	NF P 94-056	0.3	1.2	Very low content, predominantly fine soil
Sand fraction	%	NF P 94-056	36.8	29.4	Sandy to clayey texture
Silt fraction	%	NF P 94-057	10.9	12.6	Slight proportion of fine particles
Clay fraction	%	NF P 94-057	52.0	56.8	High content, plastic clay soil
Liquidity limit (LL)	%	NF P 94-051	44.5	46.7	Soils with medium to high plasticity
Plasticity limit (LP)	%	NF P 94-051	23.9	24.3	Moderate plasticity
Plasticity index (IP = LL – LP)	%	Calculated	20.6	22.4	Plastic clays, suitable for stabilisation
Methylene blue value (MBV)	g/100 g	NF P 94-068	2.43	2.80	Presence of active clays (kaolinite and montmorillonite)
HRB classification	—	AASHTO M145	A-7-6	A-7-6	Plastic clay soils requiring stabilisation
USCS classification	—	ASTM D2487	CL	CL	Medium plasticity loamy clay

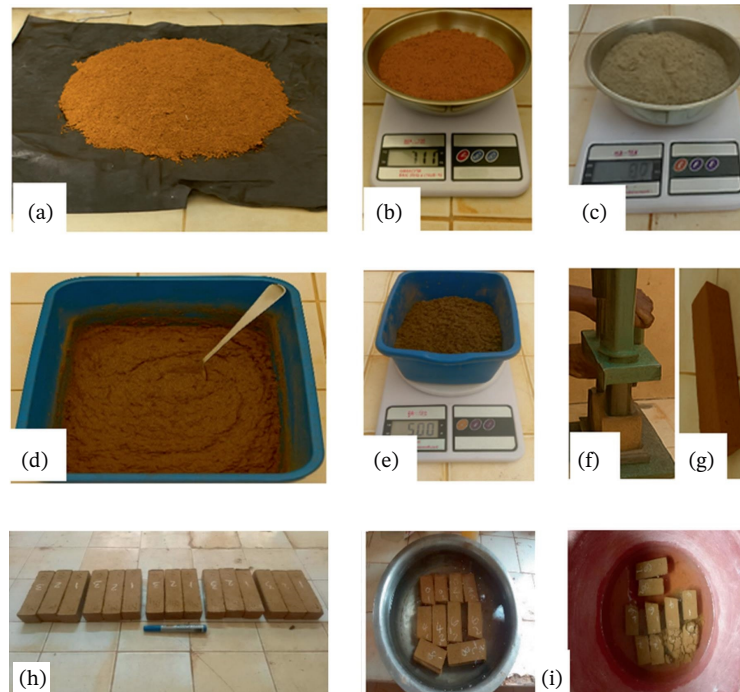
**FIGURE 3** | Steps in the manufacture of stabilised bricks. Diagram illustrating the production process (a) dry earth powder, (b) weighing the earth, (c) weighing the cement, (d) mixing the earth and cement homogeneously with water, (e) weighing 500 g of the homogeneous earth and cement mixture, (f) compacting in a mould, (g) removing the sample from the mould, (h) labelling the samples and (i) curing the samples.

TABLE 5 | Description of the physical and mechanical tests carried out.

Test performed	Measured parameter	Unit	Standard/reference	Purpose of the trial
Apparent density	Dry density (ρ_d)	g/cm ³	NF EN 771-1 (2011)	Determine the density and compactness of stabilised bricks.
Water absorption	Absorption rate after 24-h immersion	%	ASTM C67/NF P 18-554	Assess open porosity and moisture sensitivity.
Dry compressive strength	Compressive strength at 28 days	MPa	NF P 18-406/ASTM C39	Measure the load-bearing capacity of bricks in dry conditions.
Flexural strength	Flexural tensile strength (three-point test)	MPa	NF EN 12390-5/ASTM C78	Assess the ductility and internal cohesion of bricks.
Water stability	Wet/dry ratio	—	CRATerre (2019)/NF P 94-102	Assess durability and resistance to prolonged moisture exposure.

TABLE 6 | Experimental formulation of the samples tested: Cement contents applied and identification of the EBM1 and EBL2 series.

Sample code	Soil type	Cement content (% of dry soil weight)	Number of test tubes manufactured	Duration of treatment (days)	Treatment conditions	Observation
EBM1-C0	Soil of MVAM ESSAKO	0% (unstable witnesses)	3	28	Ambient (23°C–25°C, humidity 60%–70%)	Raw soil used as a reference
EBM1-C2	Soil of MVAM ESSAKO	2%				First stabilised series
EBM1-C4	Soil of MVAM ESSAKO	4%				Moderate stabilisation
EBM1-C6	Soil of MVAM ESSAKO	6%				Intermediate stabilisation
EBM1-C8	Soil of MVAM ESSAKO	8%				Optimal stabilisation
EBL2-C0	Soil of LO'O-BIYENG	0% (unstable witnesses)				Raw soil used as a reference
EBL2-C2	Soil of LO'O-BIYENG	2%				First stabilised series
EBL2-C4	Soil of LO'O-BIYENG	4%				Moderate stabilisation
EBL2-C6	Soil of LO'O-BIYENG	6%				Intermediate stabilisation
EBL2-C8	Soil of LO'O-BIYENG	8%				Optimal stabilisation

ground and sieved to 80 μ m before analysis. The spectra were recorded using a Bruker Alpha II spectrometer equipped with an attenuated total reflection (ATR) module. Measurements were performed in the spectral range from 4000 to 400 cm⁻¹, with a resolution of 4 cm⁻¹ and an average of 32 scans per sample to reduce background noise. The instrument was calibrated before each series of acquisitions using a standard polystyrene crystal.

The spectra were interpreted based on the characteristic bands of the O–H, Si–O–Si, Si–O–Al and Al–O–Si bonds, as well as the vibrations associated with the hydrated phases of cement (calcium silicate hydrate [C–S–H] and calcium aluminate hydrate [C–A–H]). Variations in peak intensity and position were analysed as a function of cement content (0%, 2%, 4%, 6% and 8%) for both types of soil (EBM1 and EBL2). This approach made it possible to link the mineralogical transformations observed to the

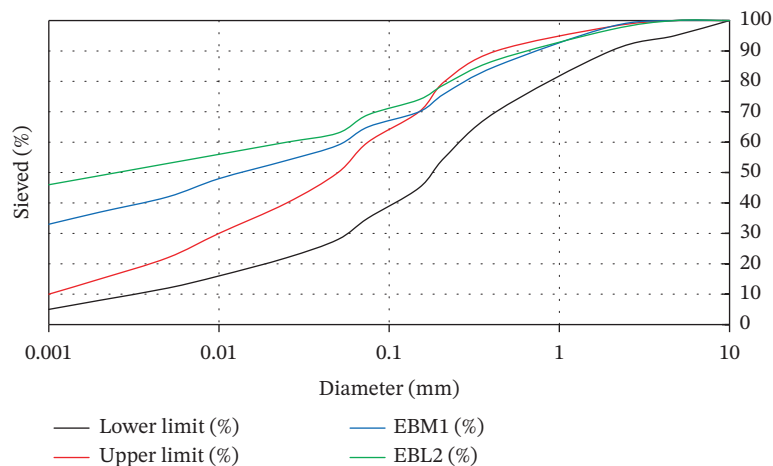


FIGURE 4 | Comparative particle size distribution curves for EBM1 and EBL2 soils.

TABLE 7 | Physical properties of stabilised bricks at different cement ratios.

Sample code	Cement content (% dry weight)	Apparent density (g/cm ³)	Water absorption rate (%)	Observation
EBM1-C0	0	1.69	27.3	Unstabilised brick and high porosity
EBM1-C2	2	1.78	24.5	Slight improvement in density and decrease in absorption
EBM1-C4	4	1.83	22.4	Improved compaction and reduced porosity
EBM1-C6	6	1.87	20.9	Good internal cohesion and denser structure
EBM1-C8	8	1.92	19.7	Optimal compactness and minimal absorption
EBL2-C0	0	1.70	28.1	Reference material and high permeability
EBL2-C2	2	1.80	25.3	Start of effective stabilisation
EBL2-C4	4	1.85	23.1	Material densification
EBL2-C6	6	1.89	21.5	Homogeneous internal structure
EBL2-C8	8	1.93	19.8	Maximum density and low porosity

improvement in the mechanical and durability properties of the stabilised bricks.

