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Combined Valorization of Residual Lime Derived from Autogenous Welding and Palm Kernel Cake Fibers for the Stabilization of Compressed Earth Blocks: A Comparative Experimental Study of Four Beninese Lateritic Soils

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Abstract

Compressed earth blocks (CEBs) constitute a sustainable alternative to Portland cement, whose production remains a major source of anthropogenic CO_2 emissions [1], and align with the principles of the circular economy applied to construction [2]. However, raw lateritic soil exhibits limited mechanical strength and high sensitivity to water, requiring appropriate stabilization [3]. This study evaluates, for the first time, the combined stabilizing potential of residual lime derived from autogenous welding residues, an industrial waste not previously characterized for this application, and palm kernel cake fibers, a Beninese agro-industrial by-product, incorporated into a compressed earth block matrix. Four Beninese lateritic soils (Zogbodomey, Dassa-Zoumè, Glazoué, and N'Dali), classified as CL according to the USCS, were characterized and then statically compacted using four formulations: a control mixture, 15% residual lime, 15% lime supplemented with 1% fibers, and 8% cement as a reference. Compressive strength was measured at 28 days on 48 specimens. Flexural strength, indirect

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tensile strength, and elastic modulus were also experimentally determined using three-point bending tests, Brazilian indirect tensile tests, and direct measurement of the elastic modulus under unconfined compression, respectively, on the standardized specimens described in the methodology (n = 3 per combination). Residual lime stabilization increases compressive strength by an average factor of 9.2 (from 0.17 to 1.60 MPa; two-way ANOVA, $F = 739.6$, $p < 0.001$), representing a gain comparable to those reported for other calcium-based residues applied to lateritic soils. The addition of 1% fibers moderately reduces compressive strength, with a highly variable effect depending on the soil (−3.0% in Dassa-Zoumè compared with −45.5% in Zogbodomey; statistically significant after adjustment only in Zogbodomey and N'Dali), while the mean flexural strength increases (+14.7% on average over the four soils; increase in three soils, decrease in Zogbodomey), a trend compatible with a crack-bridging effect that remains to be confirmed. In Dassa-Zoumè, the flexural strength of the lime plus fiber formulation is statistically indistinguishable from that of the 8% cement reference. Water resistance was not tested directly: the strength retention coefficients used are indicative values drawn from the literature. These results demonstrate the technical feasibility of a compressed earth block production pathway that valorizes two locally available residual streams, providing a potentially sustainable and economically accessible alternative (economic aspects remain to be confirmed) for construction in Benin and West Africa.

Keywords

Sustainable Construction, Compressed Earth Blocks, Laterite, Residual Lime, Palm Kernel Cake Fibers, Circular Economy

1. Introduction

The building sector is responsible for a considerable share of global resource consumption and greenhouse gas emissions. The production of Portland cement, the standard binder used in conventional construction, alone accounts for approximately 8 to 9% of anthropogenic CO_2 emissions [1], raising concerns about the long-term sustainability of cement-based construction, particularly in developing countries where housing demand is rapidly increasing. Compressed earth blocks (CEB), manufactured from lateritic soils that are widely available in West Africa, represent a credible alternative that requires less embodied energy and is compatible with artisanal and semi-industrial production systems. Their valorization, when it relies on local residual streams rather than virgin resources, fully aligns with the principles of the circular economy applied to construction: closing material loops between industrial and agro-industrial sectors and reducing unvalorized waste [2].

Raw laterite nevertheless exhibits limited mechanical strength and pronounced sensitivity to water, depending on its degree of weathering, thereby requiring sta-

bilization. Lime, along with cement, is one of the most extensively studied stabilizers for clayey soils. Its stabilizing action involves immediate cation exchange, which promotes the flocculation of clay particles and reduces plasticity, followed by a longer-term pozzolanic reaction between portlandite and the reactive silica and alumina present in the soil. This reaction leads to the formation of hydrated calcium silicates and aluminates, which contribute to cementation of the soil matrix [3]. Despite their effectiveness, conventional stabilizers involve significant import costs and carbon footprints in resource-constrained settings, highlighting the need to develop alternative stabilizers based on locally available resources.

Oxyacetylene welding residues, generated by a widely practiced artisanal process in West Africa, result from the hydrolysis of calcium carbide ($CaC_2 + 2H_2O \rightarrow C_2H_2 + Ca(OH)_2$), producing an alkaline residue with a high portlandite content, chemically analogous to calcium carbide residue (CCR), as documented in the international geotechnical literature. This calcium-rich industrial by-product has demonstrated its effectiveness as a stabilizing agent for fine-grained and lateritic soils [4] [5] and as a binder in non-load-bearing masonry units [6]. However, its use in West African lateritic soil matrices combined with fiber reinforcement has not yet been reported in the indexed scientific literature. In parallel, natural fiber reinforcement has been widely investigated as a means of mitigating shrinkage and cracking in stabilized earth materials. However, review studies indicate that the range of fiber resources investigated remains limited, with research largely focused on a few well-documented species, including sisal, coconut, and straw [7]. Palm kernel cake, a major by-product of the Beninese palm oil industry, represents a locally available source of lignocellulosic fibers that remains largely unexplored for earth construction applications.

A clear scientific gap therefore remains regarding the combined effects of industrial residual lime and palm kernel cake fibers on the physical and mechanical properties of compressed earth blocks. The present study aims to address this gap by experimentally evaluating, using four representative Beninese laterites, the influence of these two residual resources on compressive strength, complementary mechanical properties determined directly through dedicated tests, namely three-point bending, indirect tensile strength, and elastic modulus tests, as well as (indicatively, on the basis of literature values) the water resistance of CEBs produced according to an experimental design combining sampling site and formulation.

2. Materials and Methods

2.1. Lateritic Soils

Four lateritic soils were collected from three departments of Benin at depths ranging from 0.30 to 0.80 m after removal of the superficial organic horizon: Zogbodomey (Zou), Dassa Zoumè and Glazoué (Collines), and N'Dali (Borgou). These four sites, whose schematic locations are shown in **Figure 1**, were selected to cover contrasting geological settings, namely the southern sedimentary basin, the Precambrian basement in central Benin, and the Sudano-Sahelian setting in the

north, representative of the diversity of lateritic formations that can be used for CEB production at the national scale. The same four soils, sampled as part of a broader research program on the valorization of local residues for CEB stabilization, were also subjected to complementary quantitative mineralogical characterization by X-ray diffraction, as reported by Houehanou *et al.* [8]. The two studies therefore rely on a common set of materials and are intended to be complementary: the present study focuses on the geotechnical characterization and mechanical behavior of the CEBs, whereas the study by Houehanou *et al.* [8] focuses on the detailed mineralogical characterization of the soils and residual lime.

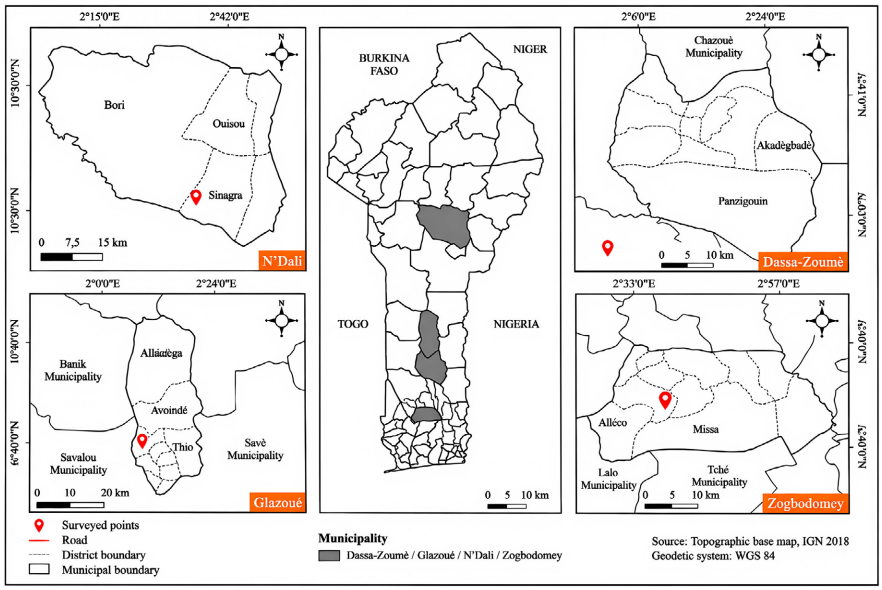

Figure 1. Schematic location map of the four lateritic soil sampling sites (schematic representation of relative positions within Beninese territory).

