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Multi-scale characterization of lateritic soils from the Adamawa region of Cameroon and their suitability for sustainable compressed earth block production

Sedako Aoudou Eneta Pierre^{1*}, Keyangue Tchouata Jules Hermann^{1*}, Ngon Ngon Gilbert François², Taypondou Darman Japhet³, Mbadi Oum Arles Bienvenu⁴, Tchedele Langollo Yannick^{4,5} and David Houivet⁵

*Correspondence:

Sedako Aoudou Eneta Pierre
sadakoaoudou@yahoo.com
Keyangue Tchouata Jules Hermann
keytchjmann@yahoo.fr

¹School of Geology and Mining Engineering, University of Ngaoundere, Meiganga, Cameroon
²Faculty of Sciences, University of Douala, P.O. Box 24157, Douala, Cameroon

³Department of Civil Engineering, National Advanced School of Public Works, P.O. Box 510, Yaounde, Cameroon

⁴Local Materials Promotion Authority (MIPROMALO), Yaounde, Cameroon

⁵Laboratoire Universitaire des Sciences Appliquées de Cherbourg (LUSAC) ER 4253, Université de Caen-Normandie, BP 78, 50130 Cherbourg-en-Cotentin, France

Abstract

This study presents a comprehensive multi-scale investigation of lateritic soils from Dir (Adamawa, Cameroon) to assess and optimize their potential for producing compressed earth blocks (CEB) and cement-stabilized earth blocks (SEB). Twenty soil samples collected from four sites underwent geotechnical, mineralogical (XRD, IR), chemical (XRF), and microstructural (SEM-EDS) characterization, alongside mechanical and durability testing of fabricated blocks. The soils exhibit suitable particle size distributions and plasticity ($PI=8-12\%$), with a mineralogy dominated by quartz and kaolinite, reflecting advanced weathering ($CIA > 96\%$). A multivariate Principal Component Analysis identified four orthogonal factors controlling soil behavior: texture/compaction, plasticity/clay activity, organic-mineral balance, and natural moisture content, providing a scientific framework for formulation. While unstabilized CEBs showed moderate compressive strength (1.47–3.91 MPa), cement stabilization (4–12%) significantly enhanced performance, achieving strengths up to 9.79 MPa in compression and 4.38 MPa in flexure. Notably, nonlinear regression models revealed a parabolic relationship with cement, identifying a minimum effective threshold near 2% and quantifying the distinct effects of organic matter (beneficial in flexure, detrimental in compression). Microstructural analysis confirmed progressive matrix densification and C–S–H formation with increasing cement content. The blocks also demonstrated favorable hydric properties (bulk density: 1.79–1.99 t/m³; porosity: 25–30%; water absorption: 11–15%). This work moves beyond empirical characterization by establishing predictive models and microstructure-property relationships, demonstrating the viability of Dir's laterites for sustainable construction and providing a rational basis for optimizing local earth-based materials in line with SDGs 9, 11, and 13.

Keywords Laterite, Compressed earth blocks, Stabilization, Geotechnical properties, Sustainable construction, Predictive modeling



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1 Introduction

Despite the major technological advances achieved over the past centuries, advances that have endowed humanity with a wide array of modern construction materials such as concrete and steel, there is a renewed interest today in traditional building materials, particularly raw and fired earth. This resurgence is evident in both industrialized and developing nations [1, 2]. The trend reflects a growing imperative to promote materials that are accessible, environmentally responsible, and sustainable, in alignment with the Sustainable Development Goals (SDGs), notably SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) [3]. In Cameroon, earthen materials represent an abundant resource, covering approximately 70% of the national territory [4]. They are widely accessible across social strata and exert a relatively low environmental impact compared to industrial materials with high carbon footprints [5]. However, the primary limitation of earthen construction lies in its modest mechanical strength and vulnerability to weathering. Many structures built with raw earth, such as adobe, cob, and mud, exhibit uncertain durability, often suffering from erosion, cracking, and even collapse under the influence of moisture and heavy rainfall [6].

To address these shortcomings, a wide array of stabilization techniques have been developed and refined. Contemporary research has moved beyond traditional stabilizers like cement and lime to explore alternative, often more sustainable, options. These include the incorporation of natural and synthetic fibers to improve tensile strength and control cracking, as well as biopolymers and industrial by-products that can enhance mechanical properties while reducing the carbon footprint associated with cement production [7, 8]. While these processes demonstrably enhance the geotechnical, mechanical, and physico-chemical properties of the material, a persistent challenge remains: the performance of these stabilized materials is not solely a function of the stabilizer type and dosage. It is intrinsically governed by the complex, multivariate nature of the soil itself, its granulometry, mineralogy, chemistry, and organic content. This inherent complexity often leads to empirical, trial-and-error approaches in practice, underscoring the need for a more fundamental, predictive understanding.

Within this context, a critical gap exists in the understanding of lateritic soils in certain regions of Cameroon, particularly in the locality of Dir (Adamawa region). While valuable descriptive studies have been conducted in nearby areas like Meiganga [7], these investigations have typically focused on individual material characterization. They have not yet leveraged advanced multivariate statistical methods, such as Principal Component Analysis (PCA), to decipher the dominant, often interacting, latent factors governing soil behavior. Furthermore, the development of non-linear predictive models for mechanical strength based on key compositional parameters, moving beyond simple linear correlations, remains largely unexplored for these local materials. Yet, this deeper level of characterization and modeling is precisely what is required to transition from empirical formulation to engineered material design. Such an approach is essential for promoting optimized, locally-sourced construction materials, reducing reliance on costly and time-consuming trial-and-error methods, and fostering inclusive and sustainable development in line with national housing priorities.

This research directly addresses these gaps by conducting a multi-scale evaluation of lateritic soils from Dir (Adamawa, Cameroon) to determine their suitability

for producing stabilized compressed earth blocks (SCEB). The originality and scientific contribution of this work lie not just in characterizing a new soil source, but in its methodological approach. By integrating detailed physical, mineralogical, and chemical characterization with (i) multivariate statistical analysis (PCA) to identify the latent factors controlling soil variability and its implications for block formulation, and (ii) the development and validation of non-linear predictive models for compressive and flexural strength, this study provides a framework that is both diagnostic and prognostic. This approach moves beyond simple description to offer a predictive understanding of how inherent soil properties and cement content interact to determine final block performance. Finally, the research intends to validate these macro-scale models by correlating them with microstructural evolution via SEM-EDS analysis, thereby offering a fundamental and practical framework for enhancing the value of Dir's lateritic soils.

This investigation thus operates on two complementary fronts: scientifically, by filling a knowledge gap for the soils of Dir and introducing a modeling-driven framework that can be replicated for other under-studied regions; and socio-economically, by providing actionable data and validated predictive tools to promote accessible, resilient, and climate-adapted housing solutions for Cameroon.

2 Location and sampling zones

2.1 Localization

Dir is located in the Adamawa Region, in the Mbéré Division, between latitude $6^{\circ} 20' 01''$ North and longitude $13^{\circ} 31' 51''$ East (Fig. 1). It covers an area of around 4,300 km², with an estimated population of 64,698, giving an average density of 15 hab/km². It is bordered to the north by the Nyambaka district, to the south by the Bétaré-oya district (Eastern region), to the east by the Ngaoundal district, and to the west by the Meiganga district. Figure 1 shows the sampling points in Dir.

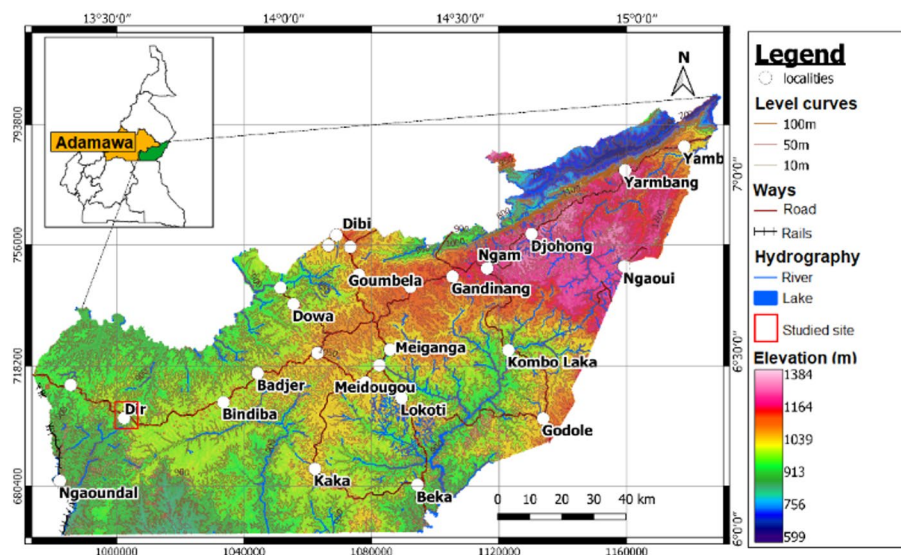


Fig. 1 localization of the study area and sampling site

2.2 Sampling

Samples were taken manually using a pickaxe, then packed into bags and labelled so that each bag contained the full identity of the sample. To account for the expected spatial heterogeneity of lateritic soils in the region, a systematic sampling strategy was adopted: twenty (20) wells (Fig. 2) with a cross-section of approximately 0.30×1.30 m and an average depth of 1.3 m were excavated over a 100 m sampling distance using a diamond mesh pattern across four zones of the Dir locality. The number of wells was chosen to ensure a statistically representative sample of soil variability, the dimensions were selected to provide sufficient material for the extensive testing program, and the depth was specifically chosen to target the construction-relevant lateritic horizon below the organically rich topsoil.

3 Experimental methodology

Soil sampling was conducted across four distinct sites in the locality of Dir: Borwarra, Jolie-soir, Lamido, and Yayouwé. A total of twenty (20) disturbed samples were collected, with five (05) samples taken from each site. These samples were subsequently transported to three specialized laboratories for analysis: the Local Material Promotion Authority (MIPROMALO) Laboratory in Yaoundé, the Laboratory of Applied Inorganic Chemistry at the University of Yaoundé I, and the Bhygraph Geotechnical Laboratory SA, also located in Yaoundé.

Natural moisture content was determined using the gravimetric method, involving successive weighing before and after oven-drying at 105°C for 24 h, in accordance with the NF P 94-050 standard.

Absolute density was measured using a pycnometer, based on the volume of solid grains and successive weighing, following the NF P 94-054 standard.

Particle size distribution was assessed through both dry and wet methods. Dry analysis was performed by sieving the air-dried sample after washing, as prescribed by NF P 94-056, while wet analysis employed sedimentation techniques in line with NF P 94-057.