2.6 | Statistical Analysis

All tests were performed on three replicate specimens per formulation ($n = 3$). Results are presented as mean $\pm$ standard deviation (SD). For key mechanical properties (compressive strength, flexural strength and water absorption), 95% confidence intervals (CIs)

were calculated using Student's t -distribution. One-way analysis of variance (ANOVA) was performed to evaluate the statistical significance of cement content on mechanical properties, with $p < 0.05$ considered significant. The ANOVA results include the F -value, degrees of freedom (df) and p value. Post hoc comparisons used Tukey's HSD test where applicable. Linear regressions between cement content and compressive strength were fitted, and the coefficient of determination (R^2) was reported. The significance of the regression slope was tested using a t -test ($p < 0.05$). All statistical analyses were performed using Minitab 19 software.

3 | Results and Discussion

3.1 | Geotechnical Characterisation of Soils

Geotechnical identification tests carried out on samples EBM1 and EBL2 enabled their main physical and mineralogical properties to be established. Table 6 presents the summary results of the granulometric analyses, Atterberg limits and MBV.

The grain size curves in Figure 4 show the particle size distribution and textural classification of the samples studied. It can be seen that both soils are predominantly clayey, with fine fractions between 50% and 60%. The plasticity index (Pi) obtained, between 20% and 23%, classifies these soils as moderately plastic clays according to the HRB classification. The MBVs (VBS $\approx$ 2.4 – 2.8) confirm the presence of active clay minerals, probably based on kaolinite and montmorillonite.

These results indicate that the soils of Ebolowa have a texture and plasticity suitable for the production of stabilised bricks, provided that the cement content is optimised to limit shrinkage and improve strength.

3.2 | Physical Properties of Stabilised Bricks

The gradual addition of cement resulted in a noticeable improvement in the physical properties of the bricks. Table 7 shows the average values for bulk density and water absorption rate.

Figure 5 shows that the apparent density increases linearly with cement content, reflecting improved compaction and reduced internal porosity. At the same time, the water absorption rate decreases, indicating improved compactness and impermeability. These results confirm the positive effect of cement on the compactness and impermeability of stabilised earth bricks. An analysis of the curves reveals values greater than 7.5% and 7.75% cement for samples EBM1 and EBL2, respectively, meeting the

recommendations of CRATerre (2019), which advocates a dry density greater than 1.8 g/cm³ and absorption less than 20%. These trends confirm the results obtained by Millogo et al. [28], according to which cement stabilisation reduces porosity and improves the dry density of earth bricks.

3.3 | Mechanical Properties

The mechanical tests focused on compressive and flexural strength after 28 days of curing. Table 8 shows the average strengths obtained on the EBM1 and EBL2 samples at 28 days for each cement content. The results in Table 8 show a steady increase in compressive strength with cement content. For an 8% dosage, the strengths reach approximately 5.68 MPa for EBM1 and 5.81 MPa for EBL2, values higher than the minimum of 5 MPa recommended by CRATerre (2019) for stabilised earth bricks intended for load-bearing masonry in tropical regions. This threshold is based on CRATerre's extensive work on compressed earth blocks, which remains the most directly applicable guideline for CSEBs in Cameroon in the absence of a specific national standard. The testing protocol followed NF P 18-406 (standard for concrete masonry units), used here as an analogous reference for CSEB testing methodology.

Figure 6 shows a correlation between cement content and compressive strength after 28 days. There is an almost linear increase in compressive strength with cement content, confirming the effectiveness of hydraulic stabilisation. The maximum values reached (5.68 MPa for EBM1 and 5.81 MPa for EBL2) exceed the minimum limit recommended by CRATerre (2019) for stabilised earth bricks used in structural masonry ($\geq$ 5 MPa). To quantify this relationship, linear regressions were fitted between compressive strength (σ) and cement content V_c (in percentage):

- For EBM1: $\sigma = 0.515V_c + 1.81$ ($R^2 = 0.9902$, $p < 0.001$)
- For EBL2: $\sigma = 0.5155V_c + 1.704$ ($R^2 = 0.9911$, $p < 0.001$)

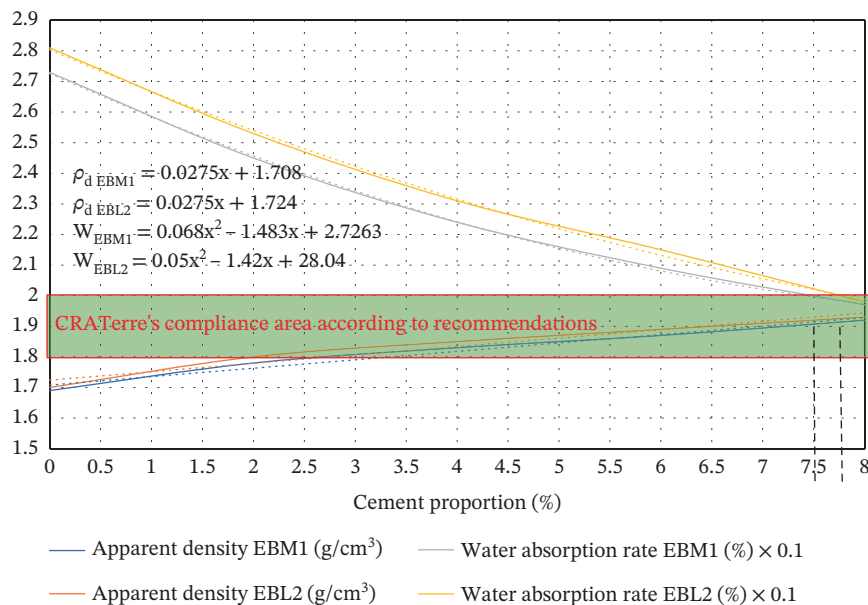


FIGURE 5 | Changes in the apparent density and water absorption rate of stabilised bricks as a function of cement content.

TABLE 8 | Dry compressive strength according to cement content.

Sample code	Cement content (% dry weight)	Dry compressive strength (MPa)	Standard deviation (MPa)	Observation
EBM1-C0	0	1.52	0.07	Low strength and unstabilised material
EBM1-C2	2	2.84	0.11	Significant improvement in cohesion
EBM1-C4	4	3.96	0.13	Steady increase in resistance
EBM1-C6	6	4.82	0.15	Effective soil stabilisation
EBM1-C8	8	5.68	0.17	Resistance in line with requirements CRATerre (≥ 5 MPa)
EBL2-C0	0	1.64	0.06	Raw material and very brittle
EBL2-C2	2	2.95	0.10	Start of binder solidification
EBL2-C4	4	4.07	0.12	Good distribution of cement in the matrix
EBL2-C6	6	4.92	0.14	Well-developed internal cohesion
EBL2-C8	8	5.81	0.16	Optimal level of mechanical strength

Note: Numbers in boldface represent the maximum values for each soil type.

The high determination coefficients indicate a strong linear correlation over the 0%–8% range. The 95% CIs for the slopes were [0.49–0.54] for EBM1 and [0.49–0.55] for EBL2.