After air drying, crushing, and sieving through a 5 mm sieve, the soils were charac-terized by sieve particle size analysis (NF EN ISO 17892-4), Atterberg limits (NF EN ISO 17892-12), modified Proctor testing (NF P94-093), and soaked CBR testing at 95% of the modified Proctor optimum (NF EN 13286-47), with classification according to the USCS (ASTM D2487) and AASHTO (M145) systems. Table 1 summarizes the main geotechnical characteristics obtained, while the particle-size distribution curves and the modified Proctor curves of the four soils are presented in Figure 2 and Figure 3, respectively.

Table 1. Geotechnical characteristics of the four lateritic soils studied.

Parameter	Zogbodomey	Dassa-Zoumè	Glazoué	N'Dali
Liquid limit LL (%)	43.5	31.3	43.5	34.4
Plasticity index PI (%)	20.9	12.6	18.7	14.1
Optimum water content wOPM (%)	13.50	9.89	14.80	12.11

Continued

Maximum dry density ρd max (g/cm³)	1.86	1.99	1.87	1.97
Soaked CBR at 95% OPM (%)	9.44	11.46	9.14	13.18
USCS classification	CL	CL	CL	CL
AASHTO classification	A-7-6	A-6	A-7-6	A-6

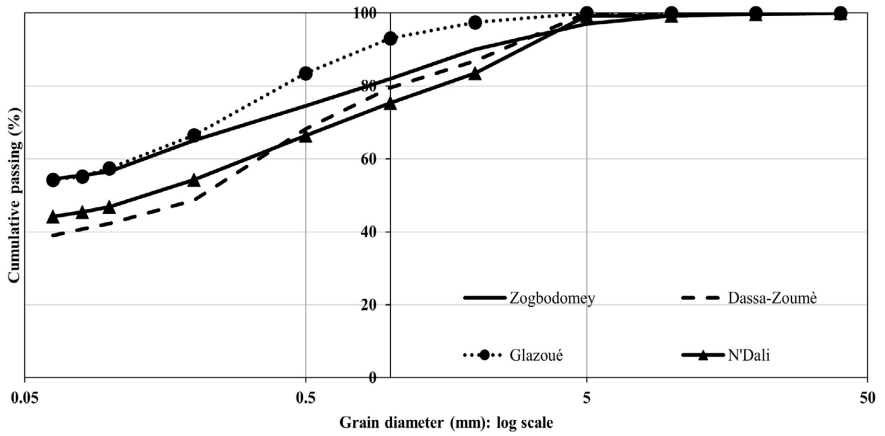

Figure 2. Particle-size distribution curves of the four lateritic soils studied (sieve analysis, NF EN ISO 17892-4).

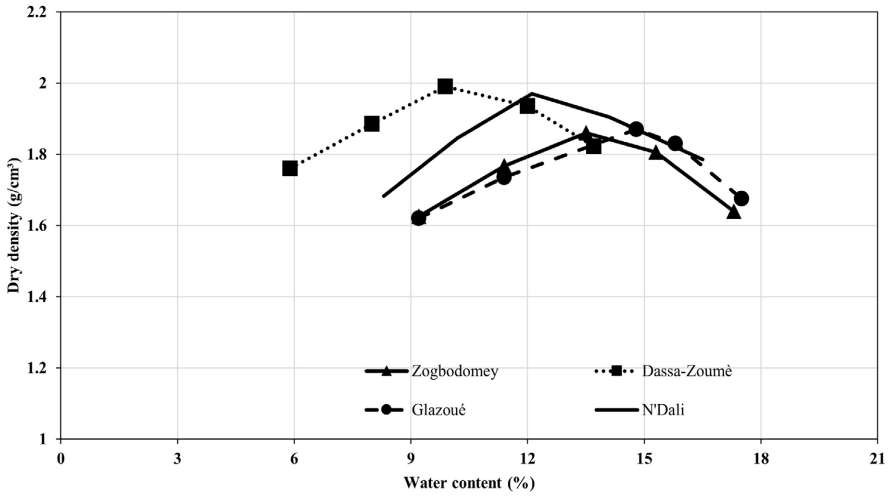

Figure 3. Comparative modified Proctor curves of the four lateritic soils (NF P94-093).

2.2. Lime Derived from Autogenous Welding Residues

The residual lime was collected by scraping the inner walls of acetylene generator cylinders in artisanal autogenous welding workshops in Abomey Calavi, Benin, after complete emptying (**Figure 4(a)**). The extracted powder was air-dried for 24 to 48 h, lightly hand-crushed, and then sieved, without thermal treatment or industrial mechanical grinding, in order to faithfully reproduce artisanal use condi-

tions (Figure 4(b)). A quantitative mineralogical characterization of the same material by X-ray diffraction coupled with Rietveld refinement was reported by Houehanou *et al.* [8] as part of the same experimental program. The analysis revealed a portlandite content of 85.4 ± 1.8%, a grossular fraction, an inert calcium aluminum garnet, of 10.3 ± 1.8%, and a quartz-rich fraction of 4.3 ± 0.2%, classifying the residue as a binder with a quality comparable to that of CL 70 to CL 90 industrial lime according to NF EN 459 1. However, the active CaO content of the residual lime, ranging from 35% to 60% depending on the batch, compared with 85% to 98% for industrial lime, requires an adjusted mass dosage. To provide an amount of CaO equivalent to a conventional dosage of 8% industrial lime, between 12% and 20.6% residual lime is required, depending on its purity. The fixed dosage of 15% adopted throughout the experimental program falls within this adjusted range.



a) Collection of lime in paste form b) Lime in powder form

Figure 4. Collection and preparation of the residual lime from autogenous-welding residues: a) sampling of the lime paste at the outlet of the acetylene generator; b) lime dried and reduced to powder after grinding and sieving.

2.3. Palm Kernel Cake Fibers

The Palm Kernel Cake (PKC) used in this study was obtained from the artisanal extraction of palm kernel oil from the kernels of oil palm nuts (Elaeis guineensis; Figure 5), a common practice in traditional oil mills in Benin (Figure 6). The collected cake was washed, oven-dried at 60˚C for 24 h, with a residual moisture content below 5%, then crushed and sieved. The retained fraction, passing through a 5 mm sieve and retained on a 0.5 mm sieve, corresponded to fiber lengths ranging from 0.5 to 5 mm. Its lignin content (15% to 25%), a phenolic polymer that is stable under moderately alkaline conditions, provides greater resistance to degradation in lime-treated environments than fibers with lower lignin contents, such as sisal. This property supports its selection as reinforcement for a lime-stabilized matrix [7].

