

SITTEC 2026

International Seminar on Technological Innovation
and Energy Transition in Tropical Contexts

August 3-4, 2026

Ebolowa, Cameroon
ACRITEE — 2nd Edition

Track 3 — Mechanical Engineering, Materials and Local Industrial Processes

REINFORCEMENT OF COMPRESSED EARTH BRICKS USING RAW AND ALKALI-TREATED OIL PALM MESOCARP FIBRES

Renforcement de briques de terre comprimée par des fibres de mésocarpe de palmier à huile brutes et traitées alcalinement

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1. RÉSUMÉ / ABSTRACT

Résumé

Cette étude analyse l'effet combiné de la teneur en fibres de mésocarpe de palmier à huile (0,25 à 2,5 wt%) et de leur traitement alcalin sur les propriétés physiques, mécaniques et hydriques de briques de terre comprimée non stabilisées élaborées à partir d'un sol camerounais. Les caractéristiques géotechniques du sol se sont révélées adaptées à cette application grâce à une granulométrie équilibrée, une plasticité modérée et une forte aptitude au compactage. L'incorporation des fibres n'a entraîné qu'une faible diminution de la masse volumique (moins de 4 %), tout en améliorant nettement les performances mécaniques. Après 28 jours, la résistance en compression a atteint 9,70 MPa pour la formulation contenant

1 % de fibres traitées, contre 1,62 MPa pour le témoin, tandis que la résistance en flexion a été portée à 2,73 MPa. Le traitement alcalin a simultanément limité l'augmentation de l'absorption d'eau et amélioré le maintien des performances après conditionnement par absorption capillaire. La formulation contenant 1 % de fibres traitées apparaît ainsi comme le meilleur compromis entre résistance mécanique et comportement hydrique, confirmant le potentiel de ces résidus lignocellulosiques pour des briques de terre destinées à la construction à faible impact environnemental.

Abstract

This study investigated the combined influence of oil palm mesocarp fibre content (0.25-2.5 wt%) and alkali surface treatment on the physical, mechanical and hydric properties of unstabilised compressed earth bricks manufactured from a Cameroonian soil. The geotechnical characterisation confirmed the suitability of the soil for brick production owing to its balanced particle-size distribution, moderate plasticity and high compaction capacity. Fibre incorporation caused only a slight reduction in bulk density (<4%) while markedly enhancing the mechanical performance. After 28 days of curing, the compressive strength reached 9.70 MPa for bricks reinforced with 1 wt% treated fibres, compared with 1.62 MPa for the control, whereas the flexural strength increased to 2.73 MPa. Alkali treatment also limited the increase in water absorption and improved strength retention after capillary water conditioning. Among the formulations investigated, 1 wt% treated fibres provided the most favourable balance between mechanical performance and hydric behaviour, highlighting the potential of oil palm mesocarp residues for producing more durable compressed earth bricks intended for sustainable building applications.

Keywords: Raffia leaf cuticle; Agroecological variability; Crystallinity; Tensile properties; Bio-based textile reinforcement

2. INTRODUCTION

The housing shortage in Cameroon, estimated at ≈ 2.5 million units with an annual need of more than 150,000 dwellings, limits access to decent housing and increases informal settlement, as well as sustainable development challenges [1]. At the same time, the country produces approximately 447,000 t of crude palm oil each year, generating a significant amount of waste, yet remains dependent on imported construction materials, resulting in a loss of local value [2], [3]. In this context, the use of local, economical, and sustainable materials becomes strategic. Compressed earth blocks (CEB) are promising thanks to their low embodied energy, local availability, and low cost. However, their low strength and sensitivity to water limit their structural use without cement or lime, the production of which is costly and energy-intensive. The valorization of agricultural residues, such as oil palm mesocarp fibers from local oil mills, constitutes a sustainable alternative. Incorporating these fibers could improve the post-cracking behavior of CEB by limiting crack propagation and increasing ductility and toughness. The alkaline treatment of the fibers, through partial removal of hemicelluloses and increased surface roughness, should strengthen fiber/matrix adhesion, amplifying the mechanical gains and moisture stability, even under prolonged curing and aging by capillary absorption [2], [4]. This approach aims to optimize stress transfer and crack bridging, offering a high-performance alternative to conventional chemical stabilization. The objective of the study is therefore to evaluate the effect of fiber content and their alkaline treatment on the physical, mechanical, and hydric properties of CEBs, in order to propose a viable solution for sustainable construction in Cameroon.