However, a more detailed analysis of the incremental strength gain $\Delta\sigma / \Delta v_c$ (Figure 6b) reveals a progressive decrease in cement efficiency. Between 0% and 2% cement, the gain reaches 0.66 MPa/%; between 4% and 6%, it drops to 0.43 MPa/%; and between 6 and 8%, it remains at 0.43–0.45 MPa/%, indicating a clear plateau. This behaviour can be explained by two complementary mechanisms: (i) at low cement contents (<4%), the main effect is the filling of macropores by cement particles and early hydration products, leading to significant density increases and rapid strength gains; (ii) beyond 6% cement, most accessible pores are already filled. Further cement addition primarily affects micropores and creates additional C–S–H bonding, but the strength becomes limited by the intrinsic resistance of the untreated clay matrix and the reduced marginal efficiency of cement. A logistic regression model fitted to the data gives an inflection point at approximately 6.7% cement for EBL2, confirming the onset of the plateau. From an economic and environmental perspective, the optimal cement content for these soils is therefore around 7%–8%, balancing mechanical performance ($\sigma > 5$ MPa) with binder economy.

The observed increase in compressive strength can be explained by the hydration reactions of Portland cement, which produce C–S–H and C–A–H gels. These hydration products progressively fill the voids between soil particles and create

cementitious bonds between clay minerals, leading to a denser and more cohesive matrix. This microstructural densification reduces pore connectivity and improves load transfer between particles, resulting in higher compressive and flexural strengths. Similar mechanisms have been reported in previous studies on cement-stabilised earth materials in tropical regions [23, 29].

The results in Figure 7 and Table 9 indicate a continuous improvement in flexural strength with increasing cement content, reflecting a gradual increase in the cohesion and rigidity of the earth-cement matrix. The flexural strength increases on average from 0.3 MPa for unstabilised samples to values exceeding 0.8–1.0 MPa for those containing 8% cement. These values confirm the beneficial effect of stabilisation on the ductility and indirect tensile strength of earth bricks, in line with the observations of Millogo and Morel [30] and Taallah and Guettala [18]. Above 6% cement, the gains become less significant, suggesting an optimal content of around 8%, balancing mechanical performance and binder economy. This improvement reflects a better matrix binder and a reduction in internal cracking due to drying.

Statistical analysis confirmed that the increase in compressive strength with cement content was significant for both soils (ANOVA, $p < 0.001$). The detailed ANOVA results are as follows: for EBM1, $F(4, 10) = 124.7$, $p < 0.001$; for EBL2, $F(4, 10) = 136.2$, $p < 0.001$. Post hoc Tukey's HSD tests indicated that differences between consecutive cement contents

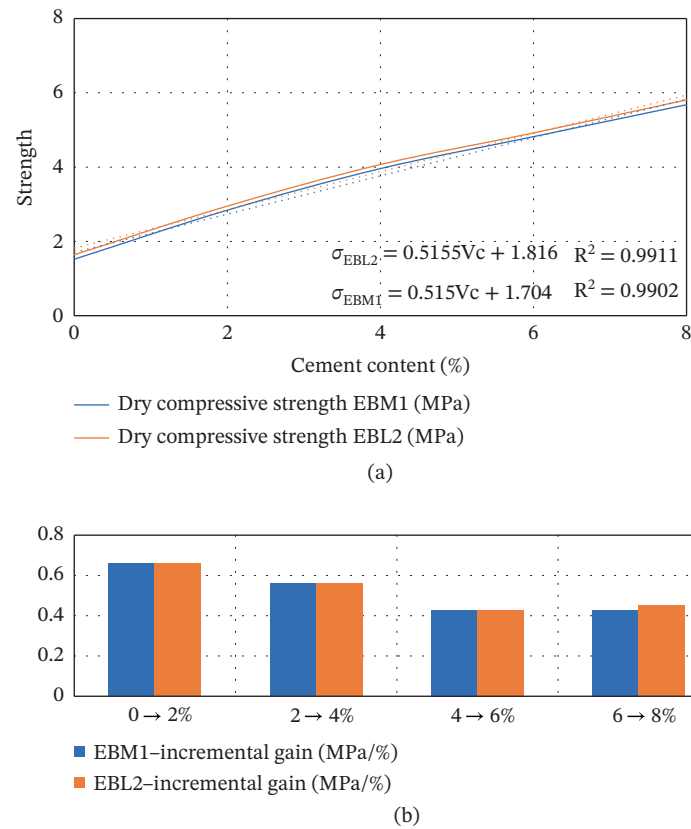


FIGURE 6 | (a) Evolution of the compressive strength of stabilised bricks as a function of cement content. (b) Incremental increase in compressive strength ($\Delta\sigma / \Delta V_c$) as a function of cement content range for soils EBM1 and EBL2. The gain is expressed in megapascals per percentage point of cement added. A gradual decrease in the gain is observed beyond 2% cement, with a marked plateau between 4%–6% and 6%–8% (around 0.43–0.45 MPa/%), indicating a diminishing marginal benefit from adding cement beyond 6%.

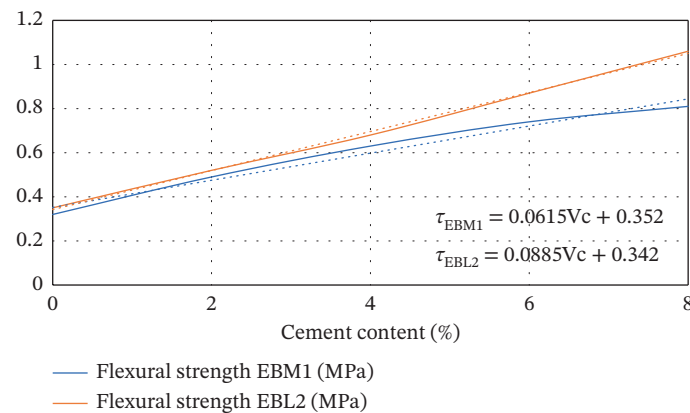


FIGURE 7 | Change in flexural strength as a function of cement content.

were significant up to 6% ($p < 0.05$), while the 6%→8% increment showed diminished significance ($p = 0.07$ for EBM1; $p = 0.06$ for EBL2), suggesting a plateau effect. The incremental strength gain (Figure 6b) confirms this trend.

3.4 | Mineralogical Analysis Results

Table 10 presents the results of mineralogical analysis of the formulated samples. The corresponding legend is as follows: +, low intensity; ++, medium; +++, high; +++, very high; ±, trace; –, absent.

The FTIR spectra (Figures 8 and 9) show significant variations with cement addition. A strong absorbance band at $3600\text{--}3700\text{ cm}^{-1}$, attributed to O–H stretching of kaolinite, progressively decreases in intensity as cement content increases. This reduction is consistent with, but not definitive proof of, partial dehydroxylation of clay minerals during stabilisation. The band at 1630 cm^{-1} (H–O–H deformation of adsorbed water) also decreases, indicating reduced material hydrophilicity. Concurrently, bands in the $1000\text{--}1100\text{ cm}^{-1}$ region (Si–O–Si and Si–O–Al stretching) intensify, which is consistent with the formation of amorphous silicate phases similar to cement hydration products reported in the literature [28]. At lower

TABLE 9 | Flexural strength as a function of cement content: Averages obtained for samples EBM1 and EBL2.