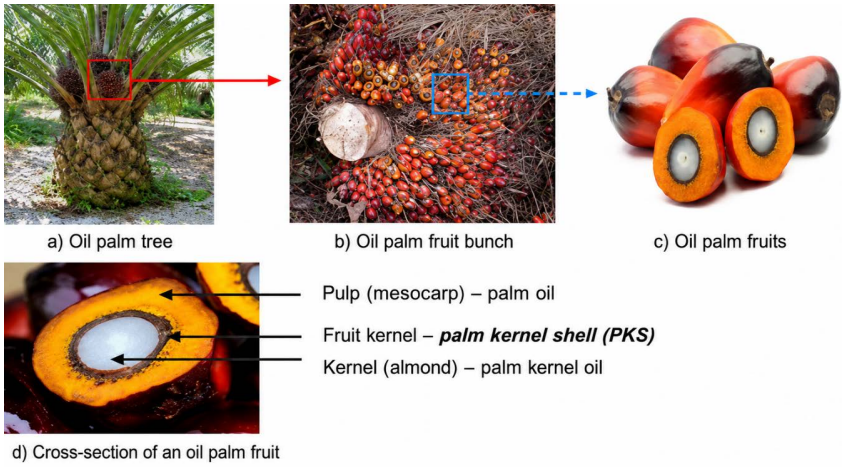

Figure 5. Anatomy of the oil palm fruit (Elaeis guineensis).



Figure 6. Artisanal extraction of palm kernel oil in a traditional Beninese oil mill, showing the pressing and manual kneading stage of the paste from which palm kernel cake is obtained after oil separation.

2.4. CEB Formulation, Coding, and Manufacturing

The experimental design combines the four soils with four fixed formulations applied identically to each soil: an unstabilized control, 15% residual lime, 15% residual lime supplemented with 1% palm kernel cake fibers, with the fiber dosage selected based on the optimal ranges of 0.25 to 1.5% reported for other short plant fibers incorporated into stabilized earth materials [9] [10], and 8% CEM II cement as a comparative reference (all dosages are expressed as a percentage of the dry mass of soil). This resulted in sixteen soils × formulation combinations. A coding system was established to unambiguously identify each combination and ensure traceability throughout the experimental program. Each code consists of a two-letter soil identifier (Zo, Da, Gl, Nd), a binder identifier and dosage (Ch15 for 15% residual lime, CI8 for 8% cement, with no binder code for the control), and, where applicable, a fiber dosage identifier (T1 for 1% palm kernel cake fibers). Thus, the code Gl Ch15 T1 designates a block manufactured from Glazoué soil, stabilized with 15% residual lime and reinforced with 1% palm kernel cake fibers (**Figure 7**). This coding system enabled the specimens to be unambiguously labeled and allocated to the different tests, including compressive strength, physical proper-

ties, and durability tests, throughout the experimental program.

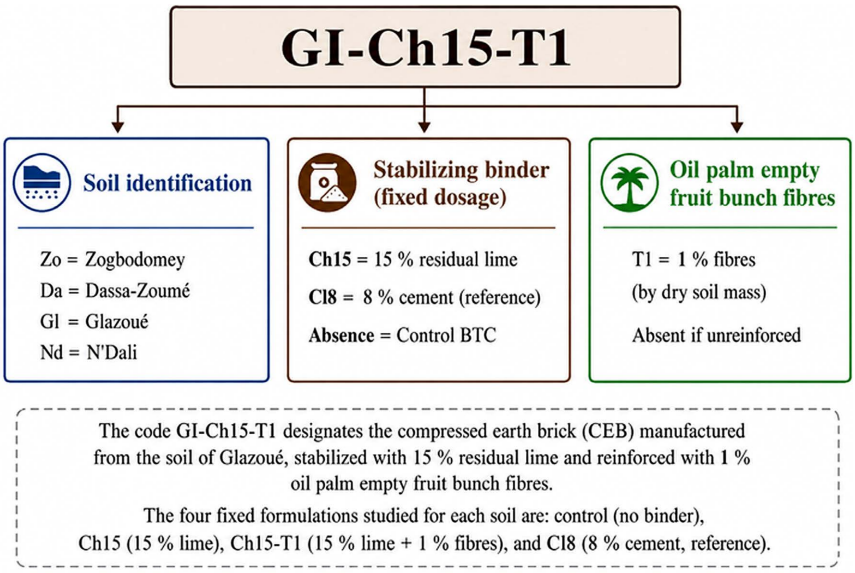

Figure 7. Diagram of the coding system used for the CEB formulations.

Full-size bricks were manufactured using a manual lever-operated CINVA Ram press (**Figure 8**), representative of the artisanal and semi-industrial presses commonly used for CEB production in West Africa. The press enabled the production of 40 × 20 × 10 cm bricks by static compaction in two layers. Laboratory specimens, consisting of cylinders 50 mm in diameter and 100 mm in height and prisms measuring 40 × 40 × 160 mm, were compacted separately using a force-controlled laboratory press (static compaction at an equivalent pressure of 4.0 MPa, held for 15 s) calibrated through pressure equivalence to reproduce the same degree of densification achieved in the full-size bricks. This condition was essential for extrapolating the mechanical results obtained from the laboratory specimens to the expected behavior of the actual bricks. In both cases, the material was introduced in two successive layers, each compacted individually, and then leveled to obtain a flat and smooth surface. A freshly demolded block is shown in **Figure 9**, and the chromatic and textural diversity of the blocks manufactured from the four soils is illustrated in **Figure 10**. The dry densities obtained ranged from 1.82 to 1.96 g/cm^3. The incorporation of 1% fibers reduced the mean dry density by 2.5 to 4.0% depending on the soil, owing to the low specific gravity of the lignocellulosic fibers.

All sixteen combinations were compacted at the optimum moisture content determined by the Proctor test for each soil (determined on the untreated soil) and then cured for 28 days before testing under a sealed film in a controlled chamber at 27 ± 2˚C and 85 ± 5% relative humidity. Using the optimum moisture content of the untreated soil for all stabilized mixtures is a practical simplification. Because the hydration of lime consumes water, and because the fibers also absorb water, the true optimum moisture content of the stabilized mixtures is slightly higher (by

approximately 1.5 to 2.2%). The mixtures were therefore compacted slightly on the dry side of their own optimum, so that the strengths reported are more likely to be conservative than overestimated. This remains to be verified by Proctor tests on the stabilized mixtures (see Section 3.8).



Figure 8. Manual lever press used for on-site compaction of the compressed earth blocks.



Figure 9. Compressed earth block freshly demolded.



Figure 10. Chromatic and textural diversity of the compressed earth blocks manufactured from the four lateritic soils studied.

2.5. Testing Program

Unconfined compressive strength was measured in accordance with XP P13 901 [11] on three cylindrical specimens per combination (n = 48 in total). Three-point flexural strength was experimentally determined using the 40 × 40 × 160 mm prismatic specimens described in Section 2.4 (n = 3 per combination), following a three-point bending protocol analogous to that used for compression, with simple support (span S = 100 mm) and midspan loading at a constant displacement rate of 0.5 mm/min until failure. Indirect tensile strength was experimentally determined using the Brazilian splitting test on the 50 × 100 mm cylindrical specimens (n = 3 per combination), loaded diametrically until failure. The elastic modulus was experimentally determined from the slope of the linear portion of the stress-strain curve recorded during the unconfined compression test on the same cylindrical specimens (the axial strain was determined directly from the crosshead displacement recorded by the LVDT displacement transducer integrated in the control unit of the press, assuming a constant initial specimen height of 100 mm). These testing campaigns therefore involved a total of 96 additional specimens (48 prisms for the flexural tests and 48 cylinders for the Brazilian tests) beyond the 48 compression specimens, the elastic modulus being derived from the compression tests themselves. Indirect tensile strength was calculated as $Rt = 2P/(\pi DL)$, where P is the breaking load and D and L are the diameter and length of the cylinder, and flexural strength as $Rf = 3PS/(2bd^2)$, where S is the support span and b and d are the width and depth of the prism. All Rt, Rf and E values were measured and recorded individually for each specimen. The individual breaking loads and the corresponding Rt, Rf and E values are provided in the Appendix (**Tables A1-A3**). Water resistance was not measured experimentally; it is described by indicative values of a strength retention coefficient, defined as the ratio of wet-state compressive strength to dry-state compressive strength, taken from the literature for formulations with comparable binder and reinforcement characteristics, since no direct immersion test was conducted on the sixteen formulations investigated in the present study. This point is addressed as a limitation of the study in Section 3.8.