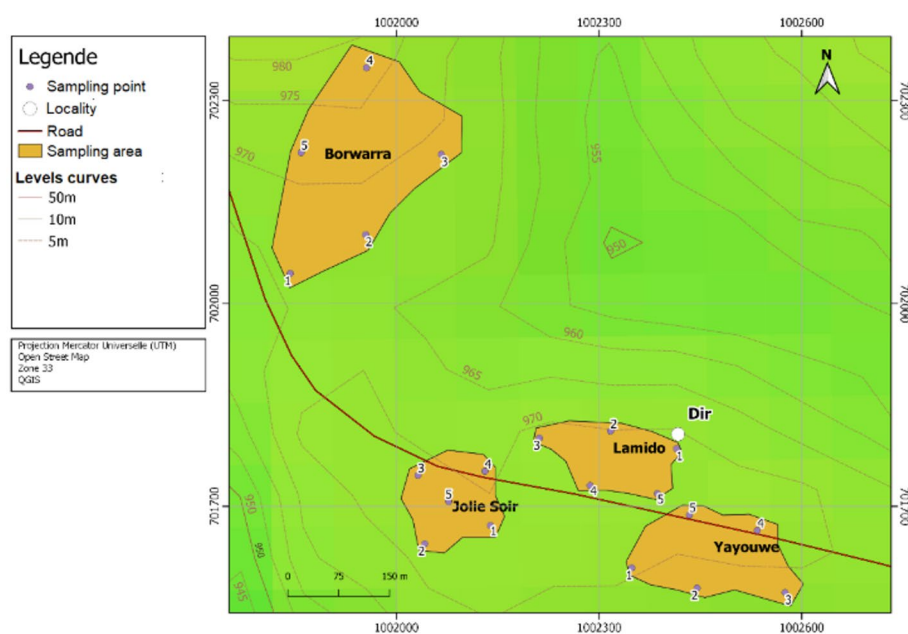


Fig. 2 Sampling map showing the spatial distribution of excavated wells

Optimal moisture content and maximum dry density were determined using the Modified Proctor test, conducted according to NF P 94-093.

Mineralogical composition was identified via two complementary techniques. X-ray diffraction (XRD) analysis was performed using a Bruker Advance diffractometer with Cu-K α radiation ($\lambda = 1.5418 \text{ \AA}$) over a 2θ range of 5° to 120° with a step size of 0.02° . Phase identification was carried out using X'Pert HighScore software coupled with the ICDD database. Additionally, infrared spectroscopy was conducted based on the vibrational frequencies of key chemical bonds within the mineral phases present in the samples, serving to confirm the XRD findings [9].

Major elemental composition was analyzed using X-ray fluorescence spectroscopy, performed with an ARL™ PERFORM'X spectrometer at the quality control laboratory of the Cimencam Figuil cement plant [10].

Atterberg limits were determined following NF P 94-051, and plasticity indices were calculated using standard mathematical relationships between liquid and plastic limits.

Methylene blue values were measured in accordance with NF P 94-068, providing insight into the clay activity and surface area of the soil particles.

Compressive strength tests were carried out on specimens measuring $4 \times 4 \times 16 \text{ cm}$, following the NF EN 13286-41 standard. Tests were performed on both unstabilized and cement-stabilized samples, using CEM II B-P 42.5R cement from Cimencam.

Water absorption rate, apparent density, and porosity were determined according to NF EN 1097-3. Water absorption was measured by submerging samples for 24 h and following consecutive weighing procedures as described in ASTM C373-7.

The fabrication of both stabilized and unstabilized earth blocks was conducted using molds of $4 \times 4 \times 16 \text{ cm}$ dimensions, specifically designed for compressive strength testing. A total of 64 specimens were produced for this study: 16 blocks without stabilizer and 48 blocks with varying cement content. For each site, soils collected from different wells were mixed in equal proportions to create a composite sample representative of that location. The preparation of test specimens adhered to conventional procedures, including soil extraction, drying, crushing, sieving, mixing with water (and stabilizer when applicable), compaction, demolding, and either air-drying or curing in the case of hydraulic stabilization. This approach ensured that the mechanical test results reflected the characteristics of each site.

To elucidate the latent factors governing soil variability and block performance, multivariate statistical analyses were performed in XLSTAT. Principal Component Analysis (PCA) was applied to a standardized dataset comprising physical parameters measured across the 16 sampling points. The number of principal components (PC) retained was determined by the Kaiser criterion (eigenvalue > 1). Subsequently, non-linear regression models were developed to predict mechanical strength. Predictor variables were selected based on their high contribution to the PCs and physical relevance. The dataset was split into training (70%) and validation (30%) sets, with model performance assessed using R^2 (coefficient of determination) and RMSE (Root Mean Square Error) to ensure predictive accuracy. The upper bound of the predictive models was set at 8% cement content. Although specimens were tested up to 12% cement to characterize the full performance envelope of the material, several model configurations were evaluated including and excluding the 12% data points. Comparison of the holdout validation metrics (R^2 and RMSE) consistently showed that the models calibrated on the 0–8% range yielded

superior predictive accuracy and better residual independence. This result is physically interpretable: at 12% cement, over-stabilization effects may alter the dominant hydration and densification mechanisms, causing these points to deviate from the quadratic relationship governing lower dosages. The 12% data are therefore presented for trend illustration and to document the upper performance envelope, but fall outside the validated predictive domain of the models.

Microstructural observations as well as elemental chemical mapping of the compressed earth blocks (CEB) were performed using a scanning electron microscope (SEM, Hitachi S-3460) coupled with an energy-dispersive X-ray spectroscopy system (EDS, ThermoNoran®). The analyses were conducted on CEB fragments collected after 28 days of curing and subsequently stored in hermetically sealed plastic bags until examination at the University Laboratory of Applied Sciences of Cherbourg (LUSAC), France.

4 Results and discussion

4.1 Physical parameters

Table 1 summarizes the results for natural moisture content, absolute density, grain size, optimum moisture content, and maximum dry density.

4.1.1 Natural moisture content

The natural moisture content of soil is a critical parameter that can reflect its water retention characteristics, compaction potential, and thus suitability for construction purposes. The observed variations in natural moisture content exhibited by the soils

Table 1 Results of the physical parameters

Sites	Well number	W (%)	Absolute density (d _r)	Compositions of granulometric elements				W _{optm} (%)	Y _{max} (t/m ³)
				Gravel	Sand	Silt	Clay		
DIA (Borwarra)	Well 1	14.60	2.58	55.38	24.38	9.40	10.84	20.1	1.852
	Well 2	21.67	2.55	1.46	56.82	23.02	18.70	18.3	1.789
	Well 3	18.85	2.61	46.32	33.74	9.54	10.40	19.8	1.767
	Well 4	21.47	2.50	5.86	61.55	17.07	15.52	14.9	1.805
	Well 5	17.91	2.48	27.26	43.87	15	13.87	17.2	1.963
	Average	18.90	2.54	27.25	44.07	14.80	13.86	18.1	1.835
DIB (Jolie soir)	Well 1	26.97	2.52	8.27	46.54	21.82	23.37	19.1	1.663
	Well 2	22.68	2.50	6.68	53.35	24.27	15.71	17.9	1.817
	Well 3	24.97	2.56	0.65	52.08	19.26	28.01	19.0	1.660
	Well 4	32.78	2.75	33.15	38.91	12.70	15.24	19.5	1.778
	Well 5	20.41	2.67	12.19	47.97	19.26	20.58	22.3	1.774
	Average	25.56	2.60	12.18	47.77	19.46	20.58	19.56	1.738
DIC (Lamido)	Well 1	23.05	2.55	32.89	21.66	12.62	32.82	20.1	1.662
	Well 2	12.78	2.72	61.68	22.61	5.82	9.89	11.3	2.067
	Well 3	11.98	2.68	52.09	27.66	9.78	10.47	11.1	1.761
	Well 4	18.70	2.70	71.05	19.98	3.58	5.38	15.3	1.862
	Well 5	16.13	2.65	54.43	20.77	10.16	14.64	16.4	1.870
	Average	16.53	2.66	54.42	22.54	8.39	14.64	14.8	1.844
DID (Yayouwé)	Well 1	16.75	2.57	43.09	33.62	15.52	7.76	11.4	1.760
	Well 2	26.24	2.63	15.59	48.42	17.99	17.99	23.7	1.754
	Well 3	22.24	2.45	1.79	66.22	15.54	17.45	19	1.903
	Well 4	13.85	2.58	58.19	26.88	6.11	8.82	17.7	1.912
	Well 5	20.16	2.53	29.67	43.98	13.34	13.01	16.0	1.909
	Average	19.85	2.55	29.66	43.82	13.70	13.01	17.56	1.847

of the four study sites (Borwarra, Jolie-soir, Lamido, and Yayouwé) can be attributed to interrelated factors such as soil texture, seasonal influences, and local environmental conditions [11, 12].

The relatively low natural moisture content values across all sites (ranging from 11.98% to 32.78%) suggest a predominance of texture rich in sandy particles. Sandy soils are distinguished by their low water retention capacity, a consequence of their large particle size and high permeability. Sandy soils can drain quickly, thereby preventing significant moisture accumulation. In addition, these soils are distinguished by their high porosity but low capillary action. This interpretation can be supported by the relatively low values of plasticity index observed for these samples. While sandy soils are conducive to effective aeration, their inability to retain water is reflected in the generally moderate natural moisture content values [13]. Samples were collected during the rainy season, which accounts for the sporadic high water content values observed. In certain soil samples, characterized by slight clay particles, water retention following precipitation events may be enhanced. However, given that the majority of natural moisture content values remain moderate, this suggests that there is short-term retention even during the rainy season. Furthermore, the rapid evaporation that is characteristic of tropical and subtropical climates can result in significant moisture loss following precipitation [14].

The Jolie-soir site exhibits the highest average of natural moisture content (25.56%) and maximum value (32.78%), which may indicate a higher proportion of fine particles (silt/clay) compared to other sites, enhancing water retention. Excessive moisture has been shown to induce shrinkage cracks during the drying process, thus compromising the integrity of the product. As posited by [4], the elevated water content observed in the materials may be indicative of the presence of expansive clay, a phenomenon known to be responsible for its high-water retention capacity. Conversely, the Lamido site exhibits the lowest mean (16.53%) and minimum value (11.98%), suggesting a probable sandy or gravelly composition, resulting in rapid drainage.

The presence of low natural moisture content in Borwarra and Lamido can also be indicative of enhanced stability for earthen construction, as excessive moisture has been shown to result in swelling or weakening. However, the presence of very low moisture levels in sandy soils may also be indicative of poor cohesion, a condition that may require compaction or stabilization measures. The generally low natural moisture content is consistent with the sandy soils of the region, while the sporadic higher values suggest the presence of localized heterogeneity or seasonal effects on the studied site. These findings carry significant ramifications for the domains of land use planning and construction, underscoring the necessity for site-specific assessments. However, according to [2] and [15], for soil to be optimal for earth bricks in construction, it should have a moderate natural moisture content (10–20%) for proper compaction to obtain acceptable molding properties during earth bricks manufacturing.

4.1.2 Absolute density

The measured Absolute density values of the studied soils (ranging from 2.48 to 2.75) provide critical insights into their suitability for compressed earth blocks (CEBs) and other earthen construction techniques. In accordance with the findings of [16], the optimal Absolute density for earth bricks is situated within the range of 2.6–2.8 g/cm³. This is because it facilitates optimal compaction and durability.