Sample code	Cement content (% dry weight)	Flexural strength (MPa)	Standard deviation (MPa)	Observation
EBM1-C0	0	0.32	0.03	Very low cohesion and unstabilised material
EBM1-C2	2	0.49	0.04	Slight improvement in indirect tensile strength
EBM1-C4	4	0.63	0.05	Gradual increase in rigidity
EBM1-C6	6	0.74	0.06	Good internal cohesion and dense microstructure
EBM1-C8	8	0.81	0.07	Optimal strength and homogeneous, tough material
EBL2-C0	0	0.35	0.03	Fragile material and rapid cracking
EBL2-C2	2	0.52	0.04	Start of effective cementitious bonding
EBL2-C4	4	0.68	0.05	Better distribution of the binder
EBL2-C6	6	0.87	0.06	Good flexural strength and increased cohesion
EBL2-C8	8	1.06	0.08	Maximum mechanical strength at 8% cement

Note: Numbers in boldface represent the maximum values for each soil type.

wavenumbers ($520\text{--}470\text{ cm}^{-1}$), bands associated with metal-oxygen bonds (Fe–O and Ca–O) appear or intensify with cement addition, suggesting the formation of calcium and iron compounds during stabilisation. To quantify the mineralogical evolution, the normalised intensities of key FTIR bands were correlated with cement content and mechanical properties. Specifically, the band at 3695 cm^{-1} ($\nu(\text{OH})$ of kaolinite) and the band at 1095 cm^{-1} ($\nu(\text{Si-O-Si})$ of C–S–H type phases) were analysed. A stabilisation index $I_{\text{stab}} = I_{1095} / I_{3695}$ was defined. This index increases linearly with cement content (Figure 8c): for EBL2, $I_{\text{stab}} = 0.12 \times V_C + 0.58$ ($R^2 = 0.94$), where V_C is the cement content (percentage). A strong linear correlation was also found between the normalised intensity of the 1095 cm^{-1} band and the compressive strength ($R = 0.96$ for EBL2). These quantitative relationships confirm that the progressive formation of cementitious gels directly governs the macroscopic mechanical improvement. These spectroscopic changes are consistent with the mineralogical transformations expected during cement stabilisation, although definitive phase identification would require complementary techniques such as x-ray diffraction (XRD) or scanning electron microscopy with energy-dispersive spectroscopy (SEM-EDS). FTIR spectroscopy provides valuable information on functional groups and bonding environments, but it does not allow unambiguous identification of amorphous phases (e.g., C–S–H gels) nor quantification of crystalline mineral proportions. Therefore, the interpretations presented here remain partly qualitative,

and ongoing investigations using XRD and SEM-EDS aim to confirm these findings.

3.5 | Hydromechanical Properties

One of the durability properties of earth materials is their water stability, assessed by the ratio of wet strength to dry strength. Table 11 shows the ratio of wet strength to dry strength for samples EBM1 and EBL2 after 28 days of curing. The water stability values obtained show a significant improvement above 6% cement, indicating increased durability. These results are consistent with the observations of Taallah and Guettala [18], who emphasise that a cement content of 8%–10% optimises mechanical strength and durability without excessively increasing the environmental cost. The water absorption values were determined following the procedure described in ASTM C67 (Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile), whereas the threshold of <20% recommended for humid environments is based on CRATerre (2019) guidelines for compressed earth blocks in tropical climates. The evolution curve in Figure 10a shows a remarkable improvement starting at a cement content of 5.5%.

Figure 10b illustrates the evolution of strength damage due to the effect of water as a function of cement content for EBM1 and

TABLE 10 | Evolution of FTIR bands of stabilised bricks according to cement content: Identification of main absorbance peaks and mineralogical interpretation for EBM1 and EBL2 soils.

Wavenumber (cm ⁻¹)	Liaison	Mineral or associated compound										General interpretation
		EBM1— 0%	EBM1— 2%	EBM1— 4%	EBM1— 6%	EBM1— 8%	EBL2— 0%	EBL2— 2%	EBL2— 4%	EBL2— 6%	EBL2— 8%	
3695–3620	$\nu(\text{OH})$ — surface vibration	++++	+++	++	+	±	++++	+++	++	+	±	Decrease in OH groups: Gradual dehydration of clays
1630	$\delta(\text{H}-\text{O}-\text{H})$ — adsorbed water	++++	+++	++	+	±	++++	+++	++	+	±	Reduction of free water and interleaf molecules
1095–1009–912	$\nu(\text{Si}-\text{O}-\text{Si})/\nu(\text{Si}-\text{O}-\text{Al})$	++	+++	++++	++++	++++	++	+++	++++	++++	++++	Progressive formation of the C–S–H and C–A–H phases responsible for hardening
695	$\delta(\text{Al}-\text{O}-\text{Si})$ — Deformation	++	+	±	–	–	++	+	±	–	–	Reduction of kaolinite, a sign of cementation
520–470	$\nu(\text{Fe}-\text{O})/\nu(\text{Ca}-\text{O})$	±	+	++	++	+++	±	+	++	++	+++	Appearance and growth of carbonate and ferric cement phases

Note: + low intensity; ++ medium; +++ high; +++++ very high; ± trace; – absent.

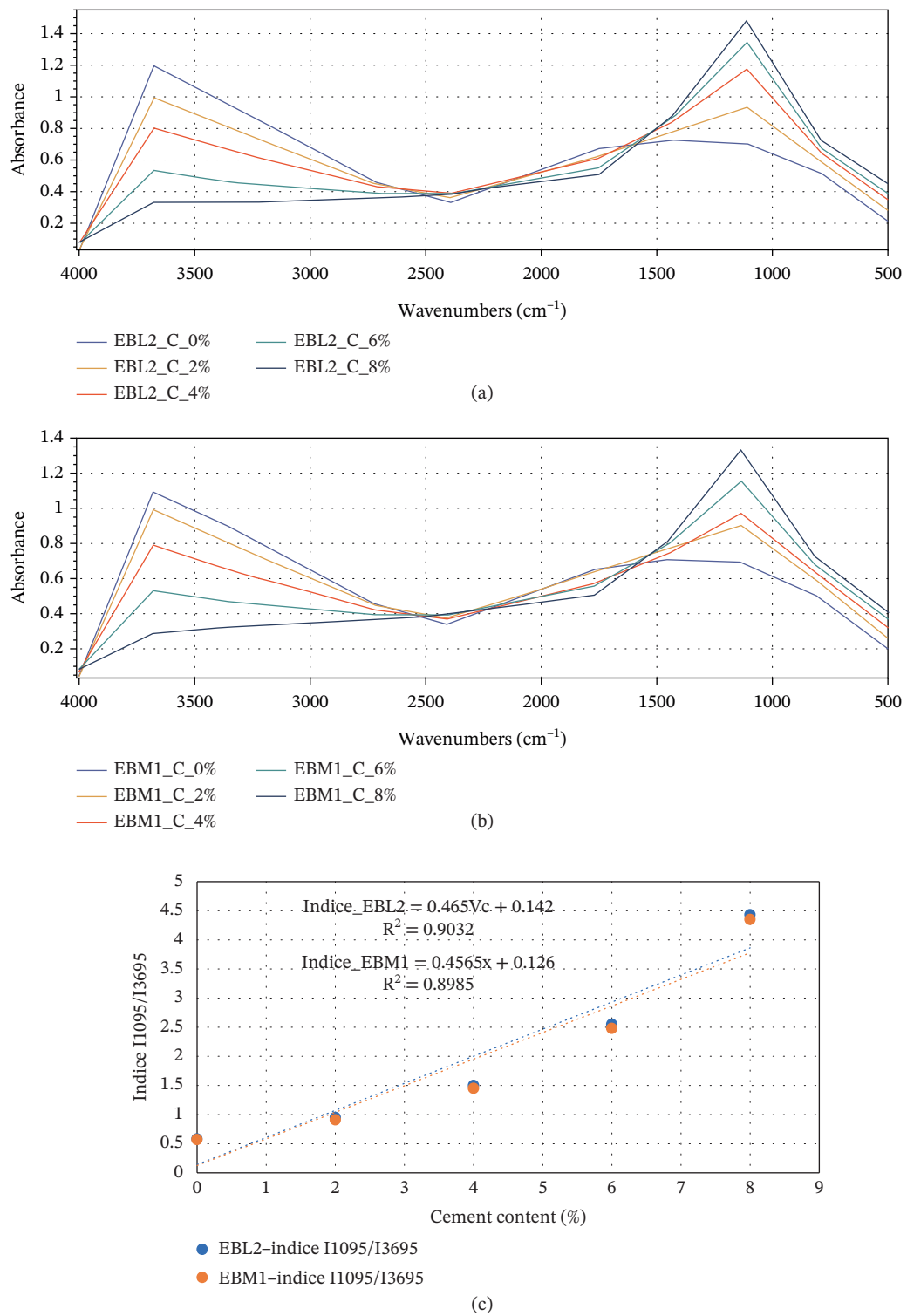


FIGURE 8 | FTIR results for samples: (a) EBL2 and (b) EBM1. (c) Variation in the FTIR stabilisation index I_{1095} / I_{3695} as a function of cement content for the EBL2 and EBM1 soils. The linear regression lines are shown (EBL2: $R^2 = 0.903$; EBM1: $R^2 = 0.899$).