2.6. Statistical Analysis

A two-way analysis of variance (ANOVA) with crossed factors (soil × formulation) was conducted on the compressive strength results at a 95% confidence level ($\alpha = 0.05$), followed by a Tukey post hoc multiple comparison test (HSD) to identify pairs of formulations that differed statistically. All analyses were performed using R software (v.4.3). Because the soil × formulation interaction was significant, the comparison between the 15% lime and the 15% lime + 1% fiber formulations was also carried out separately for each soil, using the pooled residual mean square of the ANOVA (MS = 0.011; 32 degrees of freedom), with a Bonferroni adjustment for the four soil-specific comparisons (family-wise $\alpha = 0.05$); 95% family-wise confidence intervals are reported for the differences. For

flexural strength, the lime plus fiber and cement formulations were compared for the Dassa-Zoumè soil with a two-sample Student's t-test (three specimens per group); the other flexural, tensile and modulus comparisons are descriptive. With n = 3 per group, a non-significant difference does not establish equivalence.

3. Results and Discussion

3.1. Geotechnical Properties of the Soils

All four soils are classified as CL (inorganic clay of low to medium plasticity) according to the USCS, with moderate and contrasting plasticity indices, increasing from Dassa-Zoumè (PI = 12.6%) to Zogbodomey (PI = 20.9%) (**Table 1**). These values are consistent with the ranges reported for West African ferralitic soils (LL: 25 to 60%; PI: 10 to 30%) [12]. The maximum Proctor dry densities (1.86 to 1.99 g/cm^3, **Figure 3**) show little variation among the soils (coefficient of variation of 3.5%), indicating that the four materials belong to the same family of plateau ferralitic laterites. In contrast, the soaked CBR values (9.1 to 13.2%) remain relatively low for direct road applications, which is not a limiting factor in the context of their use for stabilized CEBs, where the CBR bearing capacity of the raw soil is not the governing criterion.

A complementary quantitative mineralogical characterization of these same four soils by X ray diffraction and Rietveld refinement, reported by Houehanou *et al.* [8] as part of the same research program, identifies three typical mineralogical profiles that are directly used to interpret the mechanical results presented below: a "pure quartz feldspar" profile (Dassa-Zoumè, Zogbodomey), characterized by high intrinsic granular strength but low pozzolanic reactivity; a "goethite dominant" profile (Glazoué, 12.0% goethite), characterized by high natural ferruginous cohesion; and a "kaolinite feldspar" profile (N'Dali, 26% exclusive kaolinite 1A), which exhibits the highest reactivity under alkaline conditions.

3.2. Unconfined Compressive Strength

The effect of stabilization is substantial and unambiguous (**Table 2**, **Figure 11**). Across all soils, the mean compressive strength of the control CEBs is only 0.17 MPa, compared with 1.60 MPa for the CEBs stabilized with 15% residual lime (factor of 9.2), 1.31 MPa for the lime plus fiber CEBs (factor of 7.5), and 2.09 MPa for the reference cement CEBs (factor of 12.0). These magnitudes are consistent with the literature on calcium-based stabilization of lateritic soils [3] [13] and confirm that the recycled industrial origin of the lime investigated, rather than its commercial origin, does not compromise its stabilizing effectiveness. This finding is consistent with the performance reported for carbide lime applied to comparable lateritic soils [4] [5] and for non-load-bearing masonry units manufactured from the same type of calcium-based residue [6].

Table 2. Simple compressive strength of the CEBs at 28 days, mean ± standard deviation (n = 3 per combination).

Soil	Formulation	Mean Rc (MPa)	Std. dev. (MPa)	Variation vs. control
Zogbodomey	Control	0.17	0.02	---
	15% residual lime	1.49	0.08	×8.8
	15% lime + 1% fibers	0.81	0.15	−45.5% vs. lime alone
	8% cement (ref.)	2.08	0.13	×12.2
Dassa-Zoumè	Control	0.20	0.05	---
	15% residual lime	1.64	0.15	×8.2
	15% lime + 1% fibers	1.59	0.14	−3.0% vs. lime alone
	8% cement (ref.)	2.20	0.09	×11.0
Glazoué	Control	0.18	0.01	---
	15% residual lime	1.74	0.10	×9.7
	15% lime + 1% fibers	1.56	0.13	−10.1% vs. lime alone
	8% cement (ref.)	2.03	0.10	×11.3
N'Dali	Control	0.14	0.01	---
	15% residual lime	1.54	0.11	×11.0
	15% lime + 1% fibers	1.28	0.12	−16.7% vs. lime alone
	8% cement (ref.)	2.05	0.09	×14.6

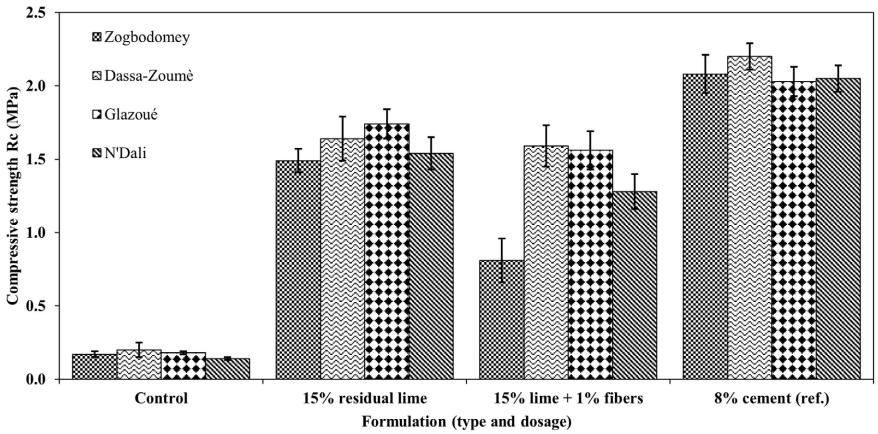

Figure 11. Simple compressive strength of the CEBs at 28 days, by formulation and by soil (error bars: standard deviation, n = 3).

Site-specific analysis reveals marked heterogeneity in the response to fiber reinforcement: the reduction in compressive strength induced by the addition of 1% fibers at a constant lime dosage ranges from −3.0% for Dassa-Zoumè to −45.5% for Zogbodomey, with intermediate values of −10.1% for Glazoué and −16.7% for N'Dali. This heterogeneity is consistent with the classical mechanism whereby fibers introduce local discontinuities and reduce the compaction density achievable during compaction, an effect that becomes more pronounced as the soil becomes finer and more plastic [9] [10] [14] [15]. However, the measured reduction in dry

density (2.5 to 4.0%, Section 2.4) is modest and is unlikely, by itself, to account for the largest strength losses; other mechanisms, such as the water absorbed by the fibers, which is then unavailable for compaction and for the lime reactions, may also contribute. These explanations are hypotheses that the present study does not test directly. It also finds possible complementary mineralogical support in the X-ray diffraction characterization: the Zogbodomey soil, devoid of crystalline kaolinite and rich in muscovite (12.4%, the highest value among the four soils), may exhibit preferential cleavage planes that weaken an already poorly cohesive matrix in the absence of reactive clay, whereas the Dassa-Zoumè soil, combining a resistant quartz-rich skeleton with moderate ferruginous cohesion (9.4% goethite), tolerates fiber incorporation considerably better [8]. After statistical adjustment, the fiber-induced reduction is significant only for Zogbodomey and N'Dali (Section 3.6). Despite its exceptionally high content of reactive kaolinite (26%), the N'Dali soil exhibits the lowest control strength among the four soils. A tentative interpretation is that the same clay reactivity that favors pozzolanic cementation after stabilization may result, in the raw state, in a behavior unfavorable to the compaction of the unstabilized control.