Compressed earth bricks (CEB) have long been recognized as a low-carbon, low-cost building material well suited to tropical contexts, but their intrinsic brittleness and sensitivity to water remain the main obstacles to wider structural use. Several studies have addressed these limitations through chemical stabilization (cement, lime) or through the incorporation of natural fibers as low-cost, locally available reinforcement. Manfo et al.

[1] highlighted the relevance of integrated eco-renovation approaches that combine local materials and climate resilience for housing in Cameroon, underlining the need for construction solutions that rely on local innovation rather than imported, energy-intensive stabilizers. Tchoko et al. [2] specifically investigated the effect of oil palm mesocarp fibers (OPMF) on cement-stabilized CEB, showing that fiber incorporation improves post-cracking behavior and mechanical toughness while requiring careful control of fiber content to avoid excessive porosity. More broadly, Beten  Ebanda et al. [3] demonstrated that tropical plant fibers can significantly enhance the mechanical performance of CEBs, confirming the crack-bridging role of fibrous reinforcement and its contribution to sustainable construction strategies in Cameroon. Across these studies, a recurring conclusion is that untreated natural fibers, despite their reinforcing potential, tend to increase water absorption and reduce durability because of their inherent hydrophilicity and the weak interfacial bonding they form with the earthen matrix.

To overcome this hydric sensitivity, several authors have turned to surface modification of natural fibers, most commonly through alkaline (NaOH) treatment [5]. This treatment is known to partially remove hemicelluloses, lignin, and waxy impurities from the fiber surface, increasing roughness and exposing reactive hydroxyl groups, which in turn promotes mechanical interlocking and chemical adhesion with the surrounding matrix [6], [7]. This mechanism has been widely reported for other natural-fiber composites and is generally associated with improved stress transfer, reduced moisture uptake, and better long-term dimensional stability of the reinforced material. While the reinforcing potential of oil palm mesocarp fibers and the benefits of alkaline treatment have each been documented separately, most previous studies on Cameroonian CEB have focused on cement-stabilized formulations, leaving the case of unstabilized, purely fiber-reinforced earth bricks comparatively unexplored. Moreover, few works combine a systematic variation of fiber content with a direct comparison between raw and alkali-treated fibers under multiple curing and aging conditions (short-term and long-term curing, plus wet/dry capillary aging), which is essential to assess real-world durability rather than short-term performance alone.

The present study addresses this gap by jointly varying fiber content (0.25–2.5 wt%) and fiber surface treatment (raw versus NaOH-treated OPMF) in a stabilizer-free CEB formulation, and by evaluating the resulting physical, mechanical, and hydric properties before and after capillary aging. This coupled approach makes it possible to identify an optimal fiber content/treatment combination that maximizes mechanical performance while limiting the durability penalty usually associated with natural-fiber reinforcement, thereby contributing a practical, low-cost valorization pathway for oil palm mesocarp residues from Cameroonian oil mills.

3. MATERIALS AND METHODS

3.1 Raw materials

The soil used in this study was collected from Bomono-ba Bengu , Cameroon (Fig. 1a,b). After sampling, it was air-dried to constant mass under laboratory conditions. Residual aggregates were gently crushed, and the soil was sieved through a 2 mm mesh to remove coarse particles and ensure a homogeneous particle-size distribution before brick production (Fig. 1c,d). Its geotechnical properties were characterised in accordance with NF P 94-056, NF P 94-051/052, NF P 94-093 and NF P 94-078 [4, enabling determination of the particle-size distribution, Atterberg limits, maximum dry density, optimum moisture content and bearing capacity, which were subsequently used to define the optimum manufacturing conditions for the compressed earth bricks (CEB).

