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Mechanical Characterization of a Composite Mortar Made from Lateritic Soils Stabilized with Autogenous Welding Lime and Reinforced with Palm Kernel Cake (PKC) for the Production of Compressed Earth Bricks (CEBs)

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Abstract

Sustainable construction in sub-Saharan Africa is confronted with a dual requirement: meeting a high demand for housing while reducing the carbon footprint of the building sector. In this context, this study investigates the mechanical performance of a composite mortar based on local resources, combining four lateritic soils from Benin, lime derived from autogenous welding (an artisanal by-product), and palm kernel cake (PKC) fibers, an agricultural waste. The experimental program, structured in two phases, is based on lateritic soils from Zogbodomey, Dassa-Zoumè, Glazoué, and N'Dali, representative of the pedological variability of Benin, with complementary X-ray diffraction (XRD) analyses used to establish relationships between mineralogy and performance. The first phase assesses the influence of lime content (0% to 30%) on compressive strength at 7, 14, and 28 days, as well as flexural strength at 28 days, while the second phase introduces PKC contents (0.25% to 2%) into the optimal formulation. The results show that a 20% lime content is optimal, with 28-day compressive strengths ranging from 4.58 to 5.51 MPa. The lime exhibits a high portlandite content (85.4%), ensuring strong reactivity, while the N'Dali soil is characterized by the presence of kaolinite (26%). The incorporation of 1% PKC improves compressive strength (up to 8.5%) and, more significantly, flexural strength (up to 66%), indicating pseudo-ductile behavior associated with crack-bridging mechanisms. The optimal formulations exceed the 4 MPa threshold required for load-bearing masonry and exhibit performance comparable to a reference cement mortar, thereby opening promising prospects to produce sustainable compressed earth blocks in Benin, within a circular economy framework and a strategy aimed at reducing CO_2 emissions.

Keywords

Laterite, Artisanal Lime, Palm Kernel Cake, X-Ray Diffraction, Compressive Strength, Flexural Strength, Response Surface Methodology

1. Introduction

Sustainable construction has now become a major challenge, particularly in sub-Saharan Africa, where rapid population growth is driving a significant demand for housing. In this context, the valorization of local resources—lateritic soils, artisanal lime, and vegetal fibers—appears as a relevant solution that is both economical and environmentally friendly. Compressed earth blocks (CEB) thus represent an appropriate solution adapted to West African conditions. However, unstabilized CEB exhibits limitations in terms of mechanical strength and durability, which necessitate the use of improvement techniques.

Lime stabilization significantly enhances the performance of CEB through pozzolanic reactions. The use of lime derived from autogenous welding, available locally, constitutes an interesting alternative to industrial lime. In addition, the incorporation of palm kernel cake fibers, an abundant by-product of the palm oil industry, contributes to improving mechanical properties (compression and flexural behavior). The present study evaluates a combination of lateritic soils from Benin, lime derived from autogenous welding, and palm kernel cake fibers, to determine to what extent this composite can meet the mechanical requirements for construction applications in tropical African environments.

Lime-stabilized CEB are widely accepted in the literature: the optimal dosage range lies between 6% and 10% of the dry soil mass, leading to compressive strengths of 4 to 9 MPa depending on soil type, compaction pressure, and curing conditions [1] [2]. Immediate ion exchange, medium-term pozzolanic reactions, and long-term carbonation are well-documented mechanisms described by Bell (1996) and Choquette *et al.* (1992), and validated in African contexts by Nshimiyimana *et al.* (2020) on Burkinabe lateritic soils through XRD and SEM analyses confirming the formation of C-S-H and C-A-H phases [3]-[5].

The incorporation of vegetal fibers into CEB transforms the brittle behavior of the matrix into a pseudo-ductile response through the crack-bridging mechanism, identified and quantified by the theory of Kelly and Tyson (1965) [6]. Flexural strength increases by 22% to 45% for fiber contents ranging from 0.5% to 1.5%, according to studies by Millogo *et al.* (2014) and Aymerich *et al.* (2012) [7] [8], at the expense of a slight reduction in compressive strength beyond 1% - 1.5% fiber content.

Palm kernel cake fibers exhibit a particularly suitable physicochemical profile: very low density (0.15 - 0.25 g/cm^3), moderate to high lignin content (15% - 25%), ensuring satisfactory resistance to alkaline degradation within lime matrices (pH = 12 - 13), and high elongation at break (15% - 30%), favorable for crack bridging [9]. The only documented study using PKC fibers in a mineral matrix construction material reports a 15% to 20% increase in flexural strength at 1% fiber content, confirming the physicochemical compatibility of these fibers with calcium-based binders (cementitious mortar) [10].

Lateritic soils in Benin, particularly those from the Abomey plateau, are characterized by a mineralogical composition dominated by kaolinite (40% - 65% of the clay fraction), accompanied by goethite and hematite, with plasticity indices of 12% - 24% and maximum dry Proctor densities of 1.72 - 1.90 g/cm^3—values indicative of good suitability for CEB production [11]. The content of reactive amorphous silica (SiO_2 reactive: 8% - 18%) ensures satisfactory pozzolanic reactivity with lime, as confirmed by analogy with lateritic soils from Burkina Faso and Cameroon, which exhibit similar mineralogical compositions [12]-[14].

Lateritic soils (locally known as “terre de barre” and ferruginous crusts) are abundant in Benin, particularly in the southern regions (plateaus of Allada, Abomey, and Sakété), as well as in the central and northern parts of the country [15]-[17]. They represent an essential construction resource, with regulated quarrying activities notably in the Zogbodomey area [15] [16].

A synthesis of African bibliographic data highlights two main convergences and one central gap. The convergences are:

1) The optimal 6% - 10% lime content range is valid for African kaolinitic laterites [5] [12] [18].

2) Vegetal fibers systematically improve the ductility of African CEB [7] [19].

The absence of studies documenting the combination of Beninese lateritic soils, artisanal lime, and palm kernel cake fibers (PKC) constitutes the scientific gap addressed in this work. The originality lies in the Beninese context, the use of autogenous welding lime, and PKC fibers. The scientific problem is therefore to determine to what extent the combination of Beninese lateritic soils, autogenous welding lime, and palm kernel cake fibers can produce a composite material meeting mechanical requirements (fc ≥ 4 MPa) for structural applications in tropical African environments.

2. Materials and Methods

2.1. Organization and Objectives of the Experimental Program

The objective of this research is to evaluate, on the one hand, the influence of lime stabilization on lateritic soil mortars and, on the other hand, the effect of incorporating palm kernel cake (PKC) fibers on the mechanical properties of lime-stabilized lateritic soil mortars reinforced with PKC fibers. More specifically, the study aims to highlight the effect of the content of the different constituents (lime and palm kernel cake) on the compressive and flexural strengths of a range of mortars produced from lateritic soils, lime, and/or PKC fibers. The experimental program is organized into two complementary phases.

The first phase consists of accurately assessing the influence of lime content on the mechanical properties (compression and flexure) of mortars produced using four different lateritic soils from Benin, to identify the optimal dosage leading to the highest strengths. It comprises sixteen (16) mortars per sampling site: one reference mortar (laterite + 10% cement + water) and fifteen mortars in which cement is replaced by lime at varying contents (2%, 4%, 6%, 8%, 10%, 12%, 14%, 16%, 18%, 20%, 22%, 24%, 26%, 28%, and 30%).

The second phase consists of introducing different amounts of palm kernel cake into the optimal mixture (laterite + 20% lime + water) to evaluate the influence of fiber content on the mechanical properties of the mortars and to identify the optimal composite formulation. It comprises ten (10) mortars per site: two reference mortars (10% cement and 20% lime without fibers), and eight mortars containing PKC fibers at varying contents (0.25%, 0.50%, 0.75%, 1.00%, 1.25%, 1.50%, 1.75%, and 2.00%).

2.2. Materials Used

2.2.1. Lateritic Soils

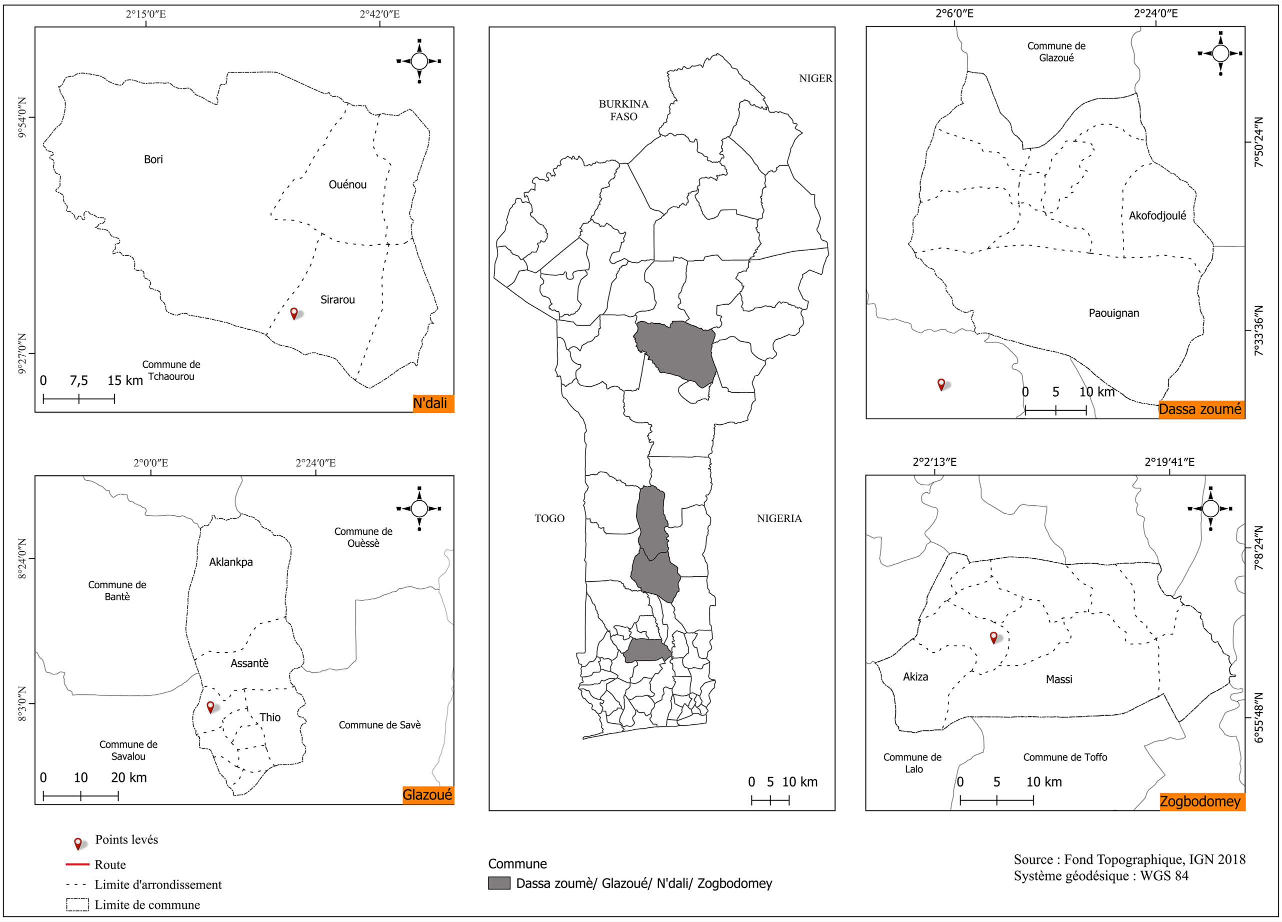
The lateritic soils used in this study were collected from four locations in Benin: Hlanhonou (Zogbodomey municipality, Zou Department), Kpékouté (Dassa-Zoumè municipality, Collines Department), Assanté (Glazoué municipality, Collines Department), and Sakarou (N'Dali municipality, Borgou Department). These sites cover a north-south gradient characteristic of the pedological variability of Benin, enabling a representative comparative analysis of lateritic resources available at the national scale. **Figure 1** shows the locations of the lateritic soil sampling sites.