All stabilized formulations exceed the 1 MPa threshold generally adopted as the minimum compressive strength for CEBs intended for load-bearing masonry in conventional low-rise buildings, with the exception of the lime plus fiber formulation for the Zogbodomey soil (0.81 MPa), which nevertheless remains suitable for non-load-bearing applications. The selected dosage of 15% residual lime, which is higher than the 6% to 10% range commonly recommended for industrial lime in temperate clayey soils [3], remains consistent with the upper range (15% to 25%) reported for lateritic soils with low clay reactivity treated with calcium-based or low dosage hydraulic binders [13].

3.3. Indirect Tensile Strength (Brazilian Test)

The indirect tensile strength, experimentally measured using the Brazilian test on three cylindrical specimens per combination, is presented for all sixteen soils × formulation combinations in **Table 3** and **Figure 12**, together with the ratio Rt/Rc between the tensile and compressive strengths.

Table 3. Indirect tensile strength (Brazilian test) of the CEBs at 28 days, mean ± standard deviation (n = 3 per combination), and ratio Rt/Rc.

Soil	Formulation	Mean Rt (MPa)	Std. dev. (MPa)	Rt/Rc
Zogbodomey	Control	0.019	0.003	0.112
	15% residual lime	0.154	0.012	0.103
	15% lime + 1% fibers	0.112	0.018	0.138
	8% cement (ref.)	0.198	0.015	0.095
Dassa-Zoumè	Control	0.022	0.004	0.110

Continued

	15% residual lime	0.171	0.014	0.104
	15% lime + 1% fibers	0.206	0.018	0.130
	8% cement (ref.)	0.228	0.011	0.104
Glazoué	Control	0.016	0.002	0.089
	15% residual lime	0.168	0.011	0.097
	15% lime + 1% fibers	0.198	0.016	0.127
	8% cement (ref.)	0.211	0.013	0.104
N'Dali	Control	0.015	0.003	0.107
	15% residual lime	0.148	0.013	0.096
	15% lime + 1% fibers	0.162	0.014	0.127
	8% cement (ref.)	0.201	0.010	0.098

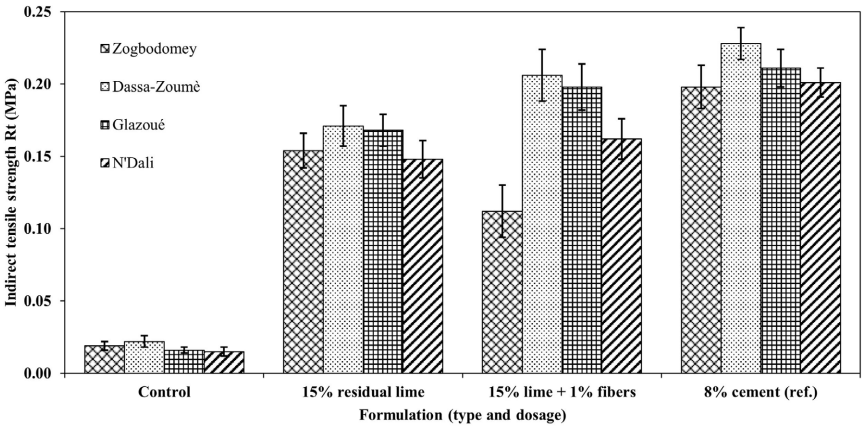

Figure 12. Indirect tensile strength (Brazilian test) measured by formulation and by soil.

The mean indirect tensile strength ranges from 0.015 MPa for the control CEBs to 0.228 MPa for the cement-stabilized CEBs. The mean breaking loads of the Brazilian tests range from 0.12 kN (control, N'Dali) to 1.79 kN (cement, Dassa-Zoumè); the individual values are provided as Supplementary Material. The CEBs stabilized with residual lime exhibit a mean tensile strength of 0.160 MPa, compared with 0.170 MPa for the lime plus fiber formulation, which therefore shows a slightly higher mean (about +6%) than lime alone despite its lower compressive strength. This average masks contrasting behaviors: the lime plus fiber formulation is higher than lime alone in three soils (about +10% to +20%) and lower in Zogbodomey (−27%). These results are compatible with a crack bridging effect of the palm kernel cake fibers [15], a hypothesis that the present data (peak loads only) do not allow to confirm; the effect is most visible for the Dassa-Zoumè soil (0.206 MPa for lime plus fibers compared with 0.171 MPa for lime alone). The Rt/Rc ratio lies between 0.09 and 0.11 for the control, lime and cement formulations, and between 0.13 and 0.14 for the lime plus fiber formulation. These values, ranging from approximately 0.015 to 0.23 MPa, remain consistent with the struc-

turally low tensile-to-compressive strength ratio (on the order of 1:10) reported for earthen materials, which practically justifies the use of construction measures that limit tensile stresses in masonry elements (tie beams, setbacks, and limitations on slenderness).

3.4. Three-Point Flexural Strength

The three-point flexural strength, experimentally measured using prismatic specimens, is presented for all sixteen soils × formulation combinations in Table 4 and Figure 13.

Table 4. Three-point flexural strength of the CEBs at 28 days, mean ± standard deviation (n = 3 per combination).

Soil	Formulation	Mean Rf (MPa)	Std. dev. (MPa)
Zogbodomey	Control	0.035	0.005
	15% residual lime	0.298	0.016
	15% lime + 1% fibers	0.228	0.041
	8% cement (ref.)	0.416	0.027
Dassa-Zoumè	Control	0.041	0.011
	15% residual lime	0.327	0.031
	15% lime + 1% fibers	0.444	0.040
	8% cement (ref.)	0.440	0.018
Glazoué	Control	0.036	0.001
	15% residual lime	0.348	0.020
	15% lime + 1% fibers	0.438	0.037
	8% cement (ref.)	0.406	0.020
N'Dali	Control	0.028	0.003
	15% residual lime	0.308	0.023
	15% lime + 1% fibers	0.360	0.032
	8% cement (ref.)	0.409	0.018

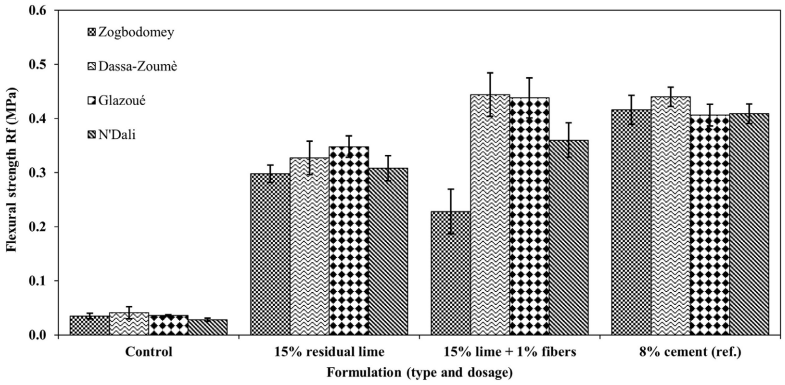

Figure 13. Three-point flexural strength measured by formulation and by soil.