Borwarra soils (2.48–2.61, average 2.54) exhibit values slightly below the optimal range, suggesting that they may require higher compaction pressure. At Jolie-soir (2.50–2.75, average 2.60), some samples meet the ideal range, but the low average suggests variability. For the Lamido site, which ranges from 2.55 to 2.72, with an average of 2.66, the studied materials demonstrate optimal suitability for CEBs within the near-optimal range. A correlation can be established between these high values of Absolute density and the moisture content. The Lamido soils, which exhibited the lowest natural moisture content values, are indicative of a predominance of coarse grains within the soils' matrix. The combination of these coarse grains with the fact that lateritic soils with higher densities may indicate a chemical composition rich in iron [17] could be the cause of the high Absolute density values obtained. Yayouwé soils (2.45–2.63, average 2.55) indicate moderate values. In general, higher Absolute density (approximately 2.7 g/cm³) has been shown to correlate with enhanced compressive strength, as evidenced by the research conducted by [18] and [4]. It appears that the values obtained in this study are similar to those obtained by [19] (2.4–2.7 g/cm³) in lateritic soils in a similar region. It can thus be deduced from the Absolute density values that the soils from the studied site may require stabilization techniques, including compaction, to be used as construction materials for the production of earth bricks that have satisfactory durability properties.

4.1.3 Grain size analysis

The granulometric characteristics of the soils studied and their particle sizes are plotted in Fig. 3.

The particle size curves demonstrate that most samples from Borwarra, Jolie-soir, and Yayouwé fall within the recommended range for compressed earth block (CEB) production, as defined by Cameroonian standards (NC 102–115). In order to ensure that earth bricks possess satisfactory mechanical properties, it is important to have a sand proportion of between 40 and 65%, with a clay fraction of greater than 5% and less than 30% [20]. These granulometric proportions are suitable for achieving proper compaction and mechanical strength. However, certain samples from Borwarra (samples 1 and 3), Yayouwé (samples 1 and 4), and Lamido (samples 2,3,4, and 5) exhibit gravel-rich compositions that exceed the 40% gravel threshold specified in the standards, necessitating corrective measures such as sieving, crushing, or stabilization to improve workability and reduce void ratios. These granulometric findings correlate well with the previously reported density and natural moisture content data. Globally, the soils from Borwarra, Lamido, and some samples from Yayouwé, characterized by a high proportion of coarse particles and low clay content, exhibit low shrinkage potential, making them naturally suited for CEB production with minimal stabilization. Nonetheless, their relatively low clay fractions may result in insufficient cohesion, requiring artificial binders such as cement or lime to enhance structural integrity and durability [21, 22]. Lamido soils, with slightly higher fines, may benefit from targeted stabilization depending on their plasticity index. Jolie-soir's elevated clay content (32%) contributes to increasing the risk of shrinkage and cracking.

These findings align with successful applications of similar lateritic soils across West Africa, where B5-type materials have proven effective for compressed earth block (CEB) production using 5–8% lime stabilization [23, 24]. Comparable practices are observed in Cameroon, where engineers routinely adjust granulometry through blending or sieving

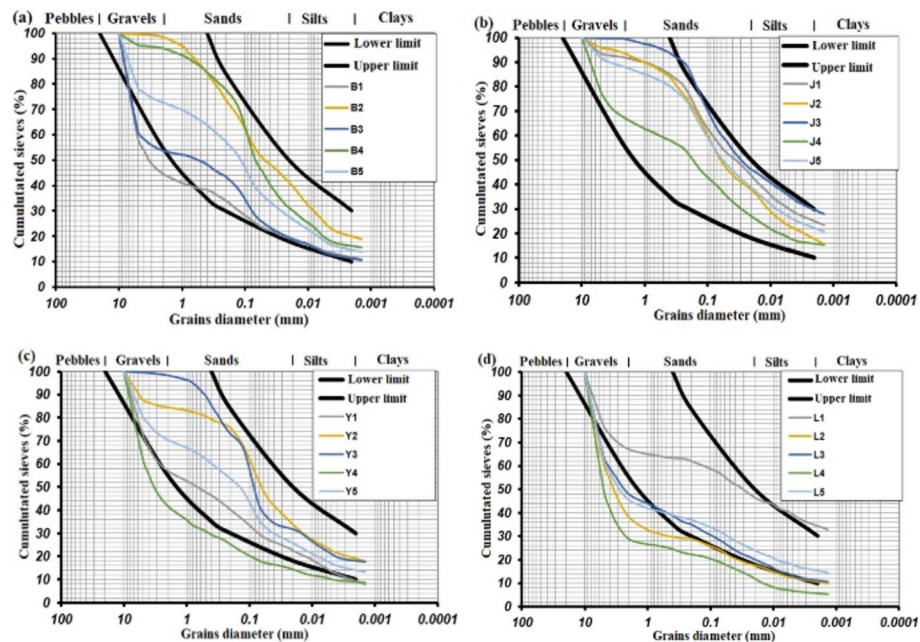


Fig. 3 Grains size distribution curves of the studied lateritic soils

to meet construction standards and enhance material consistency [25, 26]. Notably, the Jolie-soir soils exhibit the same behavior as southern Cameroonian laterites described by [27], which have high clay content and low natural strength, necessitating the use of cement-based stabilization to achieve structural durability. This parallel highlights the importance of tailoring binder strategies to the mineralogical characteristics of lateritic soils.

While most of the studied materials display favorable particle size distributions for CEB production, the variability between sites underscores the need for localized adjustments, whether through selective material sourcing, granulometric correction, or targeted stabilization, to meet optimal performance criteria. This granularity stability relationship reflects a foundational principle in earthen construction: that well-graded particle size distribution underpins mechanical integrity, while stabilization methods such as cement, lime, or biopolymer additives address residual deficiencies. Recent studies further emphasize that an optimized granular skeleton enhances dry strength and minimizes shrinkage, with stabilization techniques contributing to improved durability and water resistance [28].

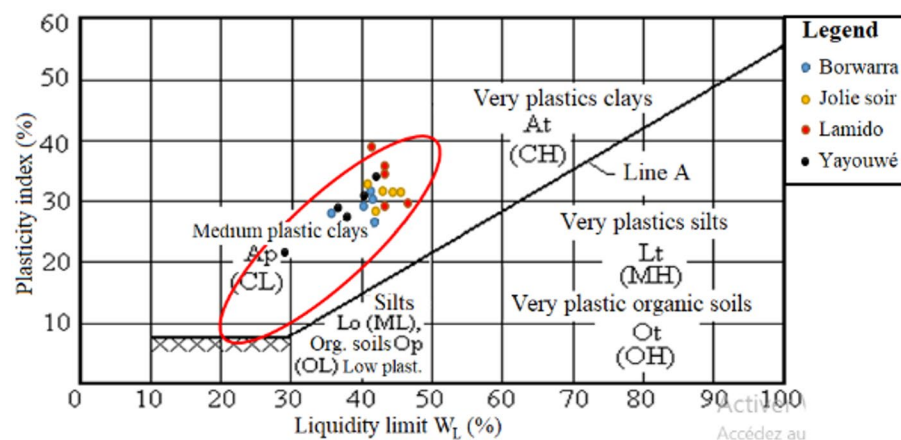
4.1.4 Atterberg Limits

Atterberg limits were determined and compared with those prescribed by the NC 102–115 standard for the manufacture of Compressed Earth Blocks. The results of the Atterberg limit tests are shown in Table 2.

Figure 4 shows the liquidity and plasticity limits of each sample projected in the Casagrande plasticity diagram. Plasticity index (PI) values of soils from the Borwarra, Jolie-soir, Lamido, and Yayouwé sites exhibit ranges of 6–16.2%, 9–14.1%, 2.3–16.5%, and 6.8–11.4%, respectively, with arithmetic means of 11%, 11.4%, 10.2%, and 8.9%. These values fall within the optimal PI range recommended by the NC 102–115 standard and [2] for the production of compressed earth blocks (CEBs), indicating that the

Table 2 Results of the Atterberg limits

Atterberg Limits (%)	Well 1	Well 2	Well 3	Well 4	Well 5	Mean
DIA						
Liquidity limit W_L	43.4	34.6	41.2	41.1	40.1	40.08
Plasticity limit W_p	27.2	28.6	30.6	30	29.1	29.1
Plasticity index PI	16.2	6	10.6	11.1	10.9	10.96
DIB						
Liquidity limit W_L	40.6	40.3	43	46.4	42.6	42.58
Plasticity limit W_p	29.6	31.3	32.6	32.4	31.5	31.48
Plasticity index PI	10.9	9	10.4	14.1	11.1	11.1
DIC						
Liquidity limit W_L	45.9	42.4	43.6	41.5	43.4	43.36
Plasticity limit W_p	29.4	28.2	35.5	39.2	33.1	33.08
Plasticity index PI	16.5	14.2	8.1	2.3	10.3	10.28
DID						
Liquidity limit W_L	29	40.6	35.8	43.1	37.1	37.12
Plasticity limit W_p	21.5	29.2	29	32.8	28.1	28.12
Plasticity index PI	7.5	11.4	6.8	10.3	9	9

**Fig. 4** Atterberg limits of the studied soils plotted on the Casagrande plasticity chart

fine-grained fraction of these soils possesses sufficient cohesion and workability for shaping and compaction without excessive shrinkage or cracking. Such plasticity levels are particularly favorable for earthen construction, as they ensure adequate moldability while maintaining structural integrity upon drying.

Similar variability is observed in Mbé soils, as documented by [4], where W_p values range from 18.1% to 32.2%, W_L values from 26.86% to 69.18%, and PI values from 6% to 38%. These differences, indicated by the wide spectrum, reflect the influence of mineralogy, particle morphology, and surface chemistry on plastic behavior. While some samples exhibit ideal plasticity for CEB production, others may require mechanical or chemical stabilization to meet performance criteria for structural use.

When these PI values are considered alongside the relatively low natural moisture content values observed across all sites, ranging from 11.98% to 32.78%, a nuanced understanding of soil behavior emerges. In many cases, the natural moisture content approaches or even falls below the plastic limit (W_p), suggesting that the soils may not be in a naturally workable state without moisture conditioning. This is especially relevant for sites like Lamido, where PI values are as low as 2.3%, and natural moisture content

values hover near the lower threshold. In such cases, water addition during block preparation may be necessary to achieve optimal plasticity and compaction [29]. Moreover, the relatively low natural moisture content contributes positively to post-compaction performance, reducing the likelihood of excessive shrinkage or cracking as the blocks dry. This balance between manageable plasticity and low moisture content enhances the structural integrity and dimensional stability of the final product [30].

According to the Unified Soil Classification System (USCS), the soils from Borwarra, Jolie-soir, Lamido, and Yayouwé are predominantly low-plasticity clays (CL), a classification that aligns well with the requirements for CEB fabrication. If these soils had a sufficient quantity of fine particles or clay, they would have been ideal for use in the manufacture of compressed earth bricks. However, the particle size analyses showed that most of these soils contained either very small amounts of clay or quantities exceeding the recommendations for optimum use in the production of CEBs. This discrepancy highlights the importance of not relying solely on Atterberg limits but also considering others parameters such as granulometric composition when assessing soil suitability. Thus, the addition of artificial binders such as cement can significantly enhance the cohesion and mechanical integrity of the bricks, thereby improving their durability and resistance to environmental degradation.

4.2 Mineralogical and chemical parameters

4.2.1 Mineralogical composition of the lateritic soils (XRD)

The X-ray diffraction results from soil samples collected in the Dir area are shown in Fig. 5.