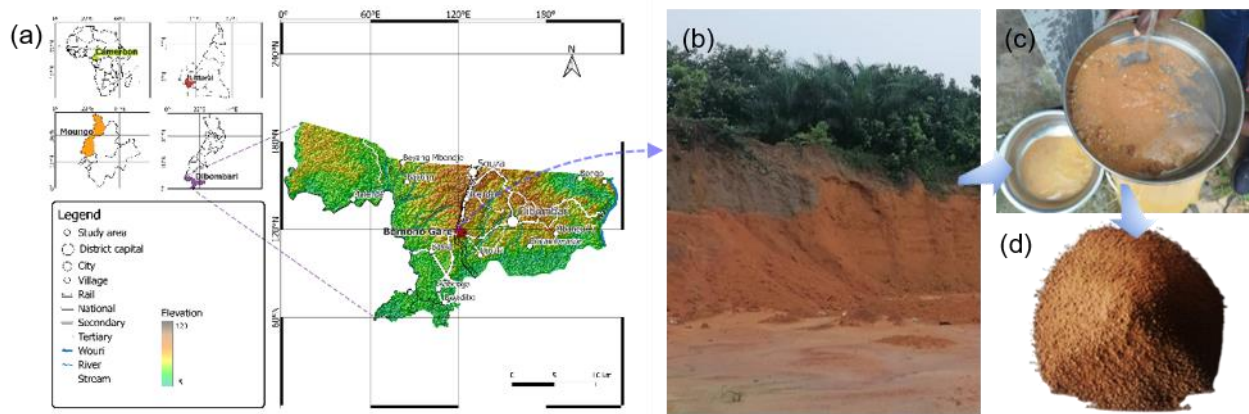


Fig. 1. (a) Geographical location and (b) panoramic view of the sampling site, (c) sieving of the soil and (c) ground and dried soil sample used in this study.

Oil palm mesocarp fibres (OPMF), obtained as residues from palm fruit processing (Fig. 2a), were collected and air-dried for 72 h under ambient conditions. The fibres were subsequently cleaned to remove adhering surface impurities. One portion was retained in its raw state (OPMF, Fig. 2b), whereas the remaining fibres were subjected to alkaline treatment in a 5 wt% NaOH solution at 80 °C for 3 h (Fig. 2c). Following treatment, the fibres were thoroughly rinsed with distilled water until a neutral pH was achieved and then dried to constant mass to obtain the treated oil palm mesocarp fibres (OPMFT) (Fig. 2d).

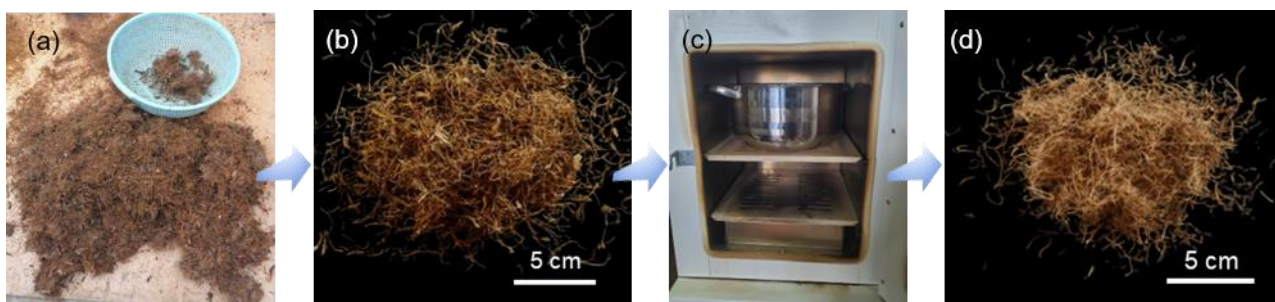


Fig. 2. (a) Collected mesocarp residues, (b) OPMF, (c) fibre treatment with 5% NaOH at 80 °C, (d) treated OPMF.