Approximately 100 kg of lateritic soil was collected from different points to ensure the representativeness of the samples at each of the four locations. The samples were then combined by site, thoroughly mixed, and subsampled after a series of three successive quartering operations to improve the homogeneity and representativeness of the laboratory batch.

2.2.2. Lime Derived from Autogenous Welding

The lime used in this study originates from a white powdery residue formed inside cylinders in which acetylene and water are introduced during autogenous welding operations. Recovery is conducted directly in welding workshops by scraping the internal walls of the cylinders. The extracted powder is then left in open air for natural drying, after which it is packaged in airtight plastic bags and stored away from moisture to preserve its reactive properties. No additional treatment is applied prior to its incorporation into the experimental formulations.

Figure 2 shows the sampling process of the lime as well as the bulk lime material.



Source : Fond Topographique, IGN 2018
Système géodésique : WGS 84

Figure 1. Location map of the lateritic soil sampling sites.


(a) Sampling of lime paste

(b) Powdered lime paste

Figure 2. Presentation of lime derived from autogenous welding.

2.2.3. Palm Kernel Cake (PKC)

In general, palm kernel cake is produced using artisanal methods according to traditional techniques observed in local oil mills. The extraction of palm oil (from the pulp) and palm kernel oil (from the kernel) is conducted using traditional processes (pounding, boiling, manual pressing) or semi-industrial processes (sterilization, threshing, screw pressing, centrifugation). Palm kernel cake corresponds to the solid residue obtained after oil extraction from palm kernels.

The production process consists of four successive steps (**Figure 3**):

1) Collection and preparation of palm kernel nuts.

2) Thermal softening by boiling, followed by manual pounding or crushing of the softened nuts to separate the pulp from the kernel shells.

3) Pressing of the pulp to extract palm oil, leaving behind a fibrous paste known as palm kernel cake.

4) Processing of the cake through drying and preparation for use as a vegetal fiber in construction applications.

Figure 3. Process of softening and extraction of palm kernel cake.

The resulting palm kernel cake exhibits characteristics considered suitable for use in construction (fibro-granular texture, low bulk density, and presence of active organic matter). Prior to incorporation into the mortars, a pretreatment process is applied to reduce residual oils, stabilize organic compounds, improve adhesion with the lateritic matrix, and limit the risk of biological degradation. The cakes are soaked in an alkaline solution (water + lime) for ten minutes, then rinsed with clean water and dried in air and in an oven. This alkaline treatment, with an optimal dosage of 2% to 5% $Ca(OH)_2$ (final pH between 10 and 12), provides a suitable balance between degreasing and improved physicochemical compatibility with the lateritic matrix.

2.2.4. Cement

The cement used as a reference binder is a composite Portland cement (CPJ 35) of type CEM II/B-M (S-L) 42.5 N, supplied by the SCB Lafarge cement plant in Onigbolo and marketed in 50 kg bags. This cement was used exclusively for the reference mortars, allowing comparison with the performance of lime-stabilized mortars.

2.3. Characteristics of the Lateritic Soils

Table 1 presents the geotechnical and physical characteristics of the four lateritic soils used. Particle size distribution tests were conducted by sieving (particles from 0.080 mm to 0.63 mm) and sedimentation (particles smaller than 0.080 mm), in accordance with standard NF EN ISO 17892-4. The liquid limit, plastic limit, and plasticity index were determined using Atterberg limit tests, in accordance with standard NF P 94-051.

Table 1. Geotechnical characteristics of the lateritic soils used.

Parameter	Zogbodomey	Dassa	Glazoué	N'Dali
Apparent Density (g/cm^3)	1.75	1.96	1.777	1.495
Absolute Density (g/cm^3)	2.21	2.36	2.648	2.650
Water Absorption (%)	14.59	8.83	33.00	44.00
Porosity (%)	19.6	18.6	32.89	43.58
Compactness (%)	80.4	81.4	67.11	56.42
Void Ratio	0.244	0.229	0.490	0.772
Liquid Limit (%)	55	33	78	91
Plastic Limit (%)	28.36	19.52	37.00	48.00
Plasticity Index (%)	26.64	13.48	41.00	43.00

The shape of the particle size distribution curves of the studied lateritic soils shows that they are fine sandy soils, and therefore well suited to produce compressed earth blocks (**Figure 4**). The presence of a considerable proportion of fine particles improves cohesion and contributes to the mechanical properties of the blocks. This observation is consistent with the findings of Laborel-Préneron *et al.* (2016) [20], who highlighted the decisive role of fine particles in enhancing the performance of stabilized compressed earth blocks (**Figure 5**). The studied lateritic soils belong to the category of highly plastic marly clays (type A4 according to NF P 11-300).

This high plasticity may be favorable for soil block production and compaction, provided it is properly controlled through lime stabilization.

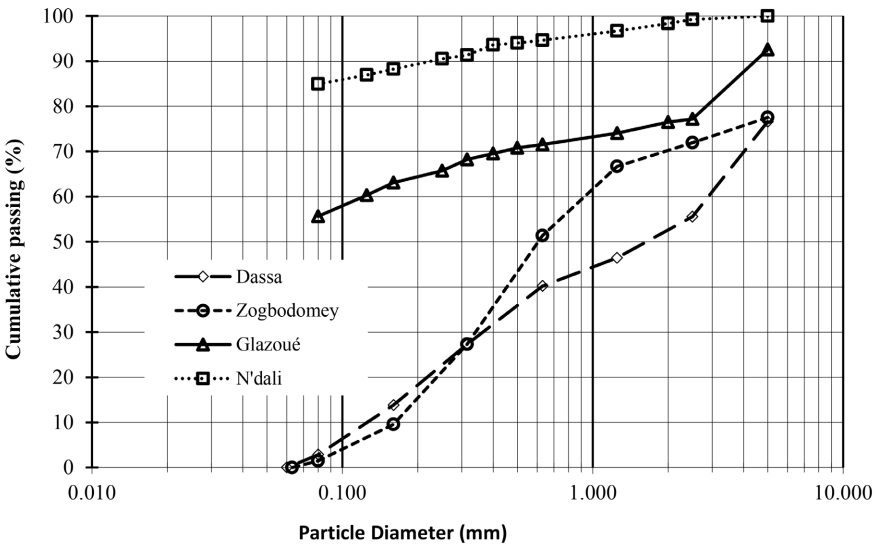


Figure 4. Grain size distribution curves of the lateritic soils used.

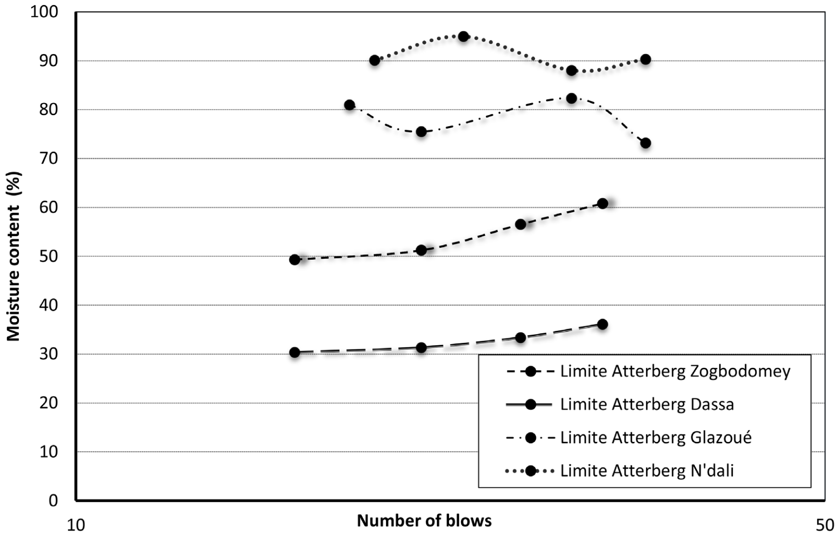


Figure 5. The resulting graph from Atterberg limits tests for the four soils used.

2.4. Preparation and Curing of Mortar Specimens

Dry lime is directly incorporated into the lateritic soil prior to wetting, to promote better homogenization of the mixture. Water is then added progressively in small successive amounts to ensure uniform hydration and to avoid the formation of lumps. The mortar mixtures are produced in a mechanical mixer under continuous mixing for five minutes. The mixing procedure and duration allow the production of a homogeneous, plastic, stable paste suitable for molding.

The mortar is placed into cylindrical metal molds (50 mm diameter and 100 mm height) and prismatic molds (40 mm × 40 mm cross-section and 160 mm length), in two successive layers compacted using a mechanical press applying a compaction force of 0.25 kN on each layer (corresponding to an approximate pressure of 12.7 MPa). The top surface is leveled using a spatula to obtain a smooth and regular face, ensuring uniform stress transfer during mechanical testing. Demolding is conducted one hour after casting. The specimens are then stored under air-drying conditions, protected from direct sunlight, in a controlled environment maintained at 25˚C ± 1˚C and 50% ± 10% relative humidity. The specimens are thus cured until the defined testing ages: 7, 14, and 28 days. The optimum water content was determined using the Modified Proctor test for each soil, with values ranging between 12% and 18% depending on material plasticity. The loading rate during mechanical testing was fixed at 0.5 mm/min.