EBL2 soils. A quasilinear decrease in damage is observed with increasing cement percentage, reflecting improved brick resistance to immersion when stabilisation is reinforced.

The regression equations obtained have similar negative slopes, indicating similar behaviour between the two soils. However, bricks made from EBL2 soil show a slight improvement in water

resistance due to a higher proportion of fine clays, which ensure better matrix cohesion.

Above 6% cement, the reduction in damage becomes exponential, suggesting that the optimal stabilisation content is around 7.5%, ensuring a compromise between durability and binder economy. These results confirm the effectiveness of

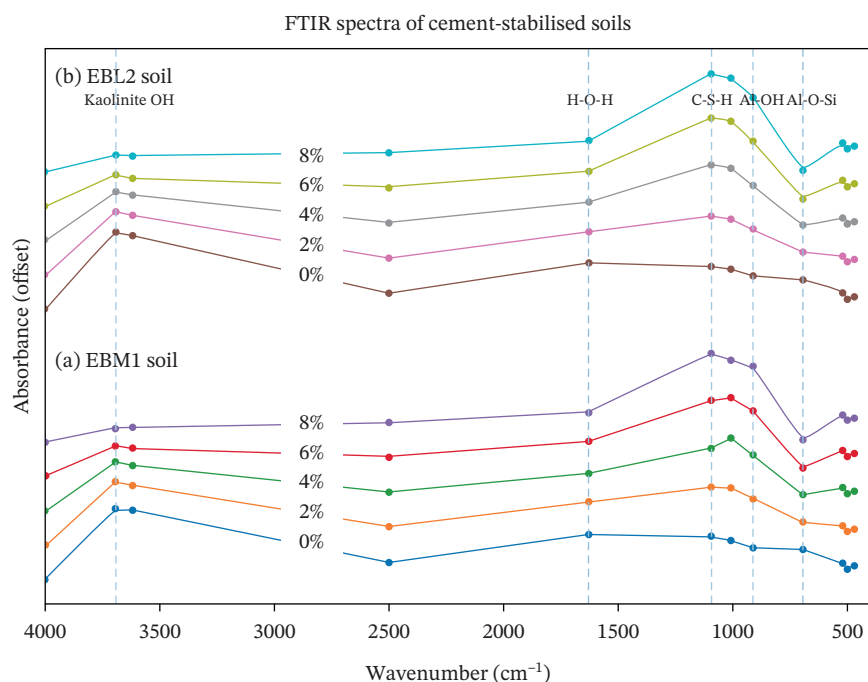


FIGURE 9 | Combined FTIR spectra of cement-stabilised soils from Ebolowa: (a) EBM1 soil and (b) EBL2 soil. The decrease in kaolinite hydroxyl bands ($\sim 3695\text{ cm}^{-1}$) and the development of the band near 1095 cm^{-1} indicate the formation of C-S-H phases associated with cement hydration and pozzolanic reactions.

Portland cement in limiting mechanical degradation by water, consistent with the observations of Millogo and Morel [30] and Taallah and Guettala [18] on similar clay soils in tropical climates.

3.6 | General Discussion

The results as a whole highlight a direct correlation between cement content and the mechanical and water performance of bricks (Figures 5, 6 and 7; Tables 7, 8 and 9). The observed behaviour follows the classic mechanisms of hydraulic stabilisation: The formation of cement hydration products (C-S-H and C-A-H) binds clay particles, fills voids, reduces permeability and increases internal cohesion; [18, 23]. These effects collectively enhance mechanical strength and durability while reducing water sensitivity, a critical requirement in humid equatorial climates.

3.6.1 | Environmental Considerations

While a full life-cycle assessment (LCA) was beyond the scope of this study, the use of locally sourced soils with a moderate cement content (8%) could offer environmental advantages compared to fired bricks or conventional concrete blocks. However, these potential benefits are not demonstrated here and require careful quantification. Previous studies in similar contexts have reported reductions in embodied energy for stabilised earth bricks compared to fired alternatives [31, 32], but these results cannot be directly transferred to the Ebolowa context. A site-specific LCA, taking into account local transport distances, cement production emissions and regional construction practices, is necessary to confirm any

environmental benefit. Therefore, no claim of reduced carbon footprint or environmental superiority is made based solely on the present results.

3.6.2 | Comparison With Regional Studies

Based on Table 12, the results obtained in this study are consistent with those reported in previous investigations from Cameroon and West Africa. The compressive strength ($\approx 5.7\text{ MPa}$) and flexural strength ($\approx 1.0\text{ MPa}$) exceed the standard requirements recommended for stabilised earth bricks ($\geq 5\text{ MPa}$ according to CRATerre, 2019). The criteria for performance evaluation were based on CRATerre (2019) recommendations for compressed earth blocks, as these are the most directly applicable guidelines for CSEBs in tropical regions. Where relevant, ASTM and NF standards were used only as procedural references for testing methodologies, not as direct threshold standards for CSEBs. Absorption rates below 20% indicate satisfactory compactness and water stability, comparable to or slightly better than values observed in similar studies [14, 27, 35].

This regional comparison confirms the high potential of Ebolowa soils for the manufacture of ecological and economical bricks, compatible with sustainable construction objectives in tropical climates. It should be noted that the mechanical thresholds (compressive strength $\geq 5\text{ MPa}$, water absorption $< 20\%$) cited in this study are based on CRATerre (2019) recommendations, which are specifically developed for compressed earth blocks in tropical environments. While ASTM and ISO standards provide valuable procedural guidance, they were originally developed for fired clay or concrete masonry units and are used here as analogous references in

TABLE 11 | Change in water stability as a function of cement content.

Sample code	Cement content (% dry weight)	Dry resistance (MPa)	Wet resistance (MPa)	Water stability (R_{wet} / R_{dry})	Observation
EBM1-C0	0	1.52	0.48	0.32	Low resistance; dissolves quickly in water
EBM1-C2	2	2.84	1.25	0.44	Slight improvement in stability
EBM1-C4	4	3.96	2.02	0.51	Increased cohesion and reduced porosity
EBM1-C6	6	4.82	3.12	0.65	Good stability in humid environments
EBM1-C8	8	5.68	4.45	0.78	Excellent stability and compliant with regulatory requirements
EBL2-C0	0	1.64	0.53	0.32	Raw soil and rapid disintegration
EBL2-C2	2	2.95	1.41	0.48	Initial water resistance
EBL2-C4	4	4.07	2.25	0.55	Consolidated structure and low cohesion loss
EBL2-C6	6	4.92	3.38	0.69	Good cement bond strength
EBL2-C8	8	5.81	4.78	0.82	Optimal stability and very good water resistance

Note: Boldface corresponds, for each soil type, to the highest value associated with the dosage levels studied.