3.2 Manufacture and conditioning of compressed earth bricks

The formulations were prepared by incorporating the fibres into the pre-conditioned soil. Dry mixing was first carried out for 3 min to ensure uniform fibre dispersion throughout the mineral matrix. Water was then gradually added until the optimum moisture content, previously determined from the geotechnical characterisation, was reached. Wet mixing was subsequently continued for 2 min to obtain a homogeneous mixture and promote complete wetting of both the soil particles and the fibres. The resulting mixtures (Table 1) were compacted by static compression at 10 MPa and 25 ± 2 °C using a rigid steel mould to produce prismatic compressed earth bricks (CEB) measuring $160 \times 40 \times 40 \pm 2$ mm³. After demoulding, all specimens were cured at 25 ± 2 °C and $60 \pm 5\%$ relative humidity until testing.

After 14 days of curing, one-third of the specimens, designated CEB-14, was subjected to mechanical characterisation. A second batch, designated CEB-28, was tested after 28 days under identical conditions. The remaining specimens were used to investigate the short-term effect of capillary water uptake on mechanical behaviour. These specimens were first cured for 28 days, after which their lateral faces were sealed with waterproof adhesive tape to ensure one-dimensional moisture ingress. After oven drying and determination of the initial mass (M_0), the specimens were partially immersed to a depth of 3 mm in distilled water for 24 h at 25 ± 2 °C, following XP P13-901 [8]. Water absorption was calculated from the relative mass increase according to $WA = 100 (M_f - M_0)/M_0$. Following capillary conditioning, the specimens were returned to the same curing environment for a further 28 days before mechanical testing and were designated CEB-28W/D. This protocol was specifically designed to assess the short-term influence of capillary water absorption on the

mechanical performance of CEB. It should therefore not be interpreted as either a durability assessment or an accelerated ageing procedure.

Table 1 - Fibre proportions and coding of the formulations studied.

Components	Fibre content (wt%)	Code
100% Earth	-	CEB
Raw mesocarp fibres (OPMF)	0,25	CEB0.25
	1	CEB1
	2,5	CEB2.5
Treated mesocarp fibres (OPMFT)	0,25	CEB0.25T
	1	CEB1T
	2,5	CEB2.5T

3.3 Physical characterisation of compressed earth bricks

The physical properties of the CEBs were first assessed by determining their bulk density after 28 days of curing. Specimen dimensions were measured using a digital calliper with an accuracy of 0.01 mm, while the dry mass was recorded using a precision balance (0.01 g). The bulk density was subsequently calculated as the ratio of the dry mass to the geometric volume of each specimen. This parameter was used as an indicator of compaction efficiency and the degree of densification achieved within the soil-fibre matrix.

3.4 Mechanical characterisation of compressed earth bricks

The mechanical properties were evaluated in accordance with EN 1015-11. Three-point bending tests were first performed on prismatic specimens using a 100 mm span under monotonic loading until failure. The flexural strength was calculated from the maximum load recorded during the test. The two half-prisms generated after bending failure were subsequently subjected to uniaxial compression between parallel steel platens to determine the compressive strength. Mechanical tests were conducted on dry specimens after 14 and 28 days of curing and repeated on specimens previously exposed to capillary water absorption in order to quantify the short-term influence of moisture on the load-bearing capacity of the CEB. At least three specimens were tested for each formulation and curing condition, and the reported values correspond to the arithmetic mean.