Compressive strength of the mortar specimens is determined by applying a uniaxial compressive load until failure. For each mortar and each curing age, three specimens are assessed, and the reported value corresponds to the arithmetic mean of the three measured strengths.

2.5. Experimental Program, Description, Identification, and Composition of Mortars

The experimental program is divided into two (2) phases, preceded by the chemical and mineralogical characterization of the materials used. X-ray diffraction (XRD) analyses are performed on the materials, namely the four lateritic soils, the lime, and the palm kernel cake fibers.

2.5.1. Phase 1 of the Experimental Program

This phase is composed of mortars based on lateritic soils, water, and hydrated lime. A reference mortar is produced for comparison purposes and consists of lateritic soil, water, and cement dosed at ten percent (10%). This reference mortar does not contain lime, and none of the mortars in this phase contains palm kernel cake. The mortars are identified using a code composed of two (2) identifiers. The first identifier consists of two (2) letters indicating the sampling site of the lateritic soil considered (Zo for Zogbodomey, Da for Dassa-Zoumè, Gl for Glazoué, and Nd for N'Dali). The second identifier indicates the binder or stabilizer used (Li for lime and Ce for cement), followed by a number indicating the mass dosage of the binder or stabilizer (2 for two percent, 20 for twenty percent).

As an illustration (Figure 6), the mortar made with lateritic soil collected from Glazoué and containing ten percent (10%) lime is designated Gl-Li-10. Table 2 presents the composition of the mortars.

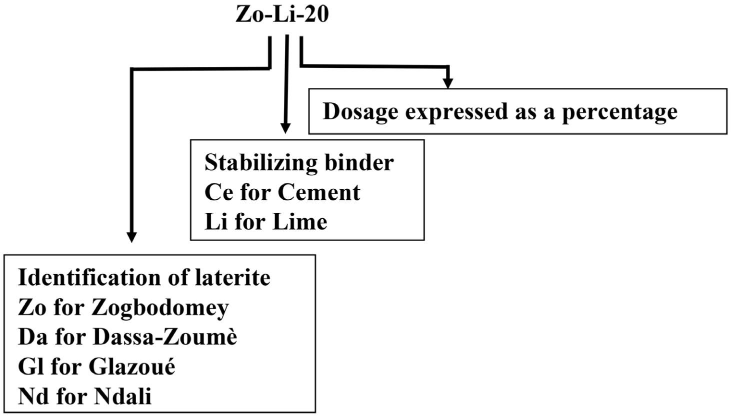


Figure 6. Diagram showing the identification of mortars from Phase 1.

2.5.2. Phase 2 of the Experimental Program

The second phase of the experimental program consists of mortars composed of lateritic soil, water, lime, and palm kernel cake. Two reference mortars are produced for comparison purposes. The first is composed of lateritic soil, water, and cement (the reference mortar from Phase 1). The second is composed of lateritic soil, water, and 20% lime (the lime dosage identified as optimal in Phase 1, providing the best mechanical performance). The reference mortar containing no lime and no palm kernel cake is identified in Phase 1 and retains its designation. The second reference mortar, containing lateritic soil, water, and lime at 20%, is designated Gl-Ch20-T0 for the lateritic soil from Glazoué.

The mortars are therefore identified using a code composed of three (3) identifiers. The first identifier consists of two letters indicating the location of the lateritic soil considered. The second identifier, Li20, indicates stabilization with 20% lime. The third identifier (P with a subscript number) indicates the presence of palm kernel cake in the mortar, where the letter P denotes fibers, and the subscript number indicates the incorporation rate.

As an illustration (Figure 7), the mortar made with lateritic soil collected from Zogbodomey, containing 20% lime and 1.25% palm kernel cake, is designated Zo-Li20-$P_{1.25}$.

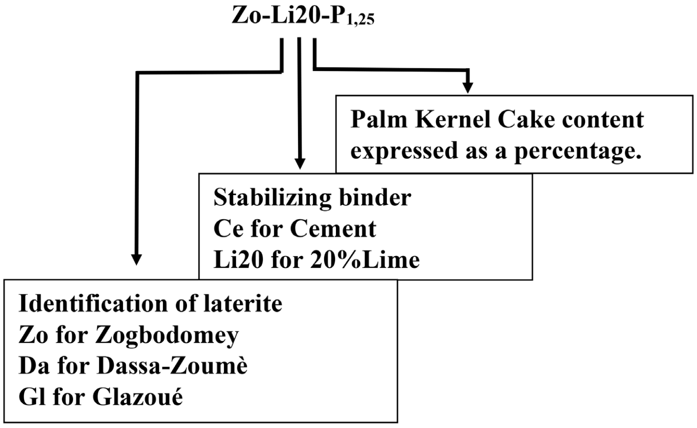


Figure 7. Diagram showing the identification of mortars from Phase 2.

The composition of the mixtures is based on mass proportions, with a constant mass of lateritic soil and a varying mass of lime expressed as a percentage of the soil mass for the first phase. In the second phase, the mass of lateritic soil is kept constant, as is the lime content, while the mass of palm kernel cake is varied as a percentage of the total mass of lateritic soil plus lime. The final water content after drying is considered negligible.

3. Experimental Results

3.1. Mineralogical Composition of the Lateritic Soils and Chemical Composition of the Lime

Table 2 presents the weight fractions of the mineralogical phases identified by XRD in the four lateritic soils studied.

Table 2. Quantitative mineralogical composition of the lateritic soils (mass %).

Phase Mineral	Dassa-Zoumé	Glazoué	N'Dali	Zogbodomey
Quartz (SiO_2)	42% ± 4%	46% ± 3%	40% ± 3%	56% ± 2%
Kaolinite-1A	Absent	Absent	26% ± 4%	Absent
Orthoclase	25% ± 2%	11.2% ± 1.1%	3.9% ± 0.8%	20.3% ± 0.8%
Albite	14.4% ± 1.4%	29% ± 3%	23.3% ± 1.4%	4% ± 3%
Goethite	9.4% ± 0.9%	12.0% ± 1.5%	0.12% ± 0.04%	7.6% ± 0.3%
Muscovite	8% ± 9%	1.79% ± 0.12%	6.3% ± 0.4%	12.4% ± 0.5%
Quartz Crystallite Size	456 Å	266 Å	555 Å	845 Å

The fundamental difference between the soils lies in the exclusive presence of kaolinite in the N'Dali soil (26%). This clay mineral reacts with lime to form hydrated calcium silicates and aluminates (C-S-H, C-A-H), which densify the matrix and enhance mechanical strength [3]. The Zogbodomey and Dassa-Zoumè soils, although devoid of kaolinite, exhibit high quartz contents (56% and 42%), providing a rigid granular skeleton, while Glazoué is distinguished by its abundant goethite content (12%), which acts as a natural binding agent and improves cohesion. The quartz crystallite size (**Figure 8**), estimated using the Scherrer equation, ranges from 266 Å (Glazoué) to 845 Å (Zogbodomey).

Table 3 presents the mineralogical composition of the lime derived from autogenous welding, determined by XRD with quantification using the Rietveld method.

Table 3. Mineralogical composition of autogenous welding lime (XRD analysis, Rietveld method).

Mineral Phase	Formula	Teneur (%)	Signification
Portlandite	$Ca(OH)_2$	85.4 ± 1.8	Main active phase—direct binding agent
Grossulaire	$Ca_3Al_2(SiO_4)_3$	10.3 ± 1.8	Calcium garnet—inert impurity
Quartz	SiO_2	4.3 ± 0.2	Siliceous residue—filler role

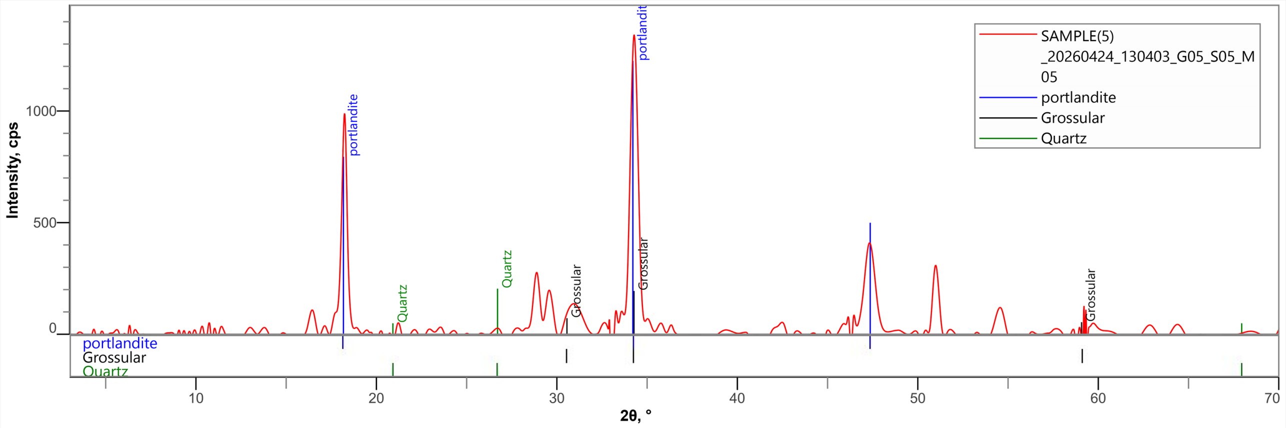


Figure 8. XRD analysis of lime (Sample 5): schematic diffractogram and quantitative composition (Rietveld method).

The crystallite size of portlandite (255 Å for the (001) peak and 220 Å for the (101) peak) indicates a fine crystallization, which is favorable to a high specific surface area and thus enhanced reactivity with soil aluminosilicates. With 85.4% active Ca $(OH)_2$, this artisanal lime is comparable to industrial hydrated lime of class CL 90 according to standard NF EN 459-1 (minimum $Ca(OH)_2$ content ≥ 85%).

The XRD analysis of the treated palm kernel cake shown in **Figure 9** reveals a diffractogram dominated by a broad amorphous halo centered at $2\theta \approx 20.12^\circ$, characteristic of partially degraded lignocellulosic organic matter. Cellulose is amorphous after alkaline treatment, and lignin is partially carbonized. This treatment improves the compatibility of the fibers with the lime-soil matrix by reducing soluble sugars (which inhibit pozzolanic reactions) and by partially hydrophobizing the fibers.