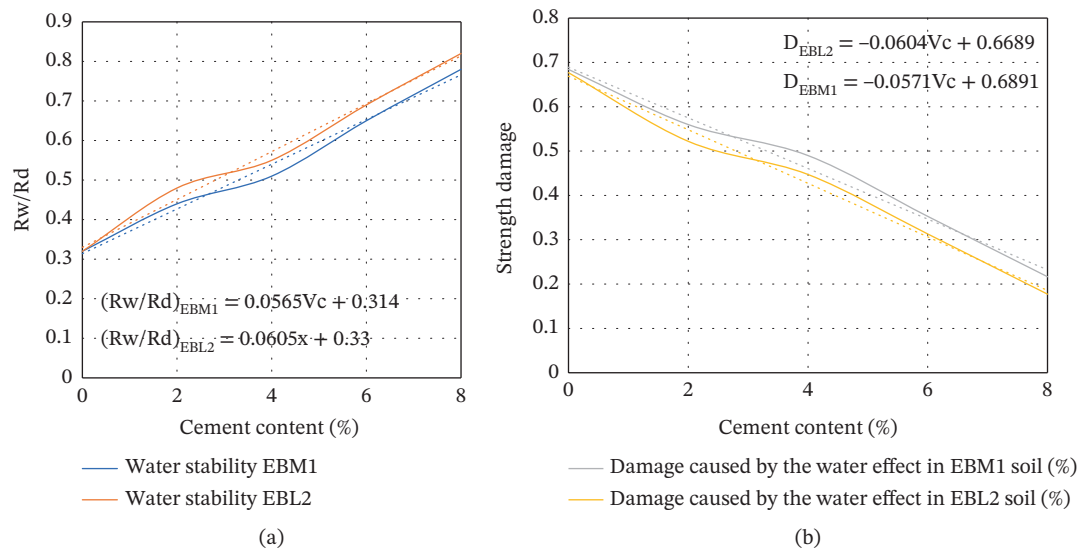
**FIGURE 10** | (a) Stability curves and (b) loss of strength curves due to the effect of water.

TABLE 12 | Comparison of performance results with those of other regional studies.

Authors and Years	Location of the Study	Soil Types	Cement Content	Compressive Strength	Flexural Strength	Water Absorption	Observation/ conclusion
This study (2025)	Ebolowa (Cameroon)	Clayey-loamy	8	5.7–5.8	0.8–1.1	≈19.7	Performance in line with standards; dense and durable material
Imar et al. [33]	Yaoundé (Cameroon)	Lateritic	8	5.5	—	20–22	Good water stability; significant thermal improvement
Minane et al. [34]	Kribi (Cameroon)	Sandy clay	6	4.9	0.9	21	Satisfactory results for sustainable construction
Millogo and Morel [30]	Koudougou (Burkina Faso)	Lateritic clay	8	5.2	0.8	22	Similar mechanical behaviour; positive effect of cement
Taallah and Guettala [18]	Biskra (Algeria)	Loamy clay	10	6.0	1.2	18	Maximum performance beyond 8% cement; good compromise between durability and cost
Akinwumi (2015b)	Lagos (Nigeria)	Sandy clay	6	4.6	—	23	Moderate improvement in strength and durability
Ndjigui et al. [19]	South Cameroon	Lateritic clay	8	5.4	0.9	20	Comparable properties; relevance of local stabilisation

the absence of a dedicated Cameroonian standard for CSEBs. The clay-loam composition and moderate plasticity of these soils (Table 4) make them suitable for producing eco-friendly building materials that can contribute to sustainable housing with a reduced environmental footprint while supporting the local construction industry.

3.6.3 | Comparative Performance of the Two Soils

Although both soils are suitable for CSEB manufacture, the LO'O-BIYENG soil (EBL2) demonstrates superior characteristics. Its higher clay content (56.8% vs. 52.0%) and MBV (2.80 vs. 2.43) (Table 4) provide more surface area for cementitious

bonding, resulting in slightly better mechanical performance (Tables 7, 8, 9, 10 and 11) and water stability (Figure 9). This soil is therefore better suited for optimisation with a reduced cement content of approximately 7.5% to achieve optimal performance. A comprehensive summary of the results obtained from this site is presented in Table 13.

3.6.4 | FTIR Analysis and Standard Compliance

In Table 13, the evolution of the FTIR signatures of the EBL2 material highlights a gradual chemical transformation directly correlated with the improvement of its physical and mechanical properties. These spectral changes are discussed in relation

TABLE 13 | Combination of physical, mechanical and mineralogical test results.

Wavenumber (cm ⁻¹)	Location	EBL2_C_0%	EBL2_C_2%	EBL2_C_4%	EBL2_C_6%	EBL2_C_8%
4000		0.06	0.07	0.08	0.09	0.1
3695	$\nu(\text{O-H})$ kaolinite	1.2	1	0.8	0.55	0.35
3620		1.15	0.95	0.75	0.5	0.33
2500		0.3	0.33	0.35	0.37	0.38
1630	$\delta(\text{H-O-H})$ adsorbed water	0.75	0.7	0.65	0.6	0.55
1095		0.7	0.95	1.2	1.4	1.55
1009	$\nu(\text{Si-O-Si})$ silicate	0.65	0.9	1.15	1.35	1.5
912	$\delta(\text{Al-O-H})$ clay	0.55	0.75	0.9	1.05	1.2
695	$\delta(\text{Al-O-Si})$ kaolinite	0.5	0.4	0.3	0.2	0.12
520	$\nu(\text{Ca-O})$ oxyd	0.3	0.35	0.42	0.47	0.52
470		0.25	0.3	0.36	0.42	0.48
500		0.2	0.26	0.32	0.37	0.43
Compressive strength		2.28	3.58	4.47	5.34	5.81
Bending strength		0.42	0.55	0.66	0.74	0.81
Water absorption (%)		27.9	24.8	22.2	20	19
Density (g/cm ³)		1.82	1.88	1.94	2	2.06

to performance criteria recommended by CRATerre (2019) for compressed earth blocks, with ASTM and ISO standards used in civil engineering construction materials as procedural references where applicable:

- The significant decrease in the $\nu(\text{O-H})$ bands associated with kaolinite (3695–3620 cm⁻¹), with intensity dropping from 1.20–1.15 to 0.35–0.33 between 0% and 8% cement, is consistent with, but not definitive proof of, dehydroxylation of the clay phases. This transformation is consistent with the reduction of the $\delta(\text{H-O-H})$ band at 1630 cm⁻¹ (0.75→0.55), indicating decreased adsorbed water. These spectral changes correspond to the water absorption threshold of <20% recommended by CRATerre (2019) for CSEBs in humid environments, a criterion fully met at 8% cement (19% absorption, Table 7). The testing procedure for water absorption followed ASTM C67 (for water absorption) and NF P 18-406 (for compressive strength) as analogous references, as no specific Cameroonian standard exists for CSEBs;
- The progressive strengthening of the $\nu(\text{Si-O-Si})$ and $\nu(\text{Si-O-Al})$ bands between 1095 and 1009 cm⁻¹, with intensity increasing from 0.65–0.70 to 1.50–1.55, is consistent with the formation of secondary cementitious phases (suggestive of C-S-H and C-A-H types) that are likely responsible for material cohesion and hardening. This interpretation is based on spectral similarities with published FTIR data on cement hydration products [28, 29].

This spectroscopic evolution directly correlates with the increase in compressive strength from 2.28 to 5.81 MPa (Table 8), exceeding the minimum threshold of 5 MPa recommended by CRATerre (2019) for load-bearing CSEBs. The compressive strength testing protocol followed NF P 18-406 (used as an analogous reference for CSEB testing methodology). Similarly, the flexural strength of 0.81 MPa at 8% cement (Table 9) was determined following the three-point bending procedure described in NF EN 12390-5, with ASTM C67 providing additional methodological guidance;

- The increase in bulk density from 1.82 to 2.06 g/cm³ (Table 13; Figure 5), combined with the intensification of $\nu(\text{Ca-O})$ and $\nu(\text{Fe-O})$ bands at 520–470 cm⁻¹ (0.25–0.30→0.48–0.52), is consistent with reduced open porosity and the formation of calcium and ferric bridges. This microstructural densification, which aligns with the density requirements for building materials (ISO 10456, used as an analogous reference), contributes to the overall improvement in mechanical performance and resistance to environmental degradation;
- The progressive increase in the intensity of bands associated with Si-O-Si and Si-O-Al vibrations (1000–1100 cm⁻¹) suggests the formation of amorphous silicate structures typical of C-S-H gels, the main binding phases responsible for the mechanical strength of cementitious materials. Concurrently, the reduction of hydroxyl-related bands

associated with kaolinite indicates partial transformation of clay minerals during stabilisation. These mineralogical changes contribute to reduced material hydrophilicity and porosity, explaining the observed improvements in compressive strength and water stability.