The diffractograms from profiles DIA to DID reveal a mineral composition largely dominated by quartz, with a prominent peak at $26.6^\circ 2\theta$. This is accompanied by phyllosilicates like muscovite, biotite, and illite, as well as kaolinitic clays, recognizable by their characteristic doublet at 12.3° and $24.8^\circ 2\theta$. Traces of iron oxides, particularly hematite (peaks between $33\text{--}35.6^\circ$ and $49\text{--}54^\circ$), are also present. Together, these minerals reflect the gradual weathering of the underlying granito-gneissic bedrock typical of

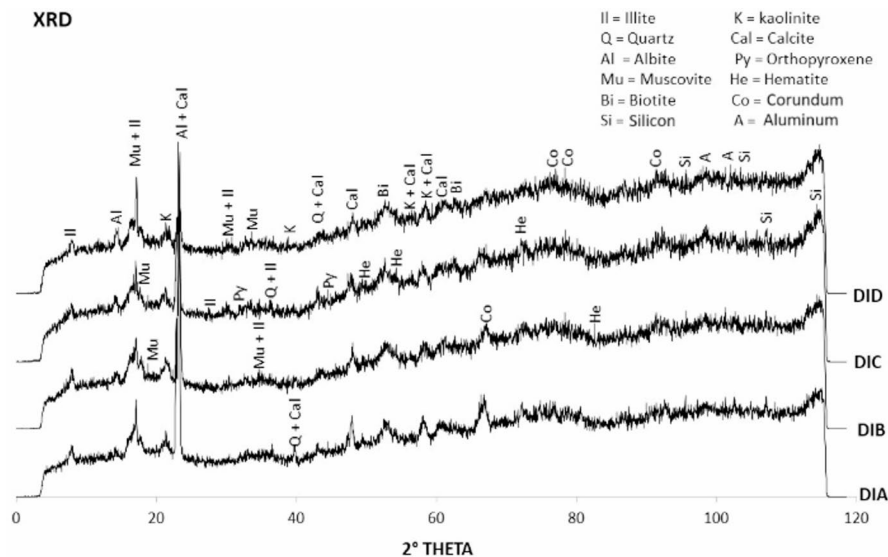


Fig. 5 X-Ray Diffractograms of representative lateritic soil samples from Dir

the Adamawa region, where kaolinite tends to form as micas and feldspars break down under humid tropical conditions [31, 32].

The co-occurrence of illite and kaolinite points to an intermediate stage of weathering, somewhere between incomplete bisiallitization and advanced monosiallitization. This transitional phase has also been observed in the lateritic soils of Garoua-Boulāï [19] and Mbé [4]. Residual albite and orthopyroxene suggest the presence of isalteritic layers that are still relatively unaltered, while iron oxides explain the reddish tint of the soils and confirm the intensity of the lateritization process [27]. The occasional detection of calcite may be linked to secondary carbonation due to water movement, or it could be an analytical artifact, which would warrant further investigation using FTIR or thermogravimetric analysis.

Some peaks observed at higher angles, associated with corundum, aluminum, or silicon, are likely due to instrumental standards and do not affect the overall interpretation. From a practical standpoint, this mixed mineralogy offers promising opportunities for earthen construction. The dominance of quartz and kaolinite, along with residual illite, suggests a material that is both dimensionally stable and sufficiently plastic for block molding [33, 34]. Hematite contributes to cohesion after drying and adds the desired coloration, while the high quartz content supports optimal dry density and good mechanical strength [35, 36].

That said, the presence of illite may increase water absorption, making moderate stabilization (typically 4 to 6% cement or lime) essential, along with careful moisture control during construction. These findings echo those from Nkoulou [18], where statistical modeling confirmed a strong link between mineral composition, maximum dry density, and compressive strength. In short, the soils of Dir show real potential as a local resource for producing compressed and stabilized earth blocks. With simple adjustments to particle size and basic treatment methods, they can meet the demands of sustainable construction, offering durability, affordability, and alignment with broader development goals [2, 3].

4.2.2 Chemical characterization of the raw materials (XRF)

The chemical composition of representative soil samples collected from each site is summarized in Table 3.

The chemical profiles of Dir’s soils reveal high concentrations of silica (SiO₂: 40.3–52.8%), alumina (Al₂O₃: 17.9–27.3%), and iron oxides (Fe₂O₃: 15.7–17.3%), while alkali and alkaline earth elements (Na₂O, K₂O, MgO, CaO) are significantly depleted, averaging below 0.2%, except for CaO in sample DIA, which reaches 4.95%. These results align closely with the XRD findings: quartz accounts for the silica content, kaolinite and gibbsite explain the elevated alumina, and hematite corresponds to the measured iron levels [4, 19]. The relatively high CaO in sample DIA may indicate the presence of calcite (CaCO₃), likely formed through secondary carbonation processes driven by

Table 3 Chemical analysis results

Sample	LOI	SiO2	Al2O3	Fe2O3	CaO	MgO	SO3	Na2O	K2O	P2O5
DIA	11.02	40.26	18.41	16.07	4.95	0.15	0.1	0.13	0.16	0.05
DIB	13.26	43.54	22.28	15.66	0.19	0.12	0	0.12	0.18	0.19
DID	15	51.62	27.29	16.82	0.17	0.08	0.1	0.14	0.18	0.14
DIC	10.86	52.76	17.88	17.26	0.08	0.05	0	0.12	0.11	0.09

bicarbonate-rich water circulation; an occurrence previously documented in nearby regions such as Mbé and Garoua-Boulāï [27]. The loss on ignition (LOI), ranging from 10.9 to 15.0%, reflects a matrix rich in clay hydroxyls and hydrated iron oxides.

To assess the degree of chemical weathering, alteration indices were calculated using molar ratios of major oxides [37, 38]:

$$\text{Chemical Index of Alteration : CIA} = \frac{\text{Al}_2\text{O}_3}{\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} + \text{K}_2\text{O}} \times 100 \quad (1)$$

$$\text{Chemical Index of Weathering : CIW} = \frac{\text{Al}_2\text{O}_3}{\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O}} \times 100 \quad (2)$$

$$\text{Plagioclase Index of Alteration : PIA} = \frac{\text{Al}_2\text{O}_3 - \text{K}_2\text{O}}{\text{Al}_2\text{O}_3 + \text{CaO} + \text{Na}_2\text{O} - \text{K}_2\text{O}} \times 100 \quad (3)$$

$$\text{S/R Ratio : S/R} = \frac{\text{SiO}_2}{\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3} \quad (4)$$

The results are striking: CIA values range from 96.8 to 97.7%, CIW and PIA are both around 98%, indicating near-complete leaching of base cations (Ca, Na, K) and advanced transformation of feldspars into kaolinitic clays. The S/R ratio varies between 1.15 and 1.50: samples DIA, DIB, and DID ($S/R < 1.33$) correspond to classic lateritic profiles, while DIC ($S/R > 1.33$) reflects more siliceous facies, consistent with the strong quartz peaks observed in XRD. These trends mirror findings from Nkoulou [18], where high CIA and CIW values were linked to dominant kaolinite and hematite content. They also reinforce broader observations by [31] and [32] regarding the extreme maturity of lateritic profiles under tropical humid climates.

The combined chemical and mineralogical data confirm that Dir's soils are well-suited for producing compressed earth blocks (CEB) and stabilized earth blocks (SEB) under the conditions previously outlined. These results are consistent with those from Mbé [4], where unstabilized CEBs reached 2 MPa and improved to 7 MPa with 4% cement, and from Garoua-Boulāï [19], where statistical models showed a strong correlation ($R^2 \approx 0.96$) between major oxides and compressive strength. In this context, Dir's highly weathered and chemically mature soils represent a strategic local resource for sustainable construction.

4.2.3 Infrared spectroscopy (IR)

Figure 6 present the infrared spectra of the lateritic materials studied, covering the range from 4000 to 500 cm^{-1} .

The four spectra shown above, which display similar profiles, correspond to samples from the different collection sites.

The infrared spectra clearly highlight the presence of kaolinite, the dominant clay mineral in Dir's lateritic profiles. Stretching bands of OH groups around 3695 and 3620 cm^{-1} correspond to internal and external structural hydroxyls in kaolinite, consistent with findings by [39], and [40]. These absorptions, observed across all four sites, confirm the high crystallinity of kaolinite and its central role in shaping the clay matrix.

Broad bands between 3525 and 3445 cm^{-1} are attributed to hydrogen-bonded water molecules, indicating the presence of interstitial moisture and adsorbed water, further

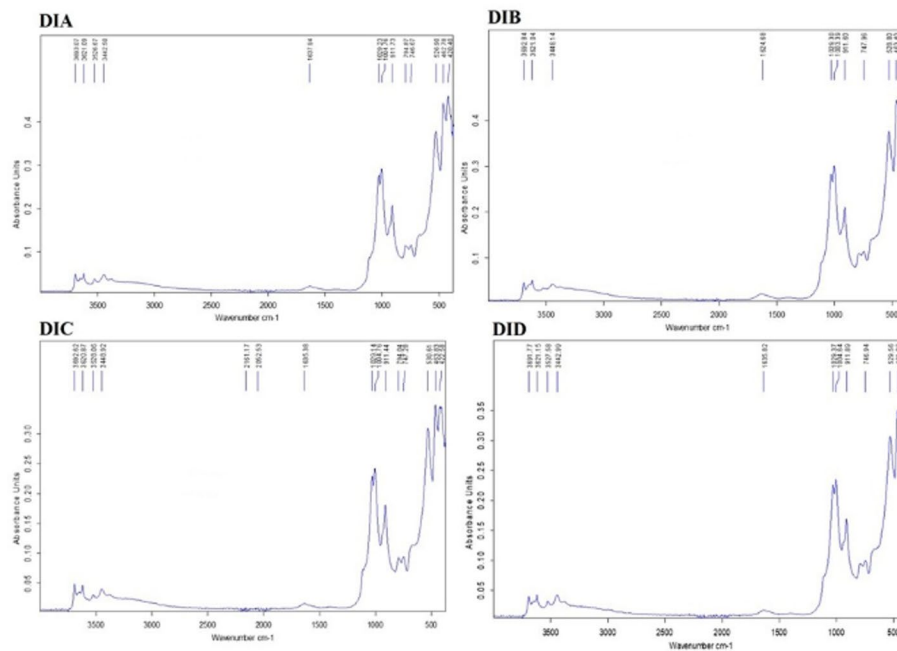


Fig. 6 Infrared (IR) spectra of representative lateritic soil samples from Dir

supported by hygroscopic water bands at 1635–1638 cm^{-1} . This combination reflects a mineralogical system typical of tropical laterites, where kaolinite coexists with both structural and bound water, a phenomenon previously noted in central Cameroon’s lateritic soils [41, 42].

Bands between 1030 and 1004 cm^{-1} correspond to Si–O–Al vibrations, indicating the simultaneous presence of kaolinite and illite. This supports the XRD results, which revealed incomplete feldspar alteration into kaolinitic clays. A distinct band near 911 cm^{-1} (Al–OH) confirms the presence of dioctahedral kaolinite layers, while secondary absorptions between 794 and 747 cm^{-1} reflect Si–O deformations in quartz and quartz–kaolinite associations, consistent with XRF data showing SiO_2 levels between 40 and 53%.