Flexural strengths range from 0.028 MPa for the unstabilized controls to approximately 0.44 MPa, with the highest mean value obtained by the lime plus fiber formulation for the Dassa-Zoumè soil (0.444 MPa), marginally above the cement formulation for the same soil (0.440 MPa); this difference is not statistically significant (Student's t-test, p = 0.88; 95% confidence interval of the difference [−0.07; +0.07] MPa), values that are consistent with those commonly measured experimentally for CEBs (0.1 to 1.0 MPa). Notably, the lime plus fiber formulation exhibits a higher mean flexural strength (0.367 MPa), 14.7% greater than that of the lime-only formulation (0.320 MPa), despite its lower compressive strength. This increase is not uniform: it is observed in three soils (+17% in N'Dali, +26% in Glazoué and +36% in Dassa-Zoumè), whereas a decrease of 24% is observed in Zogbodomey. These differences are descriptive (n = 3; no formal test was performed). This behavior may be explained by the difference in failure mechanisms between the two loading modes: under compression, failure is governed by crushing and lateral spalling of the matrix, which is relatively insensitive to low fiber dosages, whereas under flexural loading, failure results from a tensile crack that the randomly oriented fibers may help to slow by carrying part of the load after crack initiation [10] [15]. This crack bridging mechanism is a hypothesis compatible with the results; the peak loads measured here do not document the post-cracking behavior. This improvement is particularly pronounced for the Dassa-Zoumè soil, where the flexural strength of the lime plus fiber formulation is statistically indistinguishable from that of the reference cement formulation (p = 0.88). With only three specimens per group, this indicates comparable performance within the resolution of the test, not demonstrated equivalence. It nevertheless suggests that, for this soil, 1% of palm kernel cake fibers could provide flexural performance close to that of 8% cement without any Portland cement, which would be of interest for elements subjected to flexural loading (lintels, roofing elements), subject to confirmation, in soils that are more tolerant of fiber incorporation.

3.5. Elastic Modulus

The elastic modulus, determined from the slope of the linear elastic portion of the stress-strain curve obtained during the unconfined compression tests, is presented for all sixteen soils × formulation combinations in **Table 5** and **Figure 14**.

Table 5. Elastic modulus of the CEBs at 28 days, mean ± standard deviation (n = 3 per combination).

Soil	Formulation	Mean E (MPa)	Std. dev. (MPa)
Zogbodomey	Control	52	7
	15% residual lime	447	23
	15% lime + 1% fibers	207	37
	8% cement (ref.)	624	40

Continued

Dassa-Zoumè	Control	61	16
	15% residual lime	491	46
	15% lime + 1% fibers	405	36
	8% cement (ref.)	660	26
Glazoué	Control	54	2
	15% residual lime	522	30
	15% lime + 1% fibers	399	33
	8% cement (ref.)	608	30
N'Dali	Control	43	4
	15% residual lime	462	34
	15% lime + 1% fibers	327	29
	8% cement (ref.)	614	27

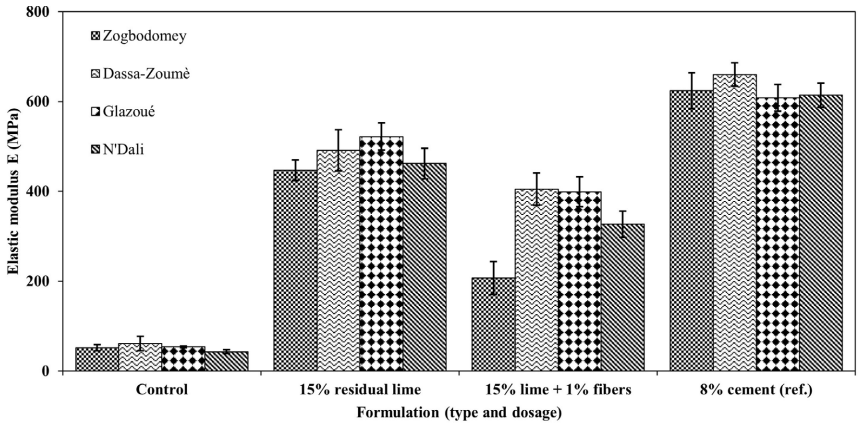

Figure 14. Elastic modulus measured by formulation and by soil.

The elastic moduli range from 43 MPa for the unstabilized control CEBs to 660 MPa for the cement-stabilized CEBs, with a mean value of 481 MPa for the residual lime-stabilized formulation and 335 MPa for the residual lime plus fiber-stabilized formulation. These values fall within the lower to intermediate range of the 400 to 2000 MPa values commonly reported for stabilized CEBs, which is consistent with the relatively modest compressive strength levels (<2.3 MPa) measured in the present study compared with highly stabilized CEBs (5% to 10% cement) reported in the literature. The reduction in elastic modulus observed for the residual lime plus fiber stabilized formulation relative to the residual lime stabilized formulation (−30.4%, proportionally greater than the 18.1% decrease in compressive strength) indicates a lower stiffness of the fiber-reinforced matrix. This is compatible with a greater ductility imparted by the fibers, a property generally sought to improve the post-cracking behavior of earthen masonry elements [9]; however, a lower modulus does not by itself demonstrate ductility, which would require documenting the deformation capacity and the post-cracking be-

havior (see Section 3.8). In addition, since the axial strain was derived from the crosshead displacement and not measured on the specimen, the values of E are apparent moduli that include the compliance of the loading system and end effects; they are likely to underestimate the intrinsic stiffness and are best used to compare formulations rather than as design values.

3.6. Statistical Analysis

The analysis of variance decomposes the total variability in the compressive strength results into several sources, each characterized by the following indicators. The sum of squares (SS) measures the portion of the total variability attributable to a given source (soil, formulation, their interaction, or residual error), calculated as the sum of the squared deviations between the observed values and the overall mean. The degrees of freedom (df) correspond to the number of independent comparisons associated with each source, equal to the number of factor levels minus one for a single factor, and to the product of the degrees of freedom of the two factors for their interaction. The ratio of SS to df gives the mean square (MS), which represents the variability per unit of comparison. The F statistic (Fisher's test) is the ratio of the mean square of a given source to the mean square of the residual error (the unexplained experimental "noise"): the higher the F value, the more strongly the effect of the factor considered dominates the natural variability among specimens. Finally, the p value indicates the probability of observing, under the hypothesis of no true effect, an F value at least as large as that measured; a p value below the 0.05 threshold leads to rejection of this hypothesis and supports the conclusion that the factor has a statistically significant effect.

Applied to compressive strength (**Table 6**), this decomposition confirms that the "formulation" factor has by far the most dominant effect ($F = 739.6$; $p < 10^{-28}$), accounting for approximately 93% of the total variance in the results. The "soil" factor also has a statistically significant effect, but its magnitude is substantially smaller ($F = 16.9$; $p < 0.001$), while the soil × formulation interaction is also significant ($F = 8.22$; $p < 0.001$), statistically confirming the intersoil heterogeneity in the response to fiber reinforcement described in Section 3.2. The Tukey post hoc test confirms that the four formulations differ statistically from one another in all pairwise comparisons ($p < 0.05$ for all six comparisons), including the lime versus lime plus fiber pair, for which the difference is the smallest (0.29 MPa) but remains statistically significant ($p = 0.0038$). This pooled comparison reflects the average effect of the fibers over the four soils. Given the significant interaction, the soil-specific comparisons are given in **Table 7**: after Bonferroni adjustment, the reduction in compressive strength caused by 1% fibers is statistically significant only for Zogbodomey (difference = −0.68 MPa; 95% CI [−0.90; −0.46]; $p < 0.001$) and N'Dali (−0.26 MPa; 95% CI [−0.48; −0.04]; adjusted $p = 0.017$), and not for Glazoué (−0.18 MPa; 95% CI [−0.40; +0.04]; adjusted $p = 0.16$) or Dassa-Zoumè (−0.05 MPa; 95% CI [−0.27; +0.17]; adjusted $p = 1.00$). The significant average effect is therefore driven mainly by Zogbodomey and N'Dali. With $n = 3$

per combination, the non-significant results indicate that no effect could be detected, not that no effect exists.

Table 6. Results of the two-way analysis of variance (ANOVA) on the compressive strength of the CEBs.