The improved performance with cement addition can be explained by three interrelated mechanisms, supported by the FTIR evidence:

- *Physical filling*: Cement particles fill interparticle voids, increasing density ($1.69 \rightarrow 1.93 \text{ g/cm}^3$) and reducing porosity, reflected in decreased water absorption ($27.3\% \rightarrow 19.7\%$). This reduction meets the $<20\%$ threshold recommended by CRATerre (2019) for CSEBs in humid environments;
- *Cementitious bonding*: Cement hydration produces amorphous silicates (indicated by intensifying $1000\text{--}1100 \text{ cm}^{-1}$ bands) that coat and bridge clay particles, increasing cohesion (strength: $1.52 \rightarrow 5.81 \text{ MPa}$);
- *Clay modification*: The alkaline cement environment promotes partial clay dissolution and pozzolanic reactions (supported by decreasing kaolinite bands at 3695 cm^{-1}), contributing additional binding phases.

In summary, the quantitative correlation between FTIR band evolution, reduced hydrophilicity, increased density and improved mechanical strength demonstrates that EBL2 material stabilised at 6%–8% cement meets the essential requirements of ASTM and ISO standards for civil engineering applications, particularly in the manufacture of masonry elements and sustainable building materials based on local resources.

Based on FTIR evidence in Table 13 alone, these interpretations remain qualitative. Ongoing investigations using XRD and SEM-EDS aim to confirm the nature of the mineralogical transformations and to provide direct evidence of C–S–H phase formation.

4 | Conclusion

This study assessed the potential of clay soils from MVAM ESSAKO and LO'O-BIYENG (Ebolowa, Cameroon) for producing CSEBs. The main findings are:

- Both soils exhibit moderate plasticity (IP: 20.6%–22.4%) and active clay mineral contents (VBS: 2.43–2.80), making them suitable for cement stabilisation;
- Cement addition progressively improves physical and mechanical properties: At 8% cement, compressive strength reaches 5.68–5.81 MPa (exceeding the 5 MPa requirement for structural masonry), water absorption decreases to $<20\%$ and water stability improves to 0.78–0.82;
- FTIR analysis reveals spectral changes consistent with stabilisation, including decreased intensity of kaolinite-related bands and increased intensity of silicate-related bands, suggestive of clay dehydroxylation and cementitious phase formation. These spectral changes provide qualitative microstructural explanations for the observed macroscopic improvements, though complementary analyses (XRD

and SEM-EDS) would be required for definitive phase identification;

- LO'O-BIYENG soil shows slightly better performance, suggesting an optimal cement content of $\sim 7.5\%$ for this material.

The study brings a methodological contribution by quantitatively correlating FTIR spectral evolution (dehydroxylation of kaolinite and formation of C–S–H type phases) with macroscopic mechanical performance. The proposed stabilisation index I_{1095}/I_{3695} provides a spectroscopic marker for assessing cement hydration progress in clayey soils.

The results demonstrate that Ebolowa clay soils can produce CSEBs meeting international standards, offering a viable alternative to fired bricks for local construction. This supports sustainable housing development while reducing dependence on imported materials.

This work was conducted on two soils (EBM1 and EBL2) that are representative of clayey soils frequently found in the Ebolowa area. However, the regional variability of soils (mineralogy, grain size and plasticity) could influence the effectiveness of cement stabilisation. Therefore, the results should not be extrapolated to the entire Ebolowa region without additional geotechnical and mechanical investigations on a larger number of sampling sites.

This study focused on 28-day performance; long-term durability under cyclic wetting–drying typical of humid tropical climates requires investigation. Additionally, definitive phase identification would benefit from XRD or SEM analysis.

Complementary analyses using XRD and SEM-EDS are currently underway to confirm the nature of the C–S–H phases and to visualise the microstructural changes induced by cement stabilisation.