4. RÉSULTS AND DISCUSSION

4.1 Geotechnical and structural properties of the Bomono-ba Bengué soil

The geotechnical characteristics of the soil (Table 2) confirm its suitability for the manufacture of CEBs. The particle-size distribution is dominated by 51.9% silt and clay, together with 41.9% sand and 6.2% gravel. This balanced grading provides an appropriate compromise between matrix cohesion and granular skeleton, thereby reducing interparticle voids and promoting efficient compaction. Consequently, a maximum dry density of 1861 kg/m³ was achieved at an optimum moisture content of 12.94 wt%, values that are consistent with earthen materials intended for structural applications [3] [9].

The Atterberg limits (LL = 44.2%, PL = 21.4% and PI = 22.8%) place the soil within the recommended range for CEB production, providing sufficient plasticity to ensure particle cohesion while limiting shrinkage-induced cracking during drying [10]. The plasticity chart further confirms that the material belongs to the class

of soils suitable for earthen construction. This moderate plasticity promotes the rearrangement of fine particles around the sandy skeleton, thereby enhancing compaction, dimensional stability and mechanical potential.

The mineralogical composition is characterised by a predominance of quartz ($\approx 43\%$), together with kaolinite, illite and anatase. Such a mineral assemblage is particularly favourable for CEB production, as quartz contributes to dimensional stability while the clay minerals provide matrix cohesion. The combined effects of a balanced particle-size distribution, moderate plasticity and a silica-rich mineralogy therefore explain the soil's ability to develop a dense microstructure and satisfactory mechanical performance after compaction.

Table 2 - Physical characteristics of the soil used in this study

Atterberg limit			Grain size distribution			Supervision test	
LL	LP	IP	Gravel (%)	Sand (%)	Silt/clay (%)	Optimum moisture content (wt%)	Maximum dry density (kg/m ³)
44,2	21,4	22,8	6,2	41,9	51,9	12,94	1861

4.2. Physical properties of CEB

The results presented in Table 3 show a progressive decrease in bulk density with increasing fibre content. After 28 days of dry curing, the bulk density declined from 2.07 g/cm³ for the control CEB to 2.00 g/cm³ for CEB2.5, corresponding to a reduction of approximately 3-4%. This trend is mainly attributed to the lower intrinsic density of the lignocellulosic fibres and the formation of additional interfacial voids within the soil matrix [11]. Nevertheless, the measured values remained relatively high, indicating that the overall compactness of the bricks was largely preserved.

Tableau 3 - Average physical, mechanical and water-related properties of mesocarp fibre-reinforced BTCs (raw and treated) under different curing and ageing conditions (standard deviations: ± 5 per cent for density and strengths; ± 6 –7 per cent for absorption parameters). The designation CEB x refers to BTC containing x wt% fibres, and the suffix T indicates that the fibres have undergone alkali treatment.

Properties	Curing time and conditions	Formulations studied						
		CEB	CEB0.25	CEB1	CEB2.5	CEB0.25T	CEB1T	CEB2.5T
Density (g/cm ³)	14 days	2,05	2,03	2,00	1,98	2,04	2,02	2,01
	28 days	2,07	2,04	2,02	2,00	2,06	2,05	2,03
	28 day W/D	2,06	2,02	2,01	1,96	2,05	2,03	2,02
Compressive strength (MPa)	14 days	1,19	1,74	2,53	3,04	2,94	4,53	4,11
	28 days	1,62	2,65	4,13	5,24	5,58	9,70	7,74
	28 day W/D	0,74	0,84	1,06	1,29	2,05	3,12	2,28
Flexural strength (MPa)	14 days	0,80	0,93	1,54	1,73	1,28	1,51	1,47
	28 days	1,15	1,46	2,28	2,92	2,19	2,73	1,95
	28 day W/D	0,61	0,68	0,92	0,97	1,15	1,37	0,98
Water absorption (wt%)	28 days	8,6	9,9	11,9	13,9	8,6	9,3	10,5
Capillary water absorption coefficient (g/cm ² .min ^{0.5})	28 days	8,0	9,0	9,9	12,1	8,0	8,5	9,2

Alkaline treatment effectively mitigated this density reduction. After 28 days, the treated formulations exhibited bulk densities ranging from 2.03 to 2.06 g/cm³, compared with 2.00 to 2.04 g/cm³ for their untreated counterparts. This improvement is consistent with the morphological observations, which revealed the partial removal of waxy and oily surface layers following alkali treatment, thereby enhancing fibre wettability and limiting interfacial defects. In addition, the moderate radial shrinkage of the fibres (approximately 14%) is likely to have promoted closer fibre packing and improved fibre-matrix integration.