Finally, low-frequency bands (530–420 cm^{-1}) correspond to Si–O–Si and Si–O–Al bending vibrations, confirming the dominance of phyllosilicate structures typical of highly weathered laterites [43, 44].

Taken together, the IR spectra reinforce and complement the XRD and XRF findings, demonstrating that Dir's soils are primarily composed of quartz, kaolinite, illite, and hematite, with minimal structural and interstitial water. This mineralogical configuration offers good dimensional stability, low swelling plasticity, and favorable characteristics for producing CEB and SEB, echoing results from Mbé [4] and Nkoulou [18] in Cameroon.

4.3 Physico-mechanical properties of stabilized compressed earth bricks

4.3.1 Compressive strength properties

The compressive strength tests were conducted on both unstabilized and cement-stabilized compressed earth block (CEB) specimens, cured for 7, 14, and 28 days (Fig. 7). Each specimen was prepared using a representative blend of soil samples from the different collection zones to ensure consistency across study areas.

The results reveal significant variability in compressive strength depending on the site and the level of stabilization. For unstabilized samples, 28-day strength values range from 1.47 MPa (Jolie-soir) to 3.91 MPa (Borwarra). Only the Borwarra samples exceed the minimum threshold of 2.4 MPa set by the Cameroonian standard NC 102–114 and the CRATerre manual for CEBs [45]. These differences are closely linked to the geotechnical and mineralogical characteristics of each site: soils with higher quartz content and better particle grading (Borwarra, Lamido) allow for more effective compaction and thus greater strength, while clay-rich or poorly graded soils (Jolie-soir) exhibit lower natural cohesion.

These findings are consistent with previous studies in Mbé [4] and Garoua-Boulai [19], which demonstrated that local geological variability strongly influences the initial mechanical performance of CEBs. They also reinforce the role of mineralogy, dominant kaolinite, residual illite, and abundant quartz, and chemical composition (high SiO_2 and Al_2O_3 , low base cation content) in shaping the mechanical behavior of the blocks, as discussed in the XRD and XRF sections.

Cement stabilization significantly improved compressive strength, with 28-day values ranging from 5.02 MPa (Yayouwé, 8% cement) to 9.79 MPa (Lamido, 12% cement). These values are reported for trend illustration and to characterize the upper performance envelope of the material; the 12% dosage falls outside the validated predictive model domain and is not considered a recommended formulation (see Sect. 4.4.2). Compressive strengths up to 8% cement remain well above international durability standards (1.26–8.24 MPa) according to [46, 47]. The progressive increase in strength with higher cement content and longer curing times is attributed to the formation of calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which reinforce the clay–silica matrix [48]. These results align with those from Nkoulou [18], where statistical modeling revealed a strong correlation between cement content, maximum dry density, and compressive strength. They also echo the conclusions of [29] and [36], who

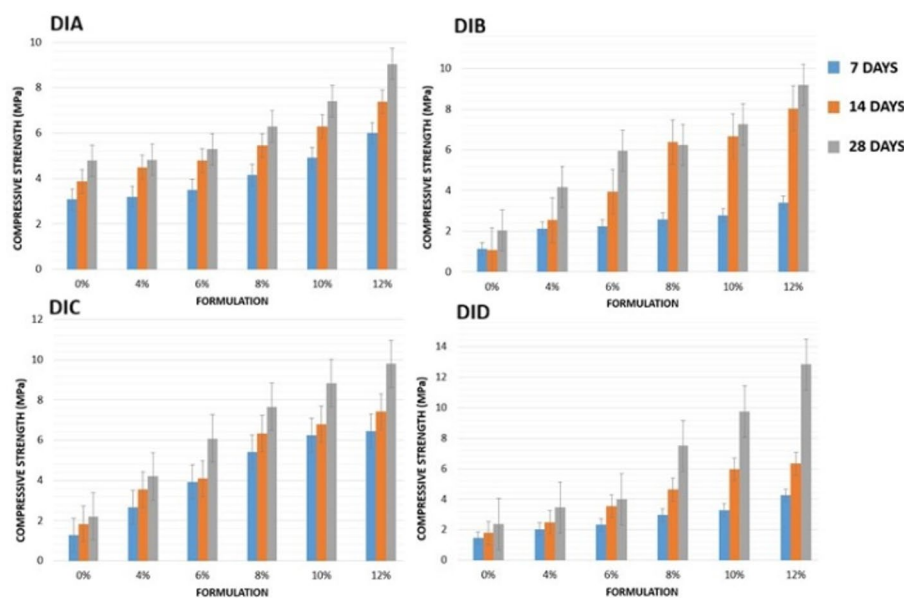


Fig. 7 Evolution of compressive strength of unstabilized and cement-stabilized CEBs with curing time

emphasized that optimal compaction combined with moderate stabilization is key to achieving mechanical performance and durability in tropical climates.

4.3.2 Flexural strength test

In addition to compression tests, flexural strength tests were conducted to assess the specimens' resistance to bending stresses. These tests were performed at 2, 7, and 28 days of curing as shown in Fig. 8.

Flexural strength tests on CEBs made from Dir soils show that initial resistance in unstabilized samples remains low, ranging from 0.15 MPa (Jolie-soir) to 0.39 MPa (Yayouwé) after 28 days. Although these values fall short of the durability benchmarks typically required for flexural applications, they reflect the limited intrinsic cohesion of clay matrices when not reinforced by hydraulic binders.

However, a clear trend emerges: flexural strength improves steadily with increased cement content and longer curing periods. At 12% cement and 28 days of curing, strength values reach 2.81 MPa (Borwarra), 2.96 MPa (Jolie-soir), 3.43 MPa (Lamido), and 4.38 MPa (Yayouwé). As with the compressive strength data, the 12% cement values are included for trend completeness only and do not represent a recommended formulation; flexural strengths at 8% cement already exceed the minimum thresholds commonly cited for stabilized CEBs (0.5–2 MPa) [2, 29]. These results confirm that cement addition triggers pozzolanic reactions and the formation of C-S-H and C-A-H phases, which enhance matrix cohesion and the blocks' ability to withstand bending stresses [48]. The variation in performance across sites also reflects the influence of local geology and mineralogy. Soils rich in quartz and with well-graded particles (Lamido, Yayouwé) develop higher flexural strength once stabilized, as optimal compaction and secondary cementation improve stress transmission. Conversely, finer, clay-rich soils (Jolie-soir) require higher binder content to achieve comparable performance as stated by [36] and [18] in other Cameroonian contexts.

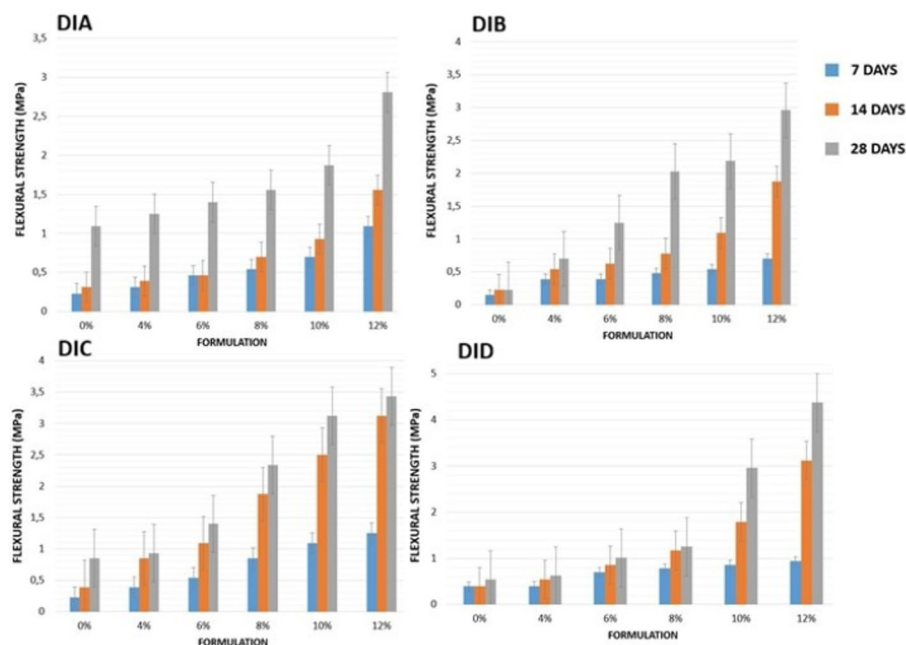


Fig. 8 Evolution of flexural strength of unstabilized and cement-stabilized CEBs with curing time

These findings mirror those from the compression tests: a balanced particle size distribution, sufficient kaolinite content (ensuring plasticity and dimensional stability), and effective cement stabilization are critical to ensuring the mechanical durability of CEBs. Though less frequently studied than compression, flexural strength emerges as a vital complementary indicator for evaluating the structural integrity of CEBs under real-world conditions (e.g., wind loads, roof weight, differential settlement). Altogether, the flexural results reinforce the suitability of Dir's soils for use in sustainable construction materials.

4.3.3 Water absorption, bulk density, and porosity tests on CEB and stabilized CEB specimens

The compressed earth block (CEB) and stabilized compressed earth block (SCEB) specimens produced for this study were subjected to water absorption, bulk density, and porosity tests to assess key physical parameters relevant to construction applications. The results obtained from samples collected at each site are illustrated in Figs. 9, 10 and 11.

The data from Dir's CEB/SCEB specimens reveal a clear inverse relationship between water absorption/porosity and bulk density. As the cement content and curing duration increase, bulk density shows a slight rise (from 1.79 to 1.99 t/m³), while porosity decreases from 35 to 37% at 7 days to 25–30% at 28 days. Water absorption stabilizes mostly between 11% and 15%. One sample (DID) slightly exceeds normative thresholds, with absorption around 16% and porosity above 30%, likely due to imbalanced particle size distribution or insufficient compaction.