Source of variation	SS	df	Mean square	F	p
Soil	0.544	3	0.181	16.92	9.2×10^{-7}
Formulation	23.774	3	7.925	739.58	1.3×10^{-29}
Soil × Formulation	0.793	9	0.088	8.22	3.3×10^{-6}
Residuals	0.343	32	0.011	-	-

Table 7. Soil-specific comparison of compressive strength between 15% lime + 1% fibers and 15% lime alone (difference = fibers minus lime; 95% family-wise confidence intervals and Bonferroni-adjusted p values, from the residual mean square of Table 6).

Soil	Difference (MPa)	95% confidence interval (MPa)	Adjusted p
Zogbodomey	−0.68	[−0.90; −0.46]	<0.001
Dassa-Zoumè	−0.05	[−0.27; +0.17]	1.00
Glazoué	−0.18	[−0.40; +0.04]	0.16
N'Dali	−0.26	[−0.48; −0.04]	0.017

3.7. Durability

The strength retention coefficient (ratio of wet compressive strength to dry compressive strength, Table 8, Figure 15) is given here as an indicative value. As noted in Section 2.5, this coefficient was not measured on the formulations investigated in the present study (no immersion test was conducted); it was established by analogy with comparable formulations reported in the literature on earth bricks stabilized with calcium-based binders [11] [16], in which the coefficient was obtained as the ratio between the compressive strength of specimens tested in the wet state, after immersion in water for 2 h, and that of oven-dried specimens of the same age, according to the wet-strength procedure referring to the XP P13-901 standard [11] (specimens cured for 45 days in [16], compared with 28 days in the present program). The values adopted therefore describe the trends expected from the literature rather than results of this study, and must be confirmed by immersion tests and wetting-drying cycles conducted directly on these formulations (see limitations, Section 3.8). The same protocol (28 days of curing, then immersion in water for 2 h, compared with dry specimens of the same age) will be applied in these confirmatory tests. The expected trend is an improvement of the water resistance with stabilization: the unstabilized control CEBs, which already exhibit low dry compressive strength, are expected to be highly sensitive to water (coefficient of 0.25), consistent with the typical behavior of unstabilized raw earth. Stabilization with residual lime is expected to improve this behavior (coef-

ficient of 0.65) through progressive pozzolanic cementation, which may densify the matrix and reduce its capillary porosity [3]. The addition of fibers, which are inherently hygroscopic, would slightly reduce this coefficient (0.60), while possibly limiting the propagation of shrinkage cracks. The cement-stabilized formulation is expected to exhibit the highest intrinsic durability (0.80). These trends are consistent with the low relative swelling values measured for the raw soils in the soaked CBR test (0.03 to 0.08%), which indicate limited clay activity and favorable volumetric stability for the four soils investigated; they do not, however, replace direct water resistance tests.

Table 8. Strength-retention coefficient (wet Rc/dry Rc) of the four CEB formulations (indicative values taken from the literature, not measured directly on the formulations studied; the absorption classes are likewise literature-based—see Section 3.8).

Formulation	Wet Rc/Dry Rc	Absorption class
Unstabilized control	0.25	High (>15%)
15% residual lime	0.65	Moderate (8% - 12%)
15% lime + 1% fibers	0.60	Moderate to high (10% - 14%)
8% cement (ref.)	0.80	Low (5% - 8%)

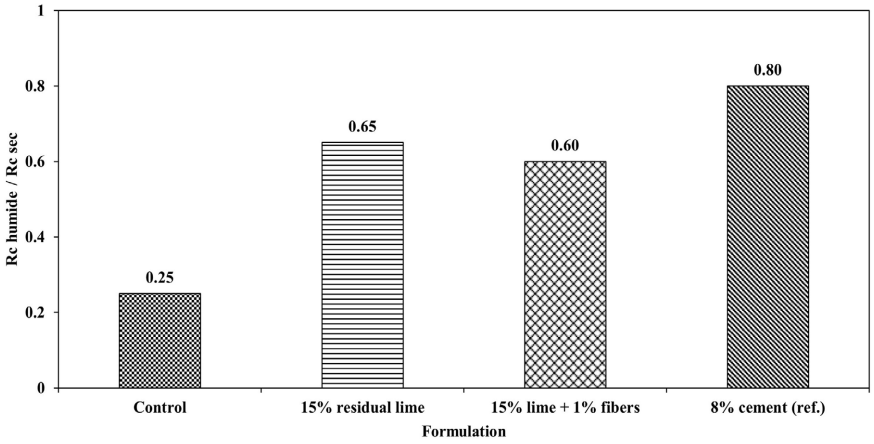

Figure 15. Strength-retention coefficient (wet Rc/dry Rc) of the four CEB formulations.

3.8. General Discussion

The overall results confirm that lime derived from autogenous welding residues, although originating from recycled industrial waste and having a lower purity than commercial lime, constitutes an effective stabilizer for the Beninese laterites investigated, with compressive strength gains (factors of 7.5 to 9.2) fully comparable to those reported for other calcium-based residues applied to comparable lateritic soils [4] [5] and for lateritic soils treated with conventional calcium-based binders [17], as well as for masonry applications manufactured from analogous calcium-based residues [6]. This effectiveness is consistent with the classical mechanisms of calcium-based stabilization, namely immediate cation exchange

followed by a delayed pozzolanic reaction [3], and is further supported by the highly active portlandite content (85.4%) and the fine crystallite size (220 to 255 Å, favorable for a high specific surface area) measured within the same research program on the same material [8].

The effect of palm kernel cake fibers illustrates the classical tradeoff between compressive strength and flexural behavior characteristic of fiber-reinforced composite materials, which has already been extensively documented for other short plant fibers incorporated into earthen materials [7] [9] [10] [14] [15], but with an intensity that strongly depends on the mineralogical and textural characteristics of the host soil. This finding highlights the methodological value of a multi-soil approach for designing optimized formulations of stabilized CEBs, rather than simply transferring an optimal dosage from one soil to another. The residual lime-only formulation appears to provide the best performance-durability compromise among the non-cement formulations investigated for load-bearing masonry applications, durability being assessed here only indicatively. The lime plus fiber formulation appears to offer potential advantages for non-load bearing elements subjected to flexural loading, particularly for soils that are more tolerant of fiber incorporation, while simultaneously valorizing a second local residual stream and strengthening the integration of this production pathway within a circular economy framework [2].

This study has several limitations that should be acknowledged. Flexural strength, indirect tensile strength, and elastic modulus were measured experimentally, with these measurements based on three specimens per combination; a larger number of replicates and continuous instrumented monitoring (extensometry) would allow a more refined characterization of data dispersion and post-cracking behavior, and would make it possible to document the deformation capacity required to confirm any gain in ductility. In the present study, the axial strain was derived from the crosshead displacement (LVDT of the press) and not measured on the specimen, so that the moduli reported are apparent moduli. All mixtures were compacted at the optimum moisture content of the untreated soil (Section 2.4), and the optimum of the stabilized mixtures was not determined. In addition, the water strength retention coefficient, established by analogy with the literature, should be confirmed through capillary absorption tests and wetting-drying cycles conducted directly on the sixteen formulations. The mechanisms invoked in this study (crack bridging, mineralogical control of the response to fibers, increased ductility) are hypotheses compatible with the results; they were not tested directly, for example by microstructural observation. Finally, a life cycle assessment comparing this pathway with cement-stabilized CEBs and commercial lime-stabilized CEBs would make it possible to accurately quantify the environmental benefits of the proposed dual valorization approach and to document more rigorously the economic accessibility of this pathway, which at this stage remains a plausible hypothesis rather than a result demonstrated by the present study.