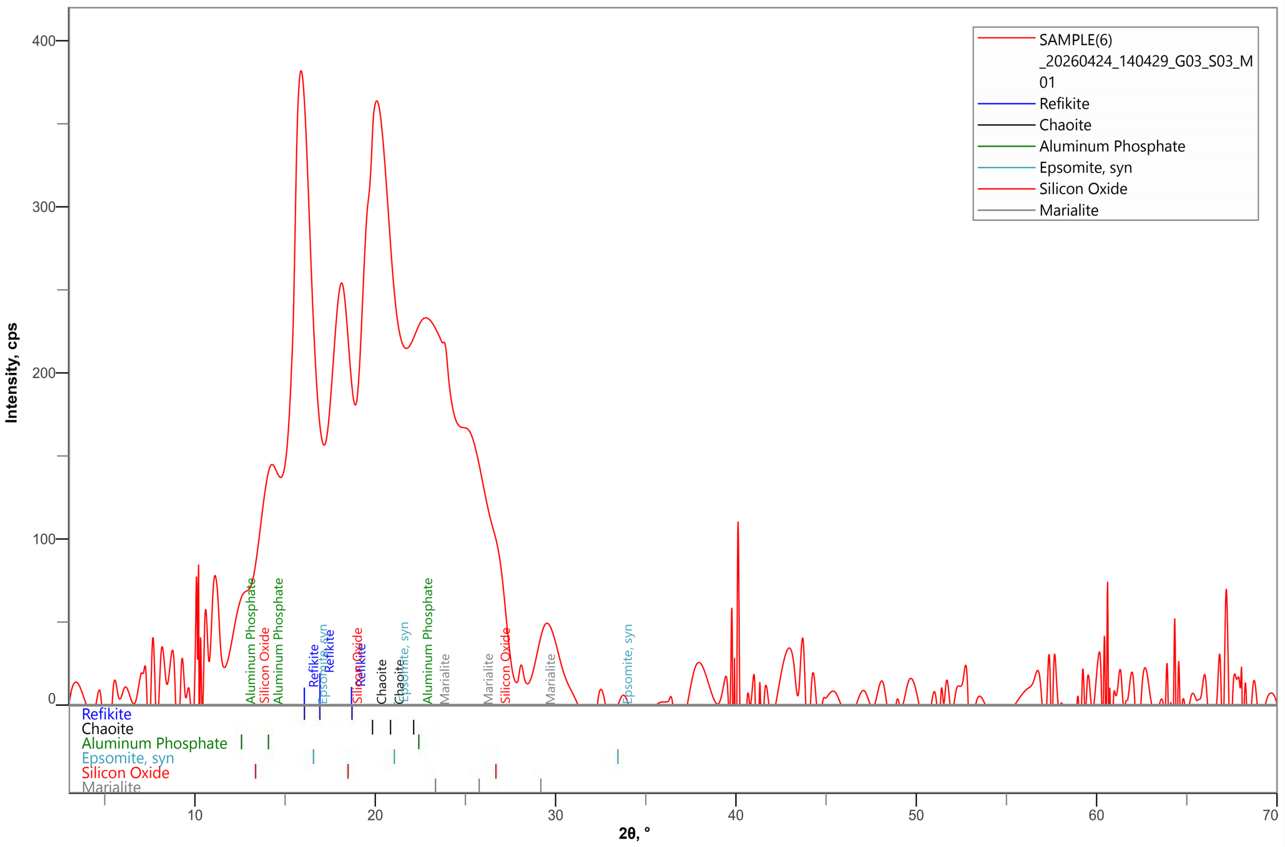


Figure 9. XRD analysis of palm kernel cake (Sample 5): schematic diffractogram and quantitative composition (Rietveld method).

Table 4 presents the mineralogical composition of the treated palm kernel cake, determined by X-ray diffraction (XRD) with quantification using the Rietveld method.

Table 4. Identified phases in the treated palm kernel cake (Sample 6) interpretation are to be considered with caution due to the amorphous nature of the material.

Identified Phase	Formula	Content (%)	Real Interpretation
Refikite	$C_{19}H_{31}COOH$	44.17 ± 0.08	Diterpenic resin—extractable organic fraction
Chaoite	C	37.88 ± 0.07	Carbon resulting from lignin/cellulose degradation
Phosphate Al	$AlPO_4$	17.83 ± 0.04	Partially mineralized organophosphate compound
Traces (3 Phases)	Divers	<0.13	Minor mineral impurities

Table 5 presents the average compressive strength values of the four studied lateritic soils for each tested lime content. Table 6 presents the average compressive strength values of the four studied lateritic soils for the optimal 20% dosage and for each tested palm kernel cake fiber content.

3.2. Phase 1: Compressive Strength of Lime-Stabilized Lateritic Soil Mortars

The results of Phase 1 show that all compressive strengths increase progressively from 7 to 28 days for all mortars and for the four studied lateritic soils. Strength development is particularly pronounced between 7 and 14 days, reflecting the kinetics of early pozzolanic reactions. The increase between 14 and 28 days remains moderate but continuous, confirming that carbonation reactions and the formation of C-S-H gels continue in the long term.

Mortars containing between 18% and 22% lime exhibit the highest compressive strengths for all sampling sites. A lime content of 20% is identified as the optimum based on the experimental results. Beyond this threshold, strength progressively decreases, a phenomenon attributed to excess free $Ca(OH)_2$ in the matrix, which weakens the structure by disrupting the chemical balance of the binding phases.

For mortars stabilized with 6% lime, 28-day compressive strengths exceed 4 MPa for the Dassa-Zoumè and Zogbodomey soils. For the N'Dali and Glazoué soils, the 4 MPa threshold is reached only from 12% and 14% lime content, respectively. Mortars produced with Zogbodomey and Dassa-Zoumè soils systematically exhibit higher performance than those based on Glazoué and N'Dali soils for equivalent compositions.

Table 5. 28-day compressive strength (MPa)—Phase 1.

Lime Content (%)	Glazoué	N'Dali	Dassa-Zoumè	Zogbodomey
Ce10 (Ref.)	5.616	5.356	5.785	6.045
Li-00	1.924	1.976	2.678	2.938
Li-02	2.093	2.574	3.289	3.432
Li-04	2.717	3.042	3.731	3.666
Li-06	3.055	3.211	**4.017**	**4.095**
Li-08	3.315	3.588	4.368	4.277
Li-10	3.484	3.926	4.615	4.602
Li-12	3.757	**4.134**	4.797	4.979
Li-14	**4.108**	4.394	4.914	5.135
Li-16	4.238	4.537	5.057	5.265
Li-18	4.498	4.719	5.239	5.421
Li-20	4.576	4.771	5.317	5.512
Li-22	4.654	4.745	5.369	5.473
Li-24	4.537	4.693	5.317	5.421
Li-26	4.381	4.576	5.148	5.356
Li-28	4.186	4.355	5.057	5.187
Li-30	3.978	4.212	4.758	4.875

The results of Phase 1 show that the 28-day flexural strengths increase with increasing lime content for all mortars and for the four studied lateritic soils. At low lime contents (0% to 6%), the strengths remain low, reflecting limited matrix cohesion. The improvement becomes more significant from 8% onwards, indicating the progressive activation of reactions between lime and clayey constituents, leading to the formation of secondary cementitious phases. This trend continues up to an optimum range between 18% and 20% lime, with maximum flexural strengths recorded at 18% for most soils (0.554 MPa for Glazoué, 0.581 MPa for N'Dali, 0.685 MPa for Dassa-Zoumè, and 0.709 MPa for Zogbodomey).

Beyond this threshold, a progressive decrease in flexural strength is observed, particularly from 22% onwards, which can be attributed to excess unconsumed portlandite, resulting in a more fragile and less homogeneous structure. Mortars based on Zogbodomey and Dassa-Zoumè soils exhibit the best performance, with values close to or even higher than those of the reference mortar Ce10 for certain dosages (notably between 14% and 20%). In contrast, Glazoué and N'Dali soils show lower strength values, although a clear improvement is observed at higher lime contents. Finally, the performance threshold of the reference mortar (approximately 0.58 to 0.60 MPa) is reached or exceeded for Dassa-Zoumè and Zogbodomey soils from 14% lime, whereas it is reached only from 18% for N'Dali and is barely achieved for Glazoué. These results confirm the existence of an optimal dosage around 18% - 20%, consistent with the compressive strength observations.

Table 6. 28-day flexural strengths (MPa)—Phase 1: four sites (mean values of three prismatic specimens 40 × 40 × 160 mm—NF EN 196-1).

Lime Content (%)	Glazoué (d28)	N'dali (d28)	Dassa-Zoumè (d28)	Zogbodomey (d28)
Ce10 (Ref.)	0.605	0.577	0.579	0.605
0	0.178	0.182	0.309	0.339
2	0.258	0.317	0.354	0.370
4	0.313	0.351	0.431	0.423
6	0.306	0.321	0.402	0.410
8	0.357	0.386	0.504	0.428
10	0.322	0.362	0.426	0.425
12	0.376	0.413	0.517	0.536
14	0.506	0.541	0.567	0.632
16	0.458	0.491	0.545	0.567
18	0.554	0.581	0.685	0.709
20	0.528	0.551	0.654	0.636
22	0.501	0.511	0.578	0.589
24	0.447	0.462	0.524	0.500
26	0.472	0.493	0.554	0.536
28	0.515	0.536	0.506	0.479
30	0.367	0.389	0.512	0.488

3.2. Phase 2: Compressive Strength of Lateritic Soil Mortars Stabilized with 20% Lime and Reinforced with Palm Kernel Cake Fibers

The results of Phase 2 clearly illustrate the beneficial effect of incorporating palm kernel cake fibers on the compressive strength of composite mortars. The time-dependent evolution of strength (7, 14, and 28 days) follows the same trend as in Phase 1, with a significant increase in strength within the first 14 days, confirming that both pozzolanic reactions and fiber reinforcement effects act synergistically at early ages.

Mortars containing 1.00% and 1.25% palm kernel cake exhibit the highest compressive strengths. A fiber content of 1.00% is identified as the optimum reinforcement level for all four studied lateritic soils, based on 28-day experimental results. Beyond 1.50%, compressive strength progressively decreases due to an increase in total porosity associated with the low density of the fibers and the development of weak interfacial zones between fibers and matrix. Table 7 presents the 28-day compressive strengths of Phase 2 mortars for the four studied lateritic soils.