This trio of parameters (absorption, porosity, and density) correlates well with the mineralogical (XRD and IR) and chemical (XRF) observations. Quartz dominance promotes mechanical densification and limits plasticity; kaolinite contributes to dimensional

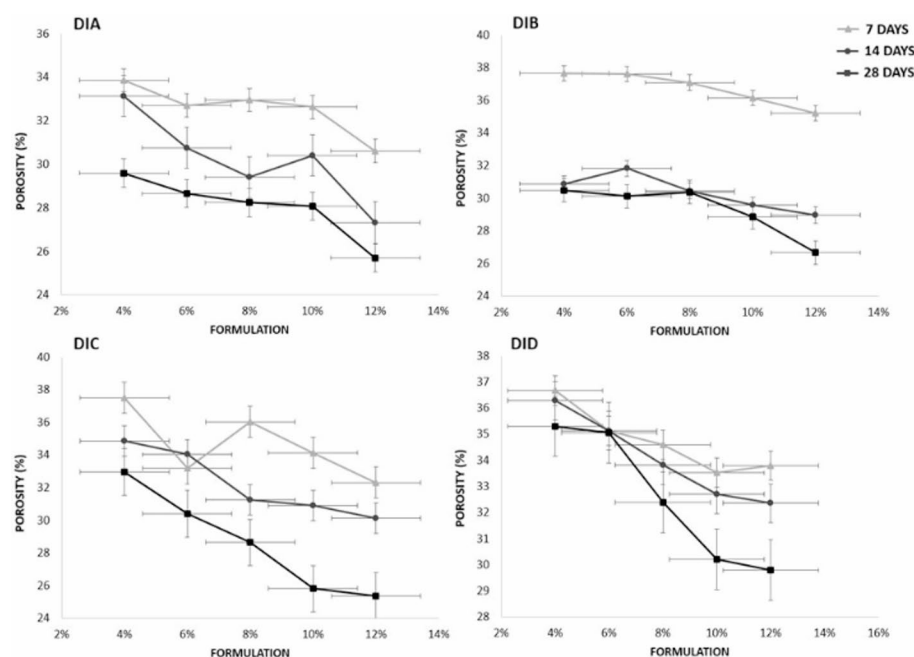


Fig. 9 Porosity of CEB and SCEB specimens as a function of cement content and curing time (error bars represent standard deviation; their visual prominence is an artefact of axis scaling and does not reflect high absolute variability)

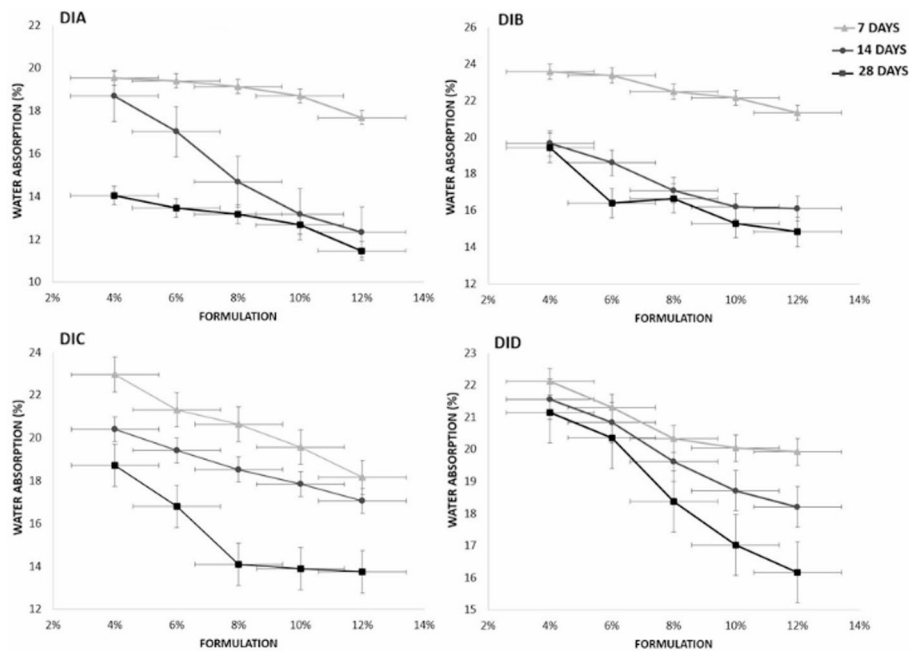


Fig. 10 Water absorption of CEB and SCEB specimens as a function of cement content and curing time (error bars represent standard deviation; see caption of Fig. 9 for a note on axis scaling)

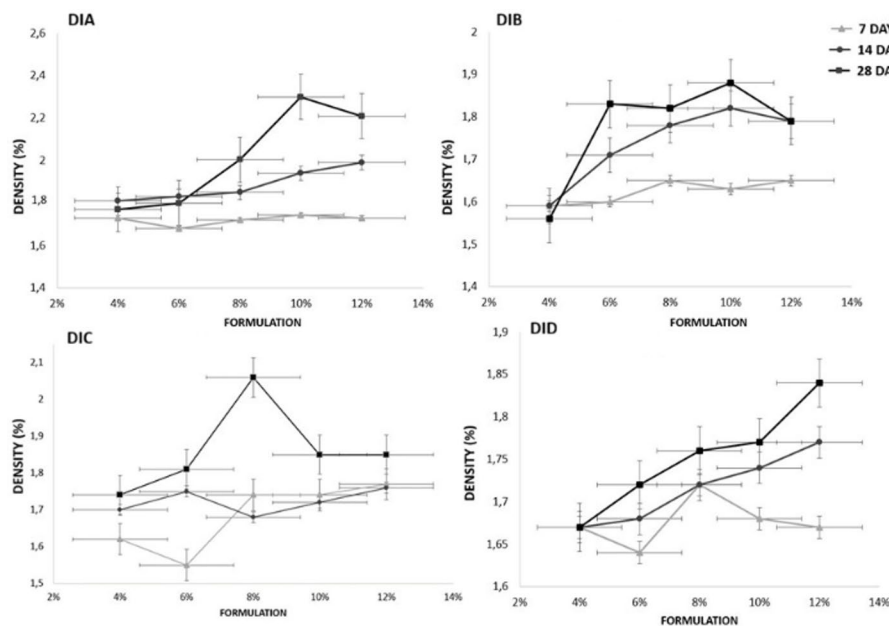


Fig. 11 Bulk density of CEB and SCEB specimens as a function of cement content and curing time (error bars represent standard deviation; see caption of Fig. 9 for a note on axis scaling)

stability and favorable hygroscopic behavior; and residual illite maintains microporosity, enhancing water adsorption. These findings are consistent with infrared analyses, which revealed broad OH bands ($3525\text{--}3445\text{ cm}^{-1}$) associated with interstitial water, confirming that adsorption capacity is closely tied to mineralogical composition. The results also align with mechanical performance data: samples with higher density and lower absorption (Lamido, Borwarra) exhibit superior compressive and flexural strength, validating

the well-documented inverse relationship between dry density, porosity, and mechanical performance [29, 36].

Comparisons with other Cameroonian studies highlight similar trends. In Mbé [4], showed that unstabilized CEBs had water absorption rates exceeding 20%, but adding 4–6% cement reduced these values below the 15% threshold set by Cameroonian standard NC 102–115. At Nkoulou [18], demonstrated through statistical correlations that water absorption decreases significantly with increased dry density and stabilizer content, confirming the pattern observed in Dir. Likewise, in Garoua-Boulai [19], found that local geological variability (ferrallitic soils rich in hematite versus sandier soils) directly influences the absorption–durability relationship.

In this study, the values obtained generally fall within international standards (compressive strength between 1.26 and 8.24 MPa, water absorption $\leq 15\%$ according to CRATerre [45, 49], reinforcing the notion that Dir's soils are well-suited for producing CEB/SCEB, provided that particle size distribution, modified Proctor optimum moisture content (OMC), and stabilization (4–8% cement or lime) are properly optimized. Ultimately, this integrated analysis demonstrates that the water durability of the blocks results from a multidimensional interaction between chemical composition (base depletion and advanced weathering maturity, CIA > 96%), mineralogy (quartz–kaolinite–hematite–illite), microstructure (residual porosity), and fabrication conditions (binder content, compaction, curing). These correlations confirm that properly formulated and stabilized CEB/SCEBs from Dir meet normative requirements and contribute meaningfully to the goals of sustainable and resilient local construction.

4.4 Statistical analysis and modeling

4.4.1 Principal Component Analysis (PCA)

A Principal Component Analysis (PCA) was performed on eleven geotechnical parameters characterizing the soils studied. This multivariate approach aims to identify underlying latent structures and reduce the dimensionality of the data, while revealing the fundamental interrelationships between geotechnical properties.

The Kaiser criterion (eigenvalue > 1; see Table 4) justifies the retention of the first four principal components (F1 to F4), which together explain 85.47% of the total variance in the data. This rate of explained variance is remarkable for geotechnical studies and allows for a significant reduction in dimensionality while retaining most of the information. F1: Eigenvalue = 4.46, explains 40.55% of the variance. F2: Eigenvalue = 2.12, explains 19.24% (cumulative: 59.79%). F3: Eigenvalue = 1.58, explains 14.33% (cumulative: 74.12%). F4: Eigenvalue = 1.25, explains 11.35% (cumulative: 85.47%). Components F5 to F11 (eigenvalues < 1) represent a negligible residual variance (14.53%) and can be excluded from the main interpretations.

The interpretation of the components is based on correlations between variables and factors (Table 5). Axis F1 (40.55% variance): The axis of Overall Grain Size and Compactness. This axis is strongly and negatively correlated with silt content (– 0.92) and

Table 4 Eigenvalue for each factor

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
Eigenvalue	4.46	2.12	1.58	1.25	0.71	0.34	0.24	0.13	0.11	0.06	0.02
Variability (%)	40.55	19.24	14.33	11.35	6.47	3.07	2.15	1.22	0.97	0.51	0.14
Cumulative (%)	40.55	59.79	74.12	85.47	91.94	95.01	97.16	98.38	99.35	99.86	100.00

sand content (-0.90), and positively correlated with gravel content (0.96) and relative density dr (0.76). It therefore contrasts coarse, gravelly soils with high relative density (positive poles) with fine, sandy and silty soils (negative poles). The moderate correlation with clay (-0.73) confirms this opposition. This axis represents the fundamental parameter of soil texture and compactness. Axis F2 (19.24% variance): The axis of plasticity and nature of fines. This axis is strongly and positively correlated with the Plasticity Index (PI) (0.78) and the Water Limit (WL) (0.64). It also has a high correlation with the Methylene Blue Value (MBV) (0.74). This axis discriminates between soils with active fines, high plasticity, and high surface activity and soils with low plasticity. It is independent of overall grain size (low correlation with gravel, sand, and silt), focusing on the properties of fines (clay). Axis F3 (14.33% variance): The Plasticity Limit and Organic Matter axis. This axis is dominated by a very strong positive correlation with the Plasticity Limit (WP) (0.80) and a very strong negative correlation with Organic Matter (OM) content (-0.70). It also shows moderate opposition to silt (0.25). This axis suggests an opposition between soils whose plasticity is controlled by mineral clays (high WP) and those where the presence of organic matter (high OM) and/or silt modulates plasticity properties, potentially reducing the effective plasticity index.

Axis F4 (11.35% variance): The Natural Water Content axis. This axis is almost exclusively defined by an extremely high correlation with natural water content W (0.89). The other correlations are weak ($|r| < 0.35$). This indicates that the variability in the natural water content of the samples is largely orthogonal (independent) to the major grain size (F1) and plasticity (F2, F3) patterns. This axis represents an environmental or state factor (in situ moisture conditions) distinct from the intrinsic characteristics of the material. Figure 12 illustrate the two first factors (F1 and F2).

The decomposition into four orthogonal dimensions provides an operational framework for the formulation of CEBs: (1) Grain size balance (F1) dictates compactness and mechanical strength; (2) plasticity (F2) determines workability and cohesion; (3) Binder quality (F3) conditions long-term stability through the exclusion of organic matter; (4) Water content (F4) is a process parameter to be controlled independently. This structure validates the scientific approach of formulation by function rather than by empirical composition.