Water absorption increased with fibre content. It rose from 8.6 wt% for the control CEB to 13.9 wt% for CEB2.5, while the capillary absorption coefficient increased from 8.0 to 12.1 g/cm².min^{0.5}. This behaviour

reflects the development of preferential moisture transport pathways associated with the hydrophilic nature of the lignocellulosic fibres. However, alkaline treatment consistently reduced both parameters. At 2.5 wt% fibre content, water absorption decreased to 10.5 wt%, whereas the capillary absorption coefficient fell to $9.2 \text{ g/cm}^2 \cdot \text{min}^{0.5}$. These results suggest a lower fibre hydrophilicity together with a denser and more cohesive fibre-matrix interface, thereby restricting water ingress into the composite.

4.3 Mechanical properties of the compressed earth bricks

The incorporation of fibres markedly enhanced the mechanical performance of the CEB (Table 3). After 28 days of curing, the compressive strength increased from 1.62 MPa for the control CEB to 5.24 MPa for CEB2.5, corresponding to an improvement exceeding 220%. Over the same period, the flexural strength increased from 1.15 to 2.92 MPa (+154%). These improvements indicate effective crack-bridging and stress redistribution mechanisms, which restrict unstable crack propagation and promote a more progressive failure mode.

Alkaline treatment further enhanced this reinforcing effect. After 28 days, CEB1T achieved compressive and flexural strengths of 9.70 MPa and 2.73 MPa, respectively, compared with 4.13 MPa and 2.28 MPa for the untreated CEB1. Relative to the control, the compressive strength therefore increased by almost 240%. This improvement is attributed to the removal of surface impurities, increased fibre surface roughness and stronger fibre-matrix adhesion, leading to more efficient stress transfer across the interface [4]. These interpretations are consistent with the morphological observations.

The curing period also exerted a pronounced influence on mechanical behaviour. Between 14 and 28 days, the compressive strength increased by 36% for the control CEB and by up to 90% for some fibre-reinforced formulations. A similar trend was observed for flexural strength. This progressive improvement reflects the continued consolidation of the earthen matrix together with the gradual development of fibre-matrix bonding. Such interfacial synergy is likewise recognised as a key factor governing the strength, stiffness and long-term integrity of plant fibre-based textile reinforcements and composite materials.

Capillary water absorption reduced the mechanical performance of all formulations. The compressive strength decreased from 1.62 to 0.74 MPa for the control CEB and from 5.24 to 1.29 MPa for CEB2.5. Nevertheless, the treated fibre composites retained substantially higher strengths, with CEB1T reaching 3.12 MPa, compared with 1.06 MPa for CEB1. This superior retention suggests a more stable fibre-matrix interface and a lower susceptibility to moisture-induced interfacial debonding.

4.4. Modelling of compressive strength and water-related properties

The correlations presented in Fig. 3a,b and Table 4 reveal a strong relationship between the relative densification index ($\frac{\rho}{\rho_0}$), where ρ denotes the bulk density of the fibre-reinforced CEB and ρ_0 that of the unreinforced control CEB, and the compressive strength. Schiller-type models accurately describe the experimental behaviour, with coefficients of determination ranging from $R^2 \approx 0.97$ to 0.999. The increase in compressive strength is accompanied by progressive improvement in the internal organisation of the matrix and the growing efficiency of fibre reinforcement. The treated formulations consistently exhibit the most favourable slopes, further highlighting the key role of fibre-matrix interfacial quality in governing the mechanical response.