Table 7. 28-day compressive strengths (MPa)—Phase 2.

Mortar	Zogbodomey	Dassa-Zoumè	Glazoué	N'Dali
Ce10 (Ref.)	6.045	5.785	5.616	5.356
Li20-P0	2.938	2.678	1.924	1.976
Li20-P0.25	5.551	5.447	4.875	5.122
Li20-P0.50	5.902	5.655	5.356	5.382
Li20-P0.75	6.045	6.071	5.577	5.655
Li20-P1.00 (Optimal)	**6.305**	**6.175**	**5.772**	**5.915**
Li20-P1.25	6.045	6.149	5.616	5.655
Li20-P1.50	5.785	5.915	5.421	5.434
Li20-P1.75	5.616	5.525	5.187	5.057
Li20-P2.00	5.135	5.343	4.836	4.745

The results of Phase 2 clearly highlight the considerable influence of palm kernel cake (PKC) fiber incorporation on the 28-day flexural strength of composite mortars. In general, the progressive addition of fibers leads to a notable improvement in mechanical performance compared to the reference mortar with 20% lime (Li20-P0), reflecting the reinforcement effect associated with fiber crack-bridging and stress redistribution mechanisms. This improvement is particularly pronounced for fiber contents between 0.75% and 1.00%, where peak values are reached for most soils. In particular, N'Dali (0.790 MPa) and Glazoué (0.743 MPa) achieve their maximum values at 0.75%, while Dassa-Zoumè reaches its peak at 1.25% (0.717 MPa) and Zogbodomey at 1.00% (0.639 MPa).

The optimal dosage can therefore be considered to lie in the range of 0.75% to 1.00% PKC for all studied soils, an interval within which strength gains are the most significant and the most consistent (Table 8). Beyond 1.25%, a decreasing trend in strength is observed, although some fluctuations persist depending on the soil type. This reduction is attributed to increased porosity and a less homogeneous dispersion of fibers within the matrix, leading to weak interfacial zones between fibers and matrix. Furthermore, the reinforced mortars exhibit, for several formulations, higher flexural strengths than the cement reference mortar (Ce10), particularly for Glazoué, N'Dali, and Dassa-Zoumè soils at optimal fiber contents, confirming the effectiveness of vegetal fiber reinforcement. In contrast, performance remains more limited for Zogbodomey, although a clear improvement is still observed. These results confirm that controlled incorporation of PKC optimizes the flexural behavior of mortars by enhancing their ductility and crack resistance.

Table 8. 28-day flexural strengths (MPa)—Phase 2 (20% lime + variable fiber content) (mean values of three specimens—four Beninese sites).

PKC Fiber (%)	Glazoué (d28)	N'dali (d28)	Dassa-Zoumè (d28)	Zogbodomey (d28)
Ce10	0.778	0.742	0.757	0.342
Li00	0.196	0.194	0.247	0.146
Li20-P0	0.476	0.477	0.526	0.360
Li20-P0.25	0.550	0.556	0.587	0.492
Li20-P0.50	0.560	0.582	0.555	0.515
Li20-P0.75	0.743	0.790	0.607	0.525
Li20-P1.00	0.656	0.670	0.665	0.639
Li20-P1.25	0.566	0.566	0.717	0.524
Li20-P1.50	0.594	0.585	0.637	0.524
Li20-P1.75	0.567	0.557	0.516	0.465
Li20-P2.00	0.528	0.541	0.534	0.415

4. Discussion

4.1. Lime Action Mechanisms on the Lateritic Matrix and Interpretation of the Optimal Dosage

The XRD analysis of the soils (Table 4) and of the lime (Table 1) now makes it possible to rigorously explain the experimentally identified optimal dosage of 20%.

Why 20% and not 6% - 10% as commonly reported in the literature? Three converging factors account for this discrepancy:

1) Absence of kaolinite in three out of four soils: Only the N'Dali soil contains kaolinite (26%). The Zogbodomey, Dassa-Zoumè, and Glazoué soils are devoid of crystalline clay minerals. Their pozzolanic reactivity therefore relies mainly on the slower weathering of feldspars (albite, orthoclase) and on the amorphous fraction. A higher lime content is thus required to compensate for this lower intrinsic reactivity.

2) Effective active portlandite content: The artisanal lime contains 85.4% active $Ca(OH)_2$ (Table 1), compared to at least 90% for a reference industrial lime (NF

EN 459-1). For a 20% mass dosage of artisanal lime, the effective portlandite content is 20% × 0.854 = 17.1%. When normalized to an industrial lime with 90% purity, the equivalent dosage becomes 17.1 / 0.90 = 19.0%.

3) Three-stage reaction mechanisms: Lime stabilization follows the classical scheme described by Bell (1996) [3]: i) immediate cation exchange (0 - 72 h) leading to clay flocculation; ii) pozzolanic reactions (1 - 28 days) between portlandite and aluminosilicates (kaolinite, feldspars) forming calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H); and (iii) slow carbonation of residual portlandite into calcite.

Table 9 summarizes the calculation of the equivalent lime dosage based on the purity determined by XRD.

Table 9. Calculation of equivalent industrial lime dosage.

Parameter	Value
Optimal mass dosage (present study)	20.0%
$Ca(OH)_2$ purity (XRD)	85.4%
Effective $Ca(OH)_2$ content	17.1%
Reference industrial lime purity (NF EN 459-1)	≥90.0%
Equivalent industrial lime dosage	~19.0%

This value of 19% falls within the upper range reported in the literature for soils with low reactive clay content (15% - 25% according to Ouedraogo *et al*., 2020, on Burkinabe lateritic soils), thereby confirming the consistency of the results [13].

The decrease in strength observed beyond 22% lime is explained by the saturation of the matrix's reactive capacity: excess unconsumed portlandite crystallizes within the pore network, creating weak zones and disrupting matrix densification [21].

The histograms in **Figures 10-13** show that all compressive strengths evolved from 7 to 14 days and from 14 to 28 days for all mortars and for the four studied lateritic soils. The increase in compressive strength between 14 and 28 days is not significant for lime-stabilized mortars. The contribution of lime to strength development is most pronounced within the first 14 days after casting. Mortars containing between 18% and 22% lime exhibit the highest compressive strengths. This study indicates that the incorporation of 20% lime is optimal.

Figure 14 highlights the mechanical behavior of mortars produced with the four lateritic soils at different lime incorporation rates after 28 days. The compressive strengths of mortars made with Zogbodomey and Dassa-Zoumè soils are higher than those obtained with Glazoué and N'Dali soils. Indeed, mortars containing lime contents between 18% and 22% exhibit the highest compressive strengths. A decrease in compressive strength is observed for mortars with lime contents greater than 22%. For identical mortar compositions, Zogbodomey and Dassa-Zoumè soils consistently show better compressive performance compared to Glazoué and N'Dali soils.

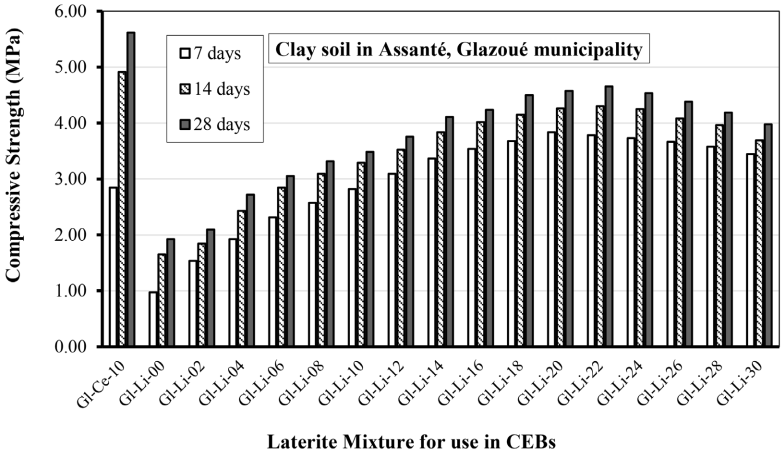


Figure 10. Compressive strengths of mortars (laterite + lime + water) prepared with lateritic soil from the Glazoué municipality (Assanté village).

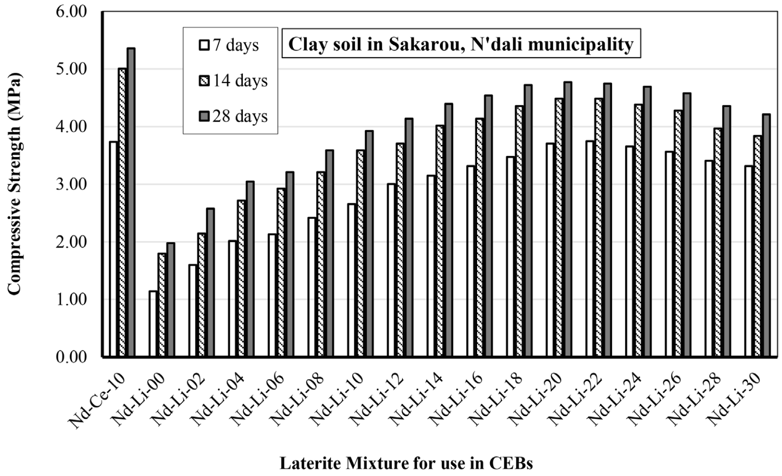


Figure 11. Compressive strengths of mortars (laterite + lime + water) prepared with lateritic soil from the N'Dali municipality (Sakarou village).

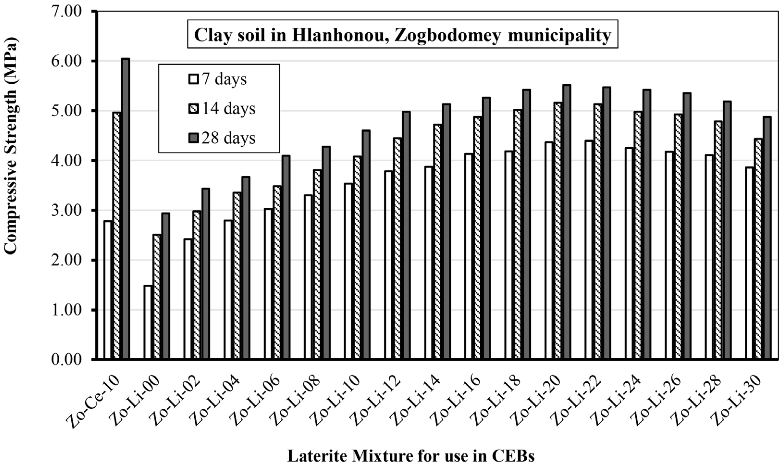


Figure 12. Compressive strengths of mortars (laterite + lime + water) prepared with lateritic soil from the Zogbodomey municipality (Hlanhonou village).