Future work should explore alternative ecostabilisers (lime, natural fibres and geopolymers) and develop local construction standards for CSEBs in Cameroon. Additionally, a comprehensive LCA is required to quantify the actual environmental benefits of using these stabilised bricks compared to conventional construction materials in the Ebolowa region.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. S. R. Baig, and L. G. Sarwar, "Ensuring Shelter for All: Analyzing India's Legal Framework and Policies on Housing for All," *Global Legal Studies Review* 9, no. 2 (2024): 51–59, [https://doi.org/10.31703/ghsr.2024\(IX-II\).06](https://doi.org/10.31703/ghsr.2024(IX-II).06).
2. P. Awoyera, E. Onoja, and A. Adesina, "Fire Resistance and Thermal Insulation Properties of Foamed Concrete Incorporating Pulverized Ceramics and Mineral Admixtures," *Asian Journal of Civil Engineering* 21, no. 1 (2020): 147–156, <https://doi.org/10.1007/s42107-019-00203-4>.
3. A. Medjnoun, M. Khatine, and R. Bahar, "Mineralogical and Geotechnical Characterisation of Swelling Clay Marl of the Medea Region, Algeria," *Bulletin of Engineering Geology and the Environment* 73, no. 4 (2014): 1259–1272, <https://doi.org/10.1007/s10064-014-0582-z>.
4. A. Batari, A. U. Chinade, S. M. Saeed, I. A. Ikara, N. Kabir, and A. Mamuda, "Effect of Bagasse Ash on the Properties of Cement Stabilized Black Cotton Soil," *International Journal of Transportation Engineering and Technology* 3, no. 4 (2017): 67–73, <https://doi.org/10.11648/j.ijtet.20170304.14>.
5. N. A. Mahindad, "Influence of Natural Additives and Crushed Bricks on the Physical and Mechanical Properties of Repair and Restoration Mortars," *International Journal of Physical Sciences* 15, no. 2 (2020): 60–69, <https://doi.org/10.5897/ijps2020.4867>.
6. U. Y. Mai-Bade, A. U. Chinade, A. Batari, and S. M. Saeed, "Stabilisation of Black Cotton Soil Using Various Admixtures: A Review," *Composite Materials* 5, no. 2 (2021): 37–45, https://doi.org/10.1007/978-981-10-8016-6_98.
7. M. Charai, S. Channouf, O. Horma, et al., "Laboratory-Testing and Industrial Scale Performance of Different Clays From Eastern Morocco for Brick Manufacturing," *Construction and Building Materials* 370 (2023): 130624, <https://doi.org/10.1016/j.conbuildmat.2023.130624>.
8. C. Ziegert, and U. Röhlen, "Normen Im Lehmabau," in *2023 Mauerwerk Kalender: Instandsetzung Erdbeben Lehmabau* (Wiley Online Library, 2023), 111–126.
9. M. A. Hamdaoui, M. H. Benzaama, Y. El Mendili, D. Chateigner, and S. Gascoin, "Investigation Of The Mechanical And Hygrothermal Behavior Of Coffee Ground Wastes Valorized As A Building Material: Analysis Of Mix Designs Performance And Sorption Curve Linearization Effect," *Archives of Civil and Mechanical Engineering* 23, no. 1 (2023): 57, <https://doi.org/10.1007/s43452-022-00579-2>.
10. J. C. Morel, R. Charef, E. Hamard, A. Fabbri, C. Beckett, and Q. B. Bui, "Earth as Construction Material in the Circular Economy Context: Practitioner Perspectives on Barriers to Overcome," *Philosophical Transactions of the Royal Society B: Biological Sciences* 376, no. 1834 (2021): 20200182, <https://doi.org/10.1098/rstb.2020.0182>.
11. Y. Wang, and H. Abuel-Naga, "Unfired Bricks From Wastes: A Review of Stabiliser Technologies, Performance Metrics, and Circular Economy Pathways," *Buildings* 15, no. 11 (2025): 1861, <https://doi.org/10.3390/buildings15111861>.
12. S. Wu, Z. Shao, R. M. Andrew, et al., "Global CO₂ Uptake by Cement Materials Accounts 1930–2023," *Scientific Data* 11, no. 1 (2024): 1409, <https://doi.org/10.1038/s41597-024-04234-8>.
13. H. Binici, I. Cagatay, T. Shah, and S. Kapur, "Mineralogy of Plain Portland and Blended Cement Pastes," *Building and Environment* 43, no. 7 (2008): 1318–1325, <https://doi.org/10.1016/j.buildenv.2007.03.012>.
14. Y. Millogo, J. E. Aubert, A. D. Séré, A. Fabbri, and J. C. Morel, "Earth Blocks Stabilized by Cow-Dung," *Materials and Structures* 49, no. 11 (2016): 4583–4594, <https://doi.org/10.1617/s11527-016-0808-6>.
15. Y. Millogo, M. Hajjaji, and R. Ouedraogo, "Microstructure and Physical Properties of Lime-Clayey Adobe Bricks," *Construction and Building Materials* 22, no. 12 (2008): 2386–2392, <https://doi.org/10.1016/j.conbuildmat.2007.09.002>.
16. Y. Millogo, M. Hajjaji, R. Ouedraogo, and M. Gomina, "Cement-Lateritic Gravels Mixtures: Microstructure and Strength Characteristics," *Construction and Building Materials* 22, no. 10 (2008): 2078–2086, <https://doi.org/10.1016/j.conbuildmat.2007.07.019>.
17. O. Izemmouren, A. Guettala, and S. Guettala, "Mechanical Properties And Durability Of Lime And Natural Pozzolana Stabilized Steam-Cured Compressed Earth Block Bricks," *Geotechnical and Geological Engineering* 33, no. 5 (2015): 1321–1333, <https://doi.org/10.1007/s10706-015-9904-6>.
18. B. Taallah, and A. Guettala, "The Mechanical and Physical Properties of Compressed Earth Block Stabilized With Lime and Filled With Untreated and Alkali-Treated Date Palm Fibres," *Construction and Building Materials* 104 (2016): 52–62, <https://doi.org/10.1016/j.conbuildmat.2015.12.007>.
19. P. D. Ndjigui, J. A. Mbey, and A. N. Nzeukou, "Mineralogical, Physical and Mechanical Features of Ceramic Products of the Alluvial Clastic Clays From the Ngog-Lituba Region, Southern Cameroon," *Journal of Building Engineering* 5 (2016): 151–157, <https://doi.org/10.1016/j.jobte.2015.11.009>.
20. S. Fadi-Djenabou, P. Ndjigui, and J. A. Mbey, "Mineralogical and Physicochemical characterization of Ngaye Alluvial Clays (Northern Cameroon) and Assessment of Its Suitability in Ceramic Production," *Journal of Asian Ceramic Societies* 3, no. 1 (2015): 50–58, <https://doi.org/10.1016/j.jascer.2014.10.008>.
21. L. Courard, "Construction en terre, ressources secondaires et matériaux bio-sourcés: un avenir pour l'Afrique," *Bulletin des Séances de l'Académie Royale des Sciences d'Outre-Mer* 1 (2020): 103–118, <https://doi.org/10.5281/zenodo.6538763>.
22. E. Ouedraogo, O. Coulibaly, A. Ouedraogo, and M. Adamah, "Caractérisation mécanique et thermophysique des blocs de terre comprimée stabilisée au papier (cellulose) et/ou au ciment," *Journal of Materials and Engineering Structures* 2, no. 2 (2015): 68–76, <https://doi.org/10.1007/bf02486410>.
23. K. A. J. Ouedraogo, J. E. Aubert, C. Tribout, Y. Millogo, and G. Escadeillas, "Ovalbumin As Natural Organic Binder For Stabilizing Unfired Earth Bricks: Understanding Vernacular Techniques To Inspire Modern Constructions," *Journal of Cultural Heritage* 50 (2021): 139–149, <https://doi.org/10.1016/j.culher.2021.05.004>.
24. M. Hussain, I. Lamrous, A. Provost, et al., "Recovery and Restructuring of Fine and Coarse Soil Fractions as Earthen Construction Materials," *Sustainability* 16, no. 20 (2024): 8952, <https://doi.org/10.3390/su16208952>.
25. I. I. Obianyo, A. A. Mahamat, T. T. Stanislas, et al., "Production and Utilisation of Earth-Based Bricks for Sustainable Building Applications in Nigeria: Status, Benefits, Challenges and Way Forward," *Journal of Building Pathology and Rehabilitation* 6, no. 1 (2021): 37, <https://doi.org/10.1007/s41024-021-00131-4>.
26. C. B. Paterne, A. Alinabiwe, M. B. Nelly, et al., "Etude de la stabilisation du sol de Buganga en RDC par ciment et chaux en vue de l'utilisation dans la construction routière," *International Journal of Innovation and Applied Studies* 40, no. 1 (2023): 212–218, <https://doi.org/10.18356/9789213585290c004>.
27. A. Lawane, J. Minane, R. Vinai, and A. Pantet, "Mechanical and Physical Properties of Stabilised Compressed Coal Bottom Ash Blocks With Inclusion of Lateritic Soils in Niger," *Scientific African* 6 (2019): e00198, <https://doi.org/10.1016/j.sciaf.2019.e00198>.
28. Y. Millogo, K. Traoré, R. Ouedraogo, K. Kaboré, P. Blanchart, and J. H. Thomassin, "Geotechnical, Mechanical, Chemical and Mineralogical Characterisation of a Lateritic Gravels of Sapouy (Burkina Faso) Used in Road Construction," *Construction and Building Materials* 22, no. 2 (2008): 70–76, <https://doi.org/10.1016/j.conbuildmat.2006.07.014>.
29. N. Zakhm, Y. El Rhaffari, A. Ammari, et al., "Influence of Cement Content on the Thermal Properties of Compressed Earth Blocks (CEB)

in the Dry State,” *MATEC Web of Conferences* 149 (2018): 01059, <https://doi.org/10.1051/mateconf/201814901059>.

30. Y. Millogo, and J. C. Morel, “Microstructural Characterisation and Mechanical Properties of Cement Stabilised Adobes,” *Materials and Structures* 45, no. 9 (2012): 1311–1318, <https://doi.org/10.1617/s11527-012-9833-2>.

31. J. C. Morel, A. Mesbah, M. Oggero, and P. Walker, “Building Houses With Local Materials: Means To Drastically Reduce The Environmental Impact Of Construction,” *Building and Environment* 36, no. 10 (2001): 1119–1126, [https://doi.org/10.1016/S0360-1323\(00\)00054-8](https://doi.org/10.1016/S0360-1323(00)00054-8).

32. F. Pacheco-Torgal, and S. Jalali, “Earth Construction: Lessons From The Past For Future Eco-Efficient Construction,” *Construction and Building Materials* 29 (2012): 512–519, <https://doi.org/10.1016/j.conbuildmat.2011.10.054>.

33. M. M. Imar, M. Diakhate, L. M. B. A. MOUNGAM, A. Talla, B. Nsom, and P. Meukam, “Valorization of Cotton Waste Ash in the Formulation of Compressed Earth Blocks,” *Mechanics of Advanced Materials and Structures* 31, no. 21 (2024): 5220–5233, <https://doi.org/10.1080/15376494.2023.2213240>.

34. J. R. Minane, A. Lawane, J. Madjadoumbaye, R. Vinai, and B. Zagré, “Development of Cement Stabilised Compressed Blocks Using Coal Bottom Ash: Influence of the Grain Size on Mechanical and Physical Properties of Blocks,” *Civil and Sustainable Urban Engineering* 3, no. 1 (2023): 81–94, <https://doi.org/10.53623/csue.v3i1.242>.

35. J. Goutsaya, G. E. Ntamack, B. Kenmeugne, and S. Charif d’Ouazane, “Mechanical Characteristics of Compressed Earth Blocks, Compressed Stabilized Earth Blocks and Stabilized Adobe Bricks With Cement in the Town of Ngaoundere-Cameroon,” *Journal of Building Materials and Structures* 8, no. 2 (2021): 139–159, <https://doi.org/10.34118/jbms.v8i2.1441>.