In addition, this PCA reveals that the geotechnical behavior of soils intended for CEB is governed by four orthogonal determinants: texture/compactness, clay activity, the

Table 5 correlation between variables and factors

	F1	F2	F3	F4
% gravel	0.96	-0.04	-0.22	0.07
% sand	-0.90	-0.14	0.17	-0.06
% silt	-0.92	0.05	0.25	0.08
% clay	-0.73	0.51	0.28	-0.19
W (%)	0.16	0.30	0.05	0.89
dr	0.76	0.27	0.29	0.12
OM	-0.16	0.33	-0.70	-0.11
Liquidity limit (WL)	0.60	0.64	0.26	-0.29
Plasticity limit (WP)	0.38	0.06	0.80	-0.13
Plasticity index (PI)	0.09	0.78	-0.26	-0.35
MBV values	-0.46	0.74	-0.02	0.39

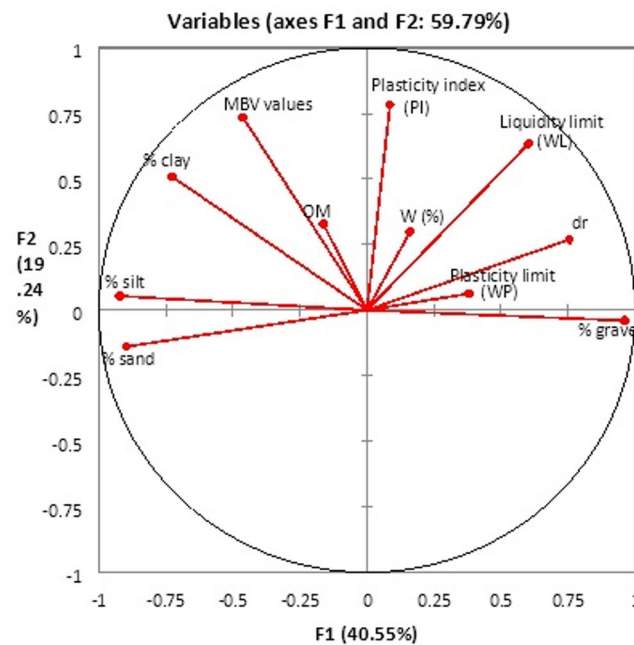


Fig. 12 Correlation circle of variables on the F1-F2 factorial plane (PCA)

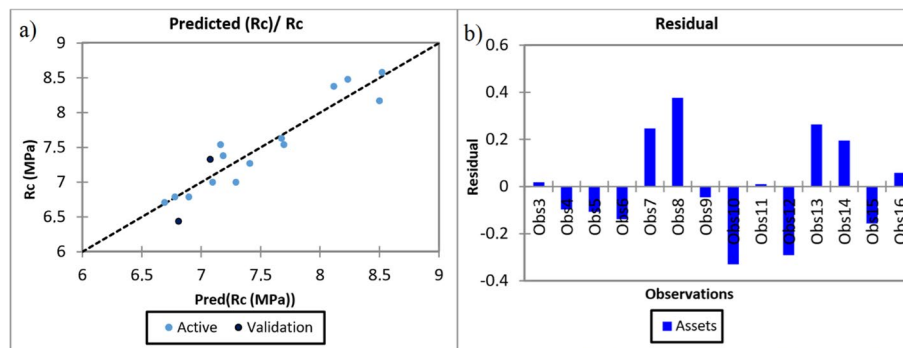


Fig. 13 a Predicted versus measured compressive strength (Rc); b Residual analysis of the predictive model

organomineral nature of fines, and water status. This decomposition not only classifies soils, but could also provide a robust predictive model in which the F1-F4 factor scores can advantageously replace the eleven initial parameters in the mechanical behavior models of CEBs. It thus provides a rational basis for soil selection and formulation optimization, transforming a craft practice into an engineering process.

4.4.2 Compressive strength predictive model for compressed earth bricks

The model (illustrated in Fig. 13) presents a robust predictive equation (Eq. 5) characterized by a significant curvature in the response to cement.

$$R_c = 9.677 - 0.0123 \times G - 0.144 \times OM - 0.137 \times PI - 0.134 \times C^2 \quad (5)$$

Where R_c =Compressive strength (MPa), G = % Gravel, OM =Organic matter (%), PI =Plasticity index, C = % Cement.

The model explains 89.7% of the variance ($R^2 = 0.897$ on the training subset) with a prediction error of $RMSE = 0.339$ MPa. These metrics are reported for the 70% training split; the validation subset (30% holdout) yielded $R^2 = 0.871$ and $RMSE = 0.362$ MPa, confirming satisfactory generalization without overfitting. The relationship $-0.134C + 0.0391C^2$ describes a convex function (upward-facing parabola). Its derivative $-0.134 + 0.0782C$ is zero at $C \approx 1.71\%$, indicating a local minimum in strength at this dosage. This counterintuitive result suggests that at low content ($< 2\%$), cement could disrupt the natural cohesive structure of the soil, or create weak points without forming a coherent network. Above 2%, the positive quadratic effect dominates, leading to accelerated growth: at 8% cement, the cement term contributes $-1.072 + 2.502 = +1.43$ MPa net. This reveals a critical efficiency threshold for the activation of binding properties.

All geotechnical coefficients are negative, indicating that high values of these parameters reduce strength, in accordance with expected physical mechanisms. OM (-0.144 MPa/%): Strongest impact. Organic matter acts as a lubricant during compaction and can decompose, creating voids and reducing long-term cohesion. PI (-0.137 MPa/point): High plasticity increases shrinkage and cracking during drying, creating discontinuities that are detrimental to strength. Gravel (-0.0123 MPa/%): Weaker but significant effect. Excess gravel can compromise homogeneity and create weak interfaces between large grains and the fine matrix.

The model is internally consistent with reduced residuals ($\max \pm 0.38$ MPa). However, its domain of definition is established as: Gravel: 0.65–71.05%; OM: 4.5–9.2%; PI: 2.3–16.5; Cement: 0–8%. Thus, a minimum cement dosage of 2% is necessary to obtain a net beneficial effect. However, a dosage of 6% offers a good compromise, with a predicted gain of ~ 1.1 MPa compared to the minimum. When selecting soils, priority should be given to reducing OM (strongest impact), followed by controlling PI. For particle size optimization: Seek a balance in gravel, avoiding extremes.

The model assumes additive and independent effects, which may mask complex interactions (e.g., cement $\times$ OM). Therefore, generalizing to other soil types would require broadening the ranges of variables, particularly for OM and PI. In summary, this model provides a quantitative predictive tool for optimizing CEB formulation, with sufficient accuracy for practical dimensioning applications.

4.4.3 Flexural Strength predictive model for compressed earth brick

Nonlinear regression analysis applied to the flexural strength of compressed earth bricks (CEBs) reveals a predictive model (Eq. 2) illustrated in Fig. 14 with exceptional accuracy ($R^2 = 0.966$ and $RMSE = 0.073$ MPa, on the training subset; $R^2 = 0.951$ and $RMSE = 0.081$ MPa, on the validation subset) and highlights determinants that are distinct from those governing compressive strength.

$$R_f = 2.486 - 0.00741 \times G + 0.0994 \times OM - 0.182 \times PI - 0.00478 \times C + 0.00642 \times C^2 \quad (6)$$

where R_f is the flexural strength, G is the percentage of gravel, OM is the organic matter, PI is the plasticity index, and C is the percentage of cement.

The equation obtained shows that flexural failure mechanisms are governed by specific factors. Remarkably, organic matter has a beneficial effect on flexural strength ($+0.099$ MPa/%), contrary to its negative impact on compression. This result suggests that a moderate OM content (6.5–7.0%) acts as a natural plasticizer, increasing toughness

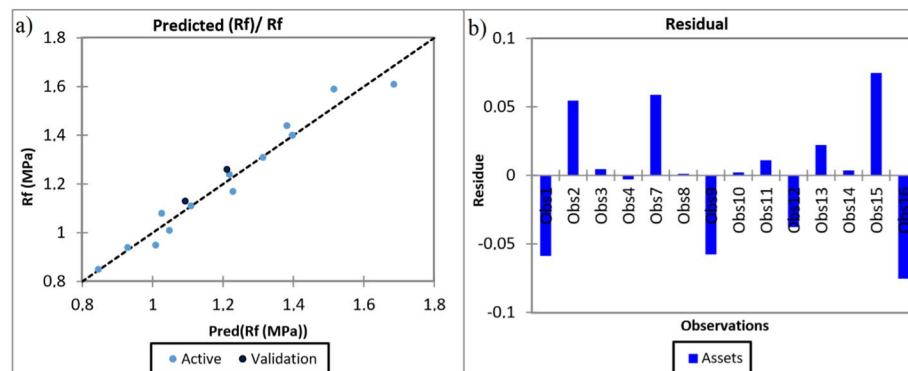


Fig. 14 **a** Predicted versus measured flexural strength (Rf); **b** Residual analysis of the predictive model

and improving the material's ability to redistribute stresses before failure. Conversely, the plasticity index appears to be the most penalizing parameter (-0.182 MPa/point), with a high PI promoting microcracking due to shrinkage, which is particularly detrimental under tensile stress. The influence of cement, although positive above 0.4%, remains marginal compared to its dominant role in compression. These results highlight that the optimization of CEB formulation must be determined by the type of mechanical stress expected. For structural elements subjected to bending, a formulation favoring a low PI (≤ 10) and moderate OM, with a secondary cement dosage ($\sim 6\%$), is recommended, illustrating the need for a differentiated design approach based on a detailed understanding of failure mechanisms.

The robustness of the model, validated by the weakness and independence of the residuals, makes it a reliable tool for the design of stabilized compressed earth block elements subjected to bending loads.

4.5 Microstructural analysis (SEM-BSE/EDS) and physico-mechanical interpretation

4.5.1 SEM observations (BSE mode)

SEM images acquired in backscattered electron (BSE) mode (Fig. 15) clearly highlight the evolution of the microstructure of the blocks as a function of cement content (0, 4, 8, and 12%).

At 0% cement content (Fig. 15a), the matrix mainly consists of an assemblage of grains and fine particle aggregates that are weakly bonded, with open intergranular zones and accessible voids at the scale of several tens of micrometers. This microstructure, dominated by point contacts between particles, is consistent with the lower mechanical strength and higher water absorption typically observed in unstabilized earthen materials.

The addition of 4% cement (Fig. 15b) leads to the appearance of a secondary binder that partially coats the grains and locally fills the voids. Although some pores remain visible, the multiplication of interparticle bridges suggests the onset of cementation and an improvement in matrix continuity, which explains the experimentally observed increase in mechanical performance and the reduction in water absorption.