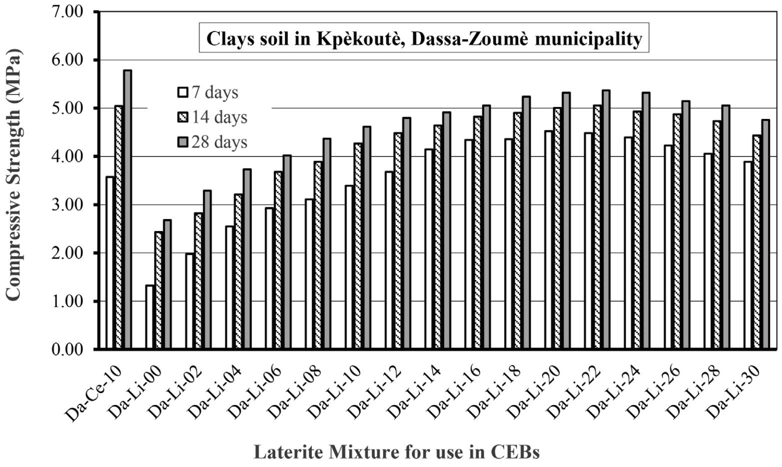


Figure 13. Compressive strengths of mortars (laterite + lime + water) prepared with lateritic soil from the Dassa-Zoumè municipality (Kpèkoutè village).

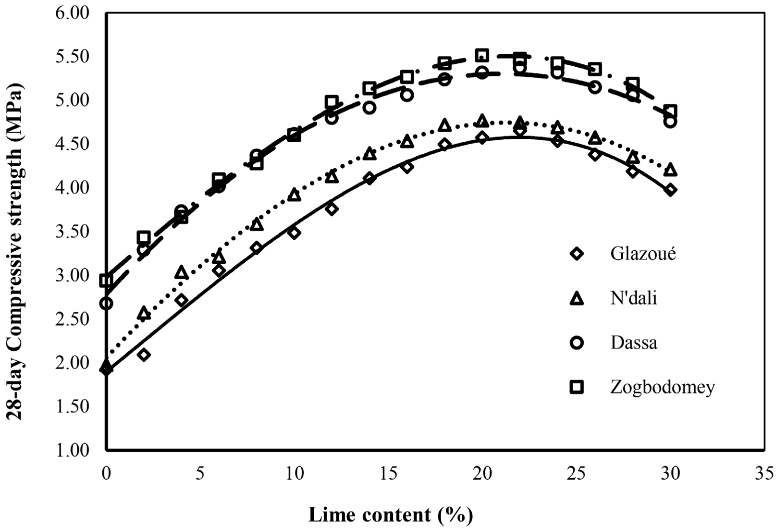


Figure 14. Effect of lime incorporation on the compressive strength of mortars (laterite + lime + water) was studied.

Figure 15 and **Figure 16** present the evolution of flexural strengths of mortars for the four lateritic soils as a function of i) lime content (Phase 1) and ii) palm kernel cake (PKC) fiber incorporation rate (Phase 2), at 28 days. In Phase 1, flexural strengths increase with lime content up to an optimum range between 18% and 20%, where maximum performances are recorded for all soils. Beyond this threshold, a progressive decrease is observed, indicating an excess of unreacted portlandite that weakens the matrix. For equivalent dosages, mortars made with Zogbodomey and Dassa-Zoumè soils exhibit higher flexural strengths than those based on Glazoué and N'Dali soils, particularly at optimal lime contents. In Phase 2, the incorporation of PKC significantly improves flexural strength compared to fiber-free mortars, with peak values obtained for fiber contents between 0.75% and 1.25%. This improvement is attributed to the role of fibers in crack bridging and stress redistribution. However, beyond 1.50%, a reduction in performance is observed due to increased porosity and less homogeneous fiber dispersion within the matrix. Furthermore, N'Dali and Glazoué soils show the best flexural performance after fiber incorporation, followed by Dassa-Zoumè, while Zogbodomey exhibits more moderate values. These results confirm the existence of an optimal combined dosage (lime + fibers) that enhances the flexural behavior of composite mortars.

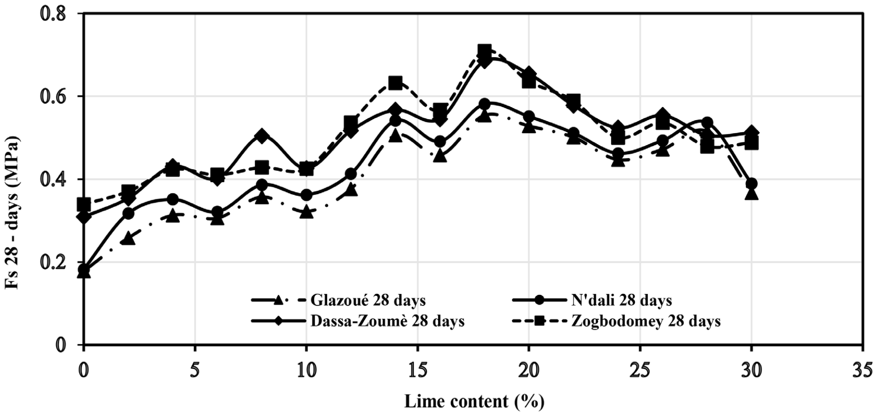


Figure 15. 28-day flexural strength vs lime content—four sites (Phase 1—optimum observed at 18% - 20% lime).

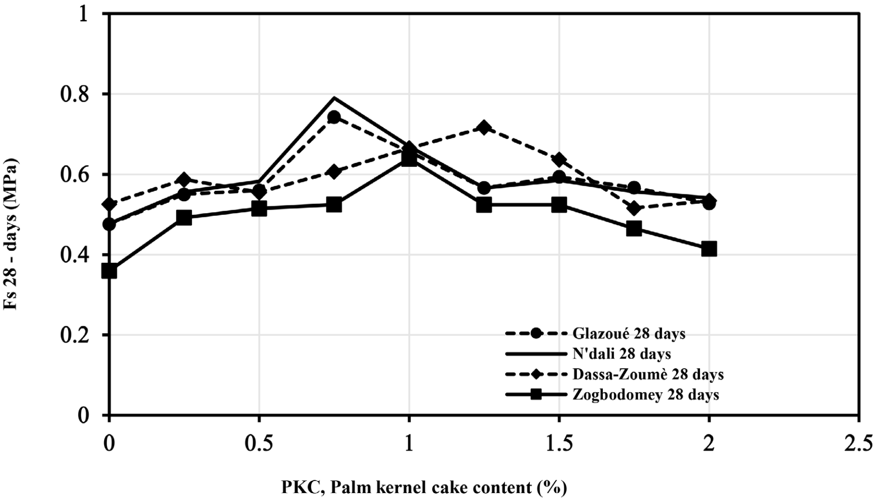


Figure 16. 28-day flexural strength vs PKC content—four sites (Phase 2—lime fixed at 20%).

The mechanical behavior of lime-stabilized lateritic soil mortars observed in this study can be explained by a well-documented reaction sequence occurring in three successive and partially overlapping stages [3] [4].

The first stage, which is immediate (within a few hours), corresponds to cation exchange between calcium ions (Ca^{2+}) supplied by lime and sodium (Na^+) and potassium (K^+) ions present in clay layers, particularly kaolinitic clays. This exchange induces clay flocculation, reduces plasticity, and improves compactability.

This mechanism explains the rapid increase in strength observed between 0 and 7 days across all formulations.

The second stage, extending over the first weeks, is dominated by true pozzolanic reactions. In a highly alkaline environment (pH > 12.4 maintained by free $Ca(OH)_2$), reactive amorphous silica (SiO_2) and alumina (Al_2O_3) from clay minerals react with Ca^{2+} ions to form calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H). These newly formed mineral phases progressively densify the clay matrix, creating a rigid binding network responsible for strength gains observed between 7 and 28 days [5].

The third and slower stage (months to years) corresponds to atmospheric carbonation of residual $Ca(OH)_2$, leading to the formation of calcium carbonate ($CaCO_3$), which contributes to long-term matrix consolidation.

The optimal 20% lime dosage identified in this study is higher than the commonly recommended range of 6% - 10% for conventional clays [1] [2]. This discrepancy can be explained by several combined factors: i) the lower content of reactive amorphous silica in the studied Beninese lateritic soils compared to reference European clays, requiring a higher $Ca(OH)_2$ supply to saturate reactive sites; ii) the incomplete purity of artisanal welding-derived lime, which contains impurities (traces of carbon and acetylene-related residues) that may reduce effective reactivity; and iii) ambient air curing conditions, which are less favorable to pozzolanic reactions than the moist curing conditions recommended by European standards. These findings are consistent with Ouedraogo *et al.* (2020) [13] on Burkinabe lateritic soils, who reported optimal lime contents between 15% and 25% for soils with low reactive clay content.

The strength reduction observed beyond 22% lime confirms the existence of a reaction saturation threshold. Above this threshold, excess unreacted $Ca\ (OH)_2$ dilutes the matrix without contributing to cementation and may even induce swelling-related stresses associated with secondary phase formation [21]. This highlights the importance of prior assessment of soil pozzolanic reactivity before large-scale application.

4.2. Role of Palm Kernel Cake Fibers in Composite Reinforcement

The histograms in **Figures 17-20** show the effect of palm kernel cake (PKC) incorporation and dosage on the compressive strength of mortars at 14 and 28 days for all mortars and for the four studied lateritic soils. As in Phase 1, where the increase in compressive strength between 14 and 28 days was not incredibly significant, fiber-reinforced mortars exhibit the same trend. The contribution of PKC incorporation and dosage to strength development is particularly significant during the first 14 days after casting, indicating that most of the reinforcement effect is activated at early ages. Mortars containing 1% and 1.25% PKC exhibit the highest compressive strengths. A fiber content of 1% is identified as the optimum based on the results of the present study.