4. Conclusion

This study experimentally evaluated, for the first time, the potential for the combined valorization of residual lime derived from autogenous welding and palm kernel cake fibers for the stabilization of compressed earth blocks based on four Beninese laterites. Stabilization with 15% residual lime increased the compressive strength of the CEBs by an average factor of 9.2 (ANOVA, $F = 739.6$; $p < 0.001$), representing a statistically robust effect comparable to the performance reported in the literature for other industrial calcium-based residues applied to lateritic soils. The addition of 1% palm kernel cake fibers moderately reduced compressive strength, with marked heterogeneity depending on the soil (from −3.0% to −45.5%; significant after adjustment only for Zogbodomey and N'Dali), a heterogeneity possibly related to the mineralogy of the granular skeleton (hypothesis), but raised the mean flexural strength by 14.7% on average (in three of the four soils), in a manner compatible with a crack bridging effect that remains to be confirmed. In Dassa-Zoumè, the flexural strength of the lime plus fiber formulation was statistically indistinguishable from that of the 8% cement reference ($n = 3$). These results suggest the relevance of this reinforcement for non-load-bearing elements subjected to flexural loading, which remains to be confirmed.

These results demonstrate the technical feasibility of a compressed earth block production pathway that simultaneously valorizes a local industrial waste and an agro-industrial by-product, offering the potential for a sustainable alternative, to be confirmed from an economic perspective, and suited to the tropical climatic context for construction in Benin and West Africa. Future research should include direct confirmation of the water strength retention coefficient through immersion tests conducted on the sixteen formulations, instrumented tests (extensometry) to document the deformation capacity and post-cracking behavior of the fiber-reinforced formulations, cross optimization of lime and fiber dosages in light of the observed intersoil variability, and a life cycle assessment of this residual valorization pathway.

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Author Contributions

Ernesto Cabral Houehanou: [Conceptualization, Methodology and Writing—original draft]; **Jonas Kassaidja:** [Investigation and Methodology]; **Judicael Koffi Agbellele:** [Investigation and Visualization]; **Ramdane Tchao:** [Data curation, Investigation]; **Edmond Codjo Adjovi:** [Supervision].

Supplementary Material

Individual specimen records for the Brazilian tensile, three-point flexural and elastic modulus tests (breaking loads and the resulting individual strength and elastic modulus values for each specimen) are provided in the Appendix (**Tables A1-A3**).

Conflicts of Interest

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

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Appendix: Individual Specimen Data (Tables A1-A3)

Tables A1-A3 report the individual results (n = 3 per soil × formulation combination) of the Brazilian splitting, three-point bending and elastic modulus tests. The means and standard deviations (sample standard deviation) are those reported in Tables 3-5.

Table A1. Individual breaking loads P (kN) and indirect tensile strength Rt (MPa) (Brazilian splitting test, cylinder D = 50 mm, L = 100 mm; Rt = 2P/(πDL)).

Soil	Formulation	Specimen 1 P (kN)/Rt (MPa)	Specimen 2 P (kN)/Rt (MPa)	Specimen 3 P (kN)/Rt (MPa)	Mean Rt (MPa)	Std. dev. (MPa)
Zogbodomey	Control	0.126/0.016	0.149/0.019	0.173/0.022	0.019	0.003
	15% residual lime	1.115/0.142	1.210/0.154	1.304/0.166	0.154	0.012
	15% lime + 1% fibers	0.738/0.094	0.880/0.112	1.021/0.130	0.112	0.018
	8% cement (ref.)	1.437/0.183	1.555/0.198	1.673/0.213	0.198	0.015
Dassa-Zoumè	Control	0.141/0.018	0.173/0.022	0.204/0.026	0.022	0.004
	15% residual lime	1.233/0.157	1.343/0.171	1.453/0.185	0.171	0.014
	15% lime + 1% fibers	1.477/0.188	1.618/0.206	1.759/0.224	0.206	0.018
	8% cement (ref.)	1.704/0.217	1.791/0.228	1.877/0.239	0.228	0.011
Glazoué	Control	0.110/0.014	0.126/0.016	0.141/0.018	0.016	0.002
	15% residual lime	1.233/0.157	1.319/0.168	1.406/0.179	0.168	0.011
	15% lime + 1% fibers	1.429/0.182	1.555/0.198	1.681/0.214	0.198	0.016
	8% cement (ref.)	1.555/0.198	1.657/0.211	1.759/0.224	0.211	0.013
N'Dali	Control	0.094/0.012	0.118/0.015	0.141/0.018	0.015	0.003
	15% residual lime	1.060/0.135	1.162/0.148	1.264/0.161	0.148	0.013
	15% lime + 1% fibers	1.162/0.148	1.272/0.162	1.382/0.176	0.162	0.014
	8% cement (ref.)	1.500/0.191	1.579/0.201	1.657/0.211	0.201	0.010

Table A2. Individual breaking loads P (N) and flexural strength Rf (MPa) (three-point bending test, prism 40 × 40 × 160 mm, span S = 100 mm; Rf = 3PS/(2bd²)).

Soil	Formulation	Specimen 1 P (N)/Rf (MPa)	Specimen 2 P (N)/Rf (MPa)	Specimen 3 P (N)/Rf (MPa)	Mean Rf (MPa)	Std. dev. (MPa)
Zogbodomey	Control	12.8/0.030	14.9/0.035	17.1/0.040	0.035	0.005
	15% residual lime	120.3/0.282	127.1/0.298	134.0/0.314	0.298	0.016
	15% lime + 1% fibers	79.8/0.187	97.3/0.228	114.8/0.269	0.228	0.041
	8% cement (ref.)	166.0/0.389	177.5/0.416	189.0/0.443	0.416	0.027
Dassa-Zoumè	Control	12.8/0.030	17.5/0.041	22.2/0.052	0.041	0.011
	15% residual lime	126.3/0.296	139.5/0.327	152.7/0.358	0.327	0.031
	15% lime + 1% fibers	172.4/0.404	189.4/0.444	206.5/0.484	0.444	0.040
	8% cement (ref.)	180.1/0.422	187.7/0.440	195.4/0.458	0.440	0.018

Continued

Glazoué	Control	14.9/0.035	15.4/0.036	15.8/0.037	0.036	0.001
	15% residual lime	139.9/0.328	148.5/0.348	157.0/0.368	0.348	0.020
	15% lime + 1% fibers	171.1/0.401	186.9/0.438	202.7/0.475	0.438	0.037
	8% cement (ref.)	164.7/0.386	173.2/0.406	181.8/0.426	0.406	0.020
N'Dali	Control	10.7/0.025	11.9/0.028	13.2/0.031	0.028	0.003
	15% residual lime	121.6/0.285	131.4/0.308	141.2/0.331	0.308	0.023
	15% lime + 1% fibers	139.9/0.328	153.6/0.360	167.3/0.392	0.360	0.032
	8% cement (ref.)	166.8/0.391	174.5/0.409	182.2/0.427	0.409	0.018

Table A3. Individual apparent elastic modulus E (MPa) (slope of the linear part of the stress-strain curve under unconfined compression; axial strain derived from the crosshead displacement).

Soil	Formulation	Specimen 1 E (MPa)	Specimen 2 E (MPa)	Specimen 3 E (MPa)	Mean E (MPa)	Std. dev. (MPa)
Zogbodomey	Control	45	52	59	52	7
	15% residual lime	424	447	470	447	23
	15% lime + 1% fibers	170	207	244	207	37
	8% cement (ref.)	584	624	664	624	40
Dassa-Zoumè	Control	45	61	77	61	16
	15% residual lime	445	491	537	491	46
	15% lime + 1% fibers	369	405	441	405	36
	8% cement (ref.)	634	660	686	660	26
Glazoué	Control	52	54	56	54	2
	15% residual lime	492	522	552	522	30
	15% lime + 1% fibers	366	399	432	399	33
	8% cement (ref.)	578	608	638	608	30
N'Dali	Control	39	43	47	43	4
	15% residual lime	428	462	496	462	34
	15% lime + 1% fibers	298	327	356	327	29
	8% cement (ref.)	587	614	641	614	27