At 8% cement content (Fig. 15c), the microstructure becomes noticeably more compact. The intergranular spaces are more effectively filled by a binding phase, and a more continuous matrix linking the mineral fragments can be observed. This microstructural densification is commonly associated with the formation of hydration products (C–S–H

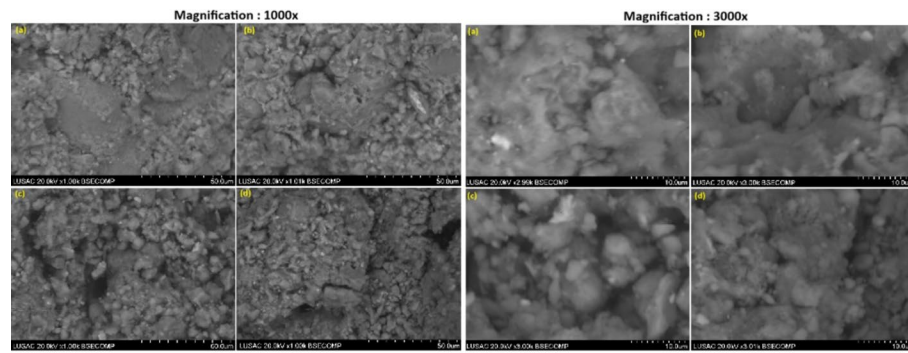


Fig. 15 SEM–BSE micrographs of the DIA sample at cement contents of **a** 0%, **b** 4%, **c** 8%, and **d** 12%, acquired at 1000x and 3000x magnifications

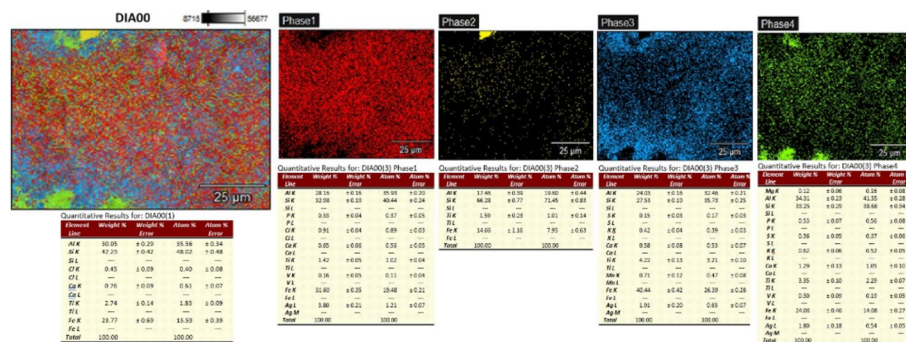


Fig. 16 EDS elemental mapping and spectra of the DIA sample with 0% cement

gels and calcium/aluminate hydrates), which reduce capillary porosity and enhance stiffness and compressive strength, as widely reported in the literature on cement-stabilized soils and stabilized earth blocks [29, 50].

Finally, at 12% cement content (Fig. 15d), the filling and bonding effects are further intensified, resulting in a globally more cohesive matrix. The occasional presence of microcracks or discontinuities may, however, be attributed to drying shrinkage and/or internal stresses related to the formation of crystalline hydration phases. This densification–shrinkage compromise is frequently reported in soil–cement materials, where increasing binder content strengthens the cementitious network but may also increase shrinkage sensitivity if curing conditions are not properly controlled [51, 52].

4.5.2 Chemical mapping and EDS microanalyses

EDS microanalyses and elemental mapping further confirm and refine the nature of the phases observed by SEM. The spectra acquired on the unstabilized sample (Fig. 16) are dominated by Si, Al, and Fe, with average contents (in wt%, normalized to detected elements) of approximately 42.23% Si, 30.05% Al, and 23.77% Fe, while Ca remains very low (0.76%). This chemical signature is characteristic of a ferruginous aluminosilicate assemblage (kaolinite/illite-type clays, quartz, and iron oxyhydroxides/oxides), commonly reported in tropical lateritic soils, where Fe-rich (goethite/hematite) and Al–Si phases largely control mechanical and hydraulic behavior [51].

At 4% cement content (Fig. 17), the marked increase in calcium (1.65–20.01%), highlighted by EDS microanalyses and with Ca-rich zones reaching up to 23.09% in the

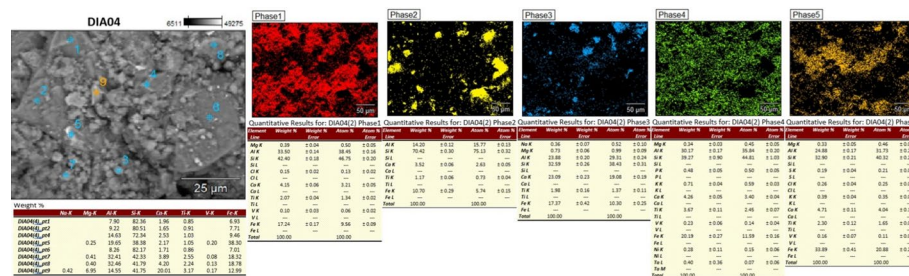


Fig. 17 EDS microanalyses and elemental mapping of the DIA sample with 4% cement

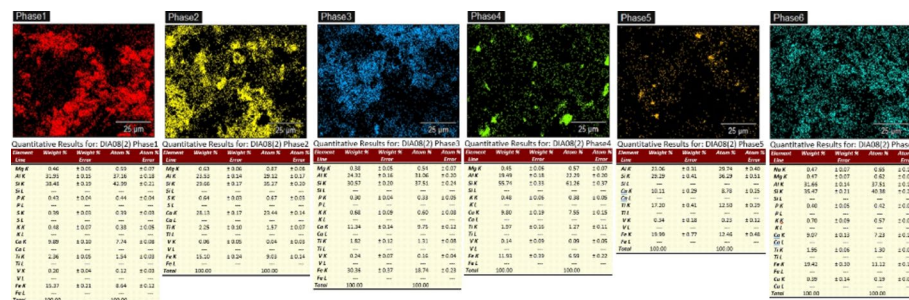


Fig. 18 EDS elemental mapping and spectra of the DIA sample with 8% cement

elemental maps, indicates the introduction of calcium-bearing phases and, more importantly, the progressive formation of cement hydration products. Elemental maps generally reveal regions where Ca is co-localized with Si (and occasionally Al), which is consistent with the presence of C–S–H/C–A–S–H gels acting as intergranular bridges and contributing to strength gain and porosity reduction. At the same time, the relative decrease in Fe (average Fe = 19.87%) reflects the fact that ferruginous grains become increasingly embedded within the cementitious matrix and thus contribute less to the overall chemical signal in the analyzed areas.

This effect is further enhanced at 8% and 12% cement contents (Figs. 18 and 19), where Ca reaches average values of 13.1% (8%) and 19.5% (12%), respectively, while Fe decreases to approximately 14.0% at 12%. This Ca↑/Fe↓ trend, combined with the persistence of an aluminosilicate background (Si and Al), suggests the development of a composite microstructure in which soil grains (quartz, clays, and iron oxides) are progressively bonded and encapsulated within a calcium hydrate network. Such assemblages are widely reported in microstructural studies of soil–cement materials, where C–S–H gels, often associated with aluminate hydrates and secondary carbonates, ensure cohesion and reduce pore connectivity, resulting in increased compressive strength and decreased water absorption [29, 50].

The occasional presence of chlorine (Cl) in some spectra, although minor, may be attributed to soil impurities (salts), sample preparation conditions (residues), or the formation of chlorine-bearing phases in the surrounding environment (e.g., Cl-containing hydrates in saline contexts). In the present study, the low measured concentrations and the absence of additional diagnostic indicators do not allow the identification of a specific phase; however, Cl remains a useful tracer of chemical heterogeneity.

Overall, the combined SEM/EDS approach provides a microstructural interpretation of the physico-mechanical results: (i) progressive densification and pore filling explain

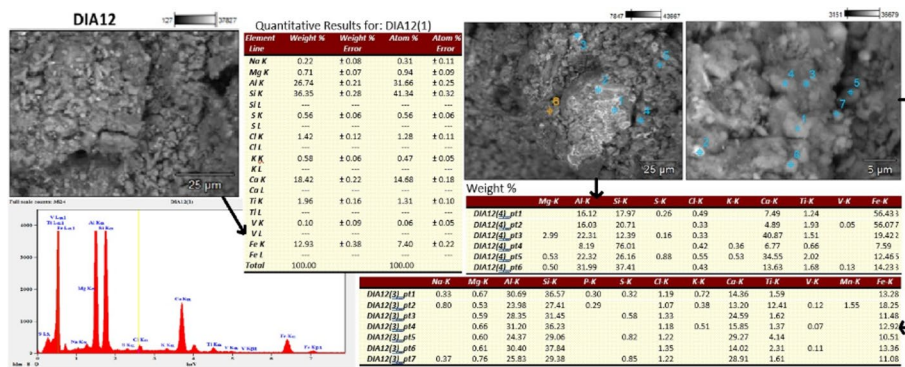


Fig. 19 EDS elemental mapping and microanalyses of the DIA sample with 12% cement

the increase in compressive and flexural strength; (ii) the reduction in accessible porosity and pore connectivity accounts for the decrease in water absorption and apparent porosity; and (iii) the expansion of Ca-rich zones attests to the formation of a hydration matrix responsible for cohesion. This approach is consistent with recommended methodologies for linking macroscopic behavior to internal structure in improved soils, where SEM observations help explain mechanical trends that cannot be inferred solely from granulometric indicators [53].

5 Conclusion

This study conducted a comprehensive multi-scale characterization of lateritic soils from Dir (Adamawa region, Cameroon) to assess their suitability for producing compressed and stabilized earth blocks (CEB/SEB). The integrated approach combining geotechnical, physico-chemical, mineralogical, microstructural, and statistical analyses demonstrates that these locally sourced materials constitute an optimizable resource for sustainable construction.

5.1 Geotechnical, mineralogical, and mechanical properties

Geotechnical and mineralogical analyses revealed that Dir lateritic soils are highly weathered facies dominated by kaolinite, quartz, and hematite, with geochemical alteration indices (CIA, CIW, PIA) exceeding 96%. This composition confers low swelling potential, high compactness, and favorable behavior for stabilization. Mechanically, cement-stabilized blocks achieved compressive strength up to 9.79 MPa and flexural strength up to 4.38 MPa (at 12% cement), substantially exceeding Cameroonian standard NC 102–115 thresholds. Hydric properties (water absorption ≤ 15%, porosity 25–30%, density 1.8–2.0 t/m³) confirm adequate durability for local climatic conditions. Microstructural analysis (SEM-BSE/EDS) correlated this macro-performance with progressive matrix densification and C-S-H gel formation upon cement addition.

5.2 Statistical analysis and predictive modeling

Principal Component Analysis (PCA) elucidated the underlying structure of soil properties, identifying four orthogonal factors: texture/compaction (F1), plasticity/activity (F2), organic-mineral balance (F3), and natural moisture state (F4). This provides a scientific framework for rational formulation. Non-linear regression modeling further revealed critical relationships, including a parabolic dependence of strength on cement content

(with a minimum effectiveness threshold around 2%), and quantified the distinct effects of key parameters: organic matter proved detrimental to compression but beneficial to flexure, while plasticity index consistently exhibited negative influence. These models transform empirical practice into an engineered, predictive approach.

5.3 Practical implications for sustainable construction

For field engineers and local builders, this study provides actionable tools to estimate block strength using a limited set of key soil parameters (clay content, plasticity index, cement dosage), reducing reliance on extensive laboratory testing. The validated performance thresholds confirm that Dir lateritic soils can reliably produce load-bearing blocks for affordable housing, contributing directly to SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

6 Limitations and future perspectives

This study acknowledges certain limitations that open avenues for further research. Durability testing (water resistance, wet/dry cycles, aging) was not extensively developed and remains essential for validating long-term performance under real climatic conditions. Future work should therefore focus on conducting comprehensive durability assessments under accelerated aging conditions, and refining predictive models with expanded datasets and developing simplified field tools.

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Author contributions

S.A.E.P., T.L.Y., and T.D.J. collected the samples in the field and analyzed them in the laboratory. They also analyzed the experimental data and wrote the manuscript. M.O.A.B., K.T.J.H., D.H., and N.N.G.F. drew graphs and tables and checked the article; All authors read and approved the final manuscript.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

Code availability

Not applicable.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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