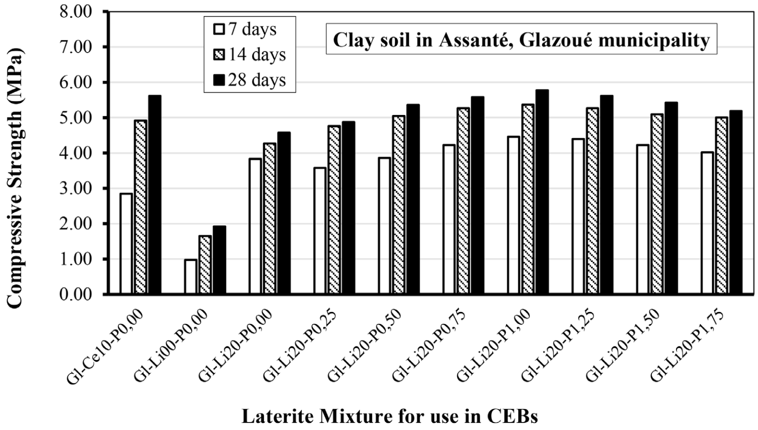


Figure 17. Compressive strengths of mortars (laterite + lime + PKC + water) prepared with lateritic soil from Glazoué municipality (Assanté village).

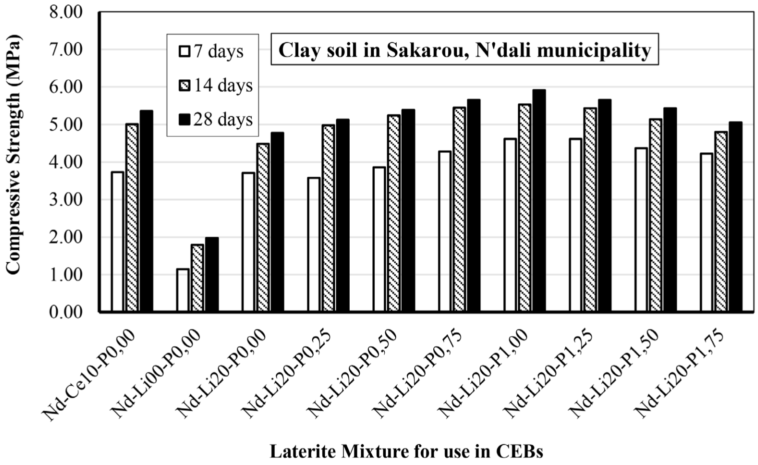


Figure 18. Compressive strengths of mortars (laterite + lime + PKC + water) prepared with lateritic soil from N'Dali municipality (Sakarou village).

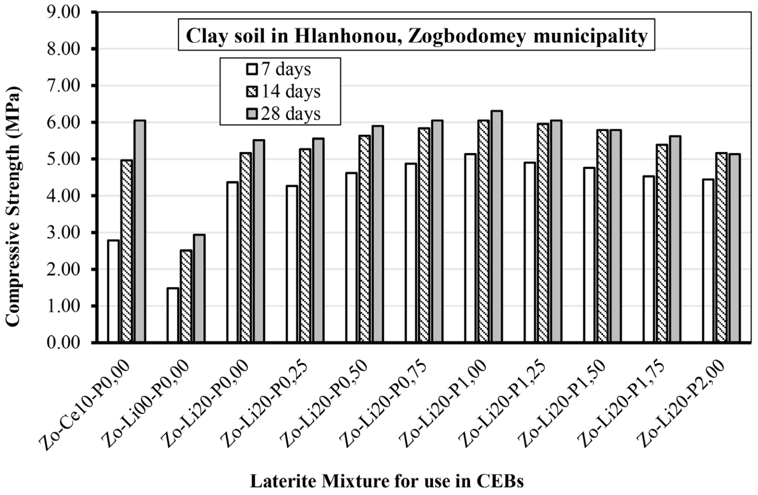


Figure 19. Compressive strengths of mortars (laterite + lime + PKC + water) prepared with lateritic soil from Zogbodomey municipality (Hlanhonou village).

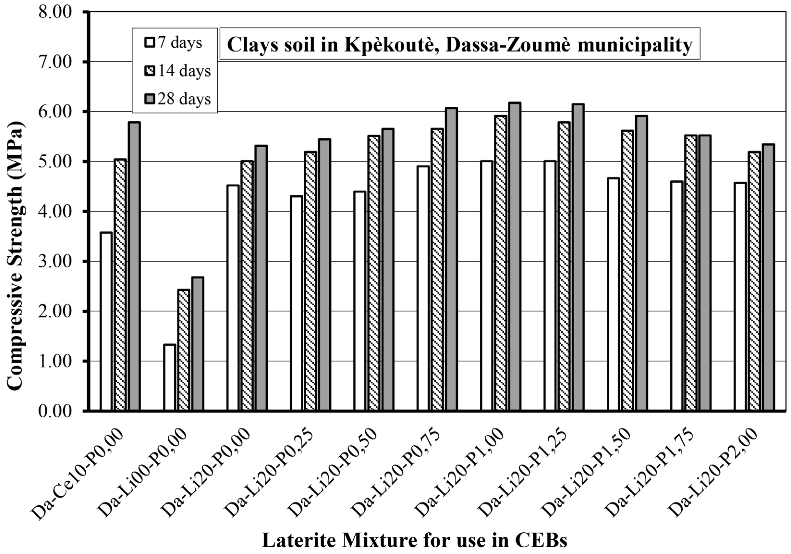


Figure 20. Compressive strengths of mortars (laterite + lime + PKC + water) prepared with lateritic soil from Dassa-Zoumè municipality (Kpèkoutè village).

The improvement in compressive strength observed with the incorporation of 1.25% palm kernel cake (PKC) into the optimal lime-stabilized mortar (Li20) requires a mechanistic explanation. Contrary to the usual expectation that vegetal fibers reduce compressive strength, the results of this study show a slight increase in strength for fiber contents between 0.25% and 1%, followed by a decrease beyond 1.25%.

This atypical behavior can be explained by two complementary mechanisms. First, at low fiber contents (<1.25%), PKC fibers, when homogeneously distributed within the lateritic matrix, function as bridges across microcracks formed during compaction. These fibers absorb part of the deformation energy, delaying the initiation and propagation of microcracks and thereby improving the apparent compressive strength [6] [7]. Second, the alkaline pretreatment of the fibers with hydrated lime removes surface oils and increases surface roughness, improving interfacial bonding between fibers and the lime-laterite matrix and reducing weak debonding zones that typically function as failure points in composite materials.

The reduction in strength beyond 1.25% is explained by two competing phenomena: i) an increase in total porosity due to the incorporation of very low-density fibers (0.15 - 0.25 g/cm^3), which introduces unfilled voids within the matrix; and ii) fiber agglomeration beyond a critical threshold, leading to heterogeneous clusters that create localized weak zones instead of a uniform reinforcement. This critical threshold of 1% - 1.25% is consistent with the findings of Millogo *et al.* (2014) [7] for Hibiscus cannabinus fibers (1.0% - 1.5%) and Aymerich *et al.* (2012) [8] for wool fibers (0.5% - 1.5%) [8].

The comparison with cement-based reference mortars (Ce10) is particularly informative. The optimal composite formulations (Li20-P1) achieve 28-day compressive strengths ranging from 5.77 to 6.31 MPa, depending on the soil, values comparable to or even higher than the cement reference mortars (5.36 to 6.05 MPa) for Zogbodomey and Dassa-Zoumè soils.

4.3. Influence of Soil Characteristics on Mechanical Performance

The variability in mechanical strengths observed among the four studied soils reflects the decisive influence of their mineralogical, granulometric, and geotechnical characteristics on stabilization mechanisms.

The Zogbodomey and Dassa-Zoumè soils, which exhibit the best mechanical performance, are characterized by high absolute densities (2.21 to 2.36 g/cm^3), moderate plasticity indices (13.48% to 26.64%), and lower porosities (18.6% to 19.6%). These properties indicate an argillaceous mineralogy dominated by kaolinite with a dense matrix structure, which is favorable to pozzolanic reactions and the development of C-S-H phases. Kaolinite, a low-swelling clay mineral, reacts effectively with lime to form stable silico-aluminous gels [3].

In contrast, the Glazoué and N'Dali soils show significantly higher porosities and plasticity indices (32.89% and 43.58% porosity; 41% and 43% plasticity index, respectively). These characteristics suggest the presence of swelling clay minerals (illite or smectite in secondary proportions), which require higher lime contents for stabilization and disrupt matrix densification during compaction. The higher optimum Proctor water content of these soils also increases the risk of segregation during placement, leading to microstructural heterogeneities that negatively affect strength development.

These results strongly suggest that soil mineralogical composition, rather than granulometry alone, is the determining factor governing pozzolanic reactivity and thus the mechanical performance potential of lateritic soil mortars. Complementary analyses using X-ray diffraction (XRD) and scanning electron microscopy (SEM) would be required to confirm this hypothesis and to quantify the proportions of C-S-H and C-A-H phases formed as a function of soil type and lime dosage.

4.4. Correlation between Mineralogy and Mechanical Performance

Table 10 establishes a direct correlation between the mineralogical composition of each soil (Table 2) and its mechanical performance for the optimal formulation Li20-$P_{0.75-1}$.

Table 10. Mineralogy-mechanical performance correlation (Li20-$P_{0.75-1}$, 28 days).

Soil	Kaolinite (%)	Goethite (%)	Quartz (%)	Cs (MPa)	Fs (MPa)	Facteur Explicative
Zogbodomey	0	7.6	56	6.31	0.639	Quartz-dominated skeleton
Dassa-Zoumè	0	9.4	42	6.18	0.665	Quartz/oxide balance
N'Dali	26	0.12	40	5.92	0.790	Kaolinite-driven C-S-H reactions
Glazoué	0	12.0	46	5.77	0.743	Goethite (natural binding effect)

Two main conclusions can be drawn.

First, compressive strength is primarily governed by the granular skeleton (quartz content and crystallite size) and natural cohesion provided by iron oxides (goethite). In this regard, Zogbodomey (56% quartz, 845 Å crystallites) and Dassa-Zoumè (42% quartz, 9.4% goethite) exhibit the highest compressive performance.

Second, flexural strength is significantly enhanced by the presence of kaolinite (N'Dali: 26%), which promotes pozzolanic reactions and improves fiber-matrix adhesion. Counterintuitively, the N'Dali soil, despite being the only kaolinitic soil, does not achieve the highest compressive strength but instead develops the best flexural performance.

This result highlights the importance of comprehensive mineralogical characterization prior to any formulation selection.

4.5. Convergences and Divergences with International Literature

This study shows several strong points of convergence with international literature. First, the time-dependent development of strength (7, 14, and 28 days) and the existence of an optimal lime content confirm the classical behavior of lime-stabilized BTCs described by Bell (1996), Walker *et al.* (2005), and Nshimiyimana *et al.* (2020) [1] [3] [5]. Second, the improvement in mechanical performance due to the incorporation of vegetal fibers at moderate dosages (1.0% to 1.5%) and the subsequent decrease beyond the saturation threshold are consistent with the findings of Millogo *et al.* (2014) and Aymerich *et al.* (2012) [7] [8].

The main divergence concerns the optimal lime dosage (20% in the present study versus 6% - 10% in European literature and 10% - 15% in African studies). As previously discussed, this difference is attributed to the moderate pozzolanic reactivity of the studied Beninese lateritic soils and the incomplete purity of the artisanal lime. A comparative chemical characterization of the artisanal lime against a reference industrial lime would make it possible to quantify this gap in reactivity and define a correction factor applicable to practical mix design.

A notable convergence is observed with the study of Aboubakar *et al.* (2021) regarding the compatibility of palm kernel cake fibers with a calcium-based matrix: the reported flexural strength gains in cement mortars (15% - 20% at 1% PKC) are consistent with the strength improvements observed in the present study, confirming the potential of PKC fibers as a vegetal reinforcement in lime-based binder systems [10].

4.6. Statistical Analysis of Results

The descriptive statistical analysis of the experimental data is presented in **Table 11** and **Table 12**. The calculated parameters include the arithmetic mean (μ), the empirical standard deviation (σ, computed with Bessel's correction N−1), and the coefficient of variation (CV = $\sigma/\mu \times 100\%$). These statistics were computed across all four sites for each dosage level (N = 4 sites), allowing the assessment of inter-site variability in 28-day strengths.

Table 11. Descriptive statistics of 28-day compressive strength—Phase 1 (4 sites).

Lime Content (%)	μ Cs28 (MPa)	σ Cs28	CV28 (%)
0	2.38	0.43	18.2
4	3.29	0.41	12.4
8	4.21	0.35	8.3
12	4.74	0.50	10.5
16	5.10	0.43	8.3
20	5.05	0.40	7.9
24	5.50	0.38	7.0
28	4.95	0.35	7.0

The 20% lime dosage corresponds to the identified optimum.

Table 12. Descriptive statistics at 28 days—Phase 2 (aggregated across 4 sites).

PKC Content (%)	μ Cs28 (MPa)	σ Cs28	CV28 Cs (%)	μ Fs28 (MPa)	σ Fs28	CV28 Fs (%)
0 (Li20)	5.05	0.42	8.4	0.46	0.07	15.0
0.25	5.26	0.30	5.7	0.56	0.05	8.4
0.50	5.57	0.23	4.1	0.55	0.03	4.7
0.75	5.84	0.22	3.7	0.67	0.12	17.7
1.00	6.04	0.19	3.2	0.66	0.04	6.6
1.25	5.87	0.25	4.2	0.59	0.08	13.8
1.50	5.64	0.22	3.9	0.59	0.05	7.8
1.75	5.35	0.24	4.6	0.53	0.04	7.8
2.00	5.02	0.25	5.1	0.51	0.06	11.3

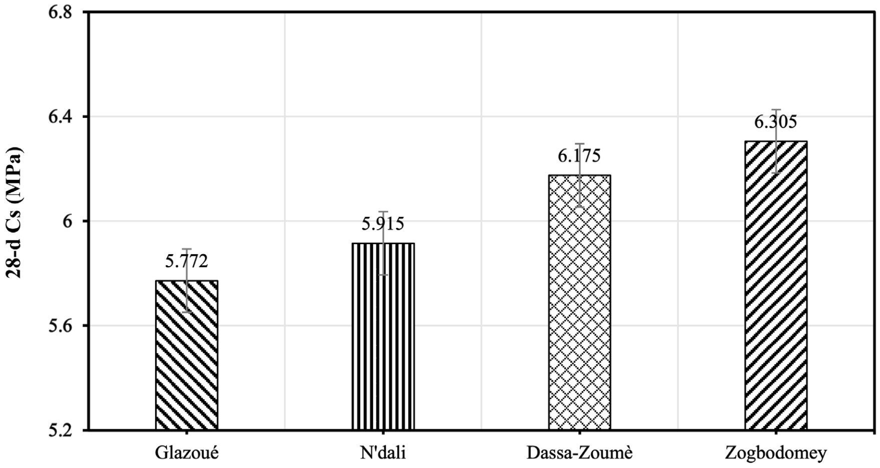
The standard deviations (σ) were calculated across the four sites (N = 4). Intra-site variability (three specimens per formulation) is not reflected in these values. The 1.00% PKC dosage corresponds to the identified optimum.

The analysis of the coefficients of variation (CV) reveals several important trends. For 28-day compressive strength in Phase 1 (Table 11), the CV decreases steadily with increasing lime content: from 18.2% at 0% lime to 7.9% at 20% lime. This reduction in inter-site variability reflects the homogenizing effect of lime stabilization on the mineralogical and textural differences of Beninese lateritic soils. Lime, by preferentially reacting with the most reactive clay phases (kaolinite and amorphous phases), tends to homogenize the microstructure of the matrices regardless of their initial composition.

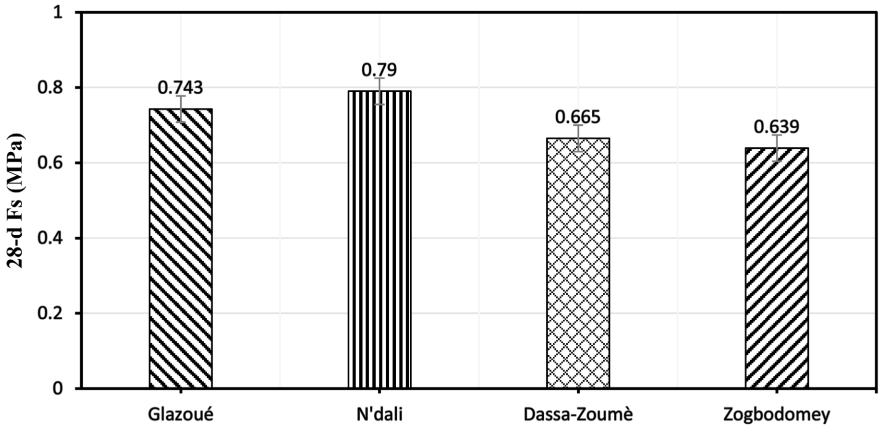
To confirm this trend, a one-way analysis of variance (ANOVA) followed by a Tukey post-hoc test ($\alpha = 0.05$) was performed on the 28-day strengths for the 18%, 20%, and 22% lime formulations. The results indicate that there is no statistically significant difference between these three dosages ($p > 0.05$). The 20% dosage was therefore retained as the optimum due to its central value and its position within the maximum performance range.

In Phase 2 (**Table 12**), the CV of Cs28 remains low (3.2% - 8.4%) for all PKC-reinforced formulations, with a minimum of 3.2% observed at 1.00% PKC, confirming the excellent repeatability of the results and the robustness of the experimental program at this optimum.

In contrast, the CV of Fs28 (**Figure 21**) is higher (4.7% - 17.7%), particularly at 0.75% PKC (CV = 17.7%) and 1.25% PKC (CV = 13.8%). This increased variability reflects the sensitivity of flexural strength to the spatial distribution of fibers within the specimen, which depends on mixing homogeneity and may vary slightly between sites due to differences in matrix texture. The 1.00% PKC dosage provides the best compromise between maximum mechanical performance (Fs28 = 6.04 MPa) and low variability (CV Cs = 3.2%, CV Fs = 6.6%).



(a) Optimal Cs (Li%+P1%) ± standard deviation



(b) Optimal Fs (Li%+P0,75-1%)± Standard deviation

Figure 21. Descriptive statistics of optimal strengths (Cs and Fs) at 28 days (Li20% + P1% formulation—error bars = ± standard deviation—CV values indicated).

The study presents several major scientific strengths. The first is its novel positioning within the literature: no previous study has documented the combination of Beninese lateritic soil, autogenous welding lime, and palm kernel cake fibers, giving the findings a genuinely original scientific contribution. The second strength lies in the multi-site approach (four localities covering a north-south geographical gradient), which provides the conclusions with greater robustness and geographical representativeness than most studies on African compressed earth materials, which are limited to a single soil source. The third strength is the simultaneous valorization of two local industrial by-products (welding lime and palm kernel cake) within a circular economy framework, constituting a concrete contribution to sustainable development goals in West Africa.

From a practical perspective, the optimal formulations identified (Li20-P1) exceed the structural threshold of 4 MPa for all four studied soils, with performances comparable to, and in some cases higher than, those of the cement-based reference mortar.

5. Conclusions

The present study systematically and rigorously evaluated the mechanical properties of mortars intended to produce compressed earth bricks using four Beninese lateritic soils stabilized with autogenous welding lime and reinforced with palm kernel cake (PKC) fibers. The results obtained lead to the following conclusions.

Regarding lime stabilization, the optimal dosage was found to be 20% of the dry soil mass for the studied lateritic soils, leading to 28-day compressive strengths ranging from 4.58 MPa to 5.51 MPa depending on the pozzolanic reactivity of the soil. This dosage, higher than the conventional 6% - 10% range commonly reported in the literature, reflects the moderate pozzolanic reactivity of the Beninese lateritic soils and the incomplete purity of the artisanal lime. Strength development occurs during the first 14 days, in agreement with the kinetics of early pozzolanic reactions.

Regarding reinforcement with palm kernel cake fibers, the optimal dosage was identified as 1% for all four soils, resulting in compressive strength improvements ranging from 4.4% to 8.5% compared with lime-only mortars. The optimal composite formulations (Li20-P1) achieved strengths between 5.77 and 6.31 MPa, comparable to or higher than those of the cement-based reference mortars (Ce10), thereby validating the technical feasibility of replacing cement with this composite stabilization system.

From a scientific perspective, this study fills an important gap in the literature by providing the first experimental data on the combination of Beninese lateritic soils, artisanal lime, and PKC fibers. It demonstrates the feasibility of simultaneously valorizing two local industrial by-products within a circular economy and sustainable construction framework.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

b	Width	m
C	Cement mass	kg
e	Thickness	m
G	Gravel mass	kg
h	Height	m
L	Length	m
M	Mass	kg
N	Nodule mass	kg
S	Sand mass	kg
t	Time	s
T	Temperature	˚C
V	Volume	m^3
α	Slope of the regression line for short times	-
β	Slope of the regression line for long times	-
ρ	Density	kg/m^3
σ	Stress	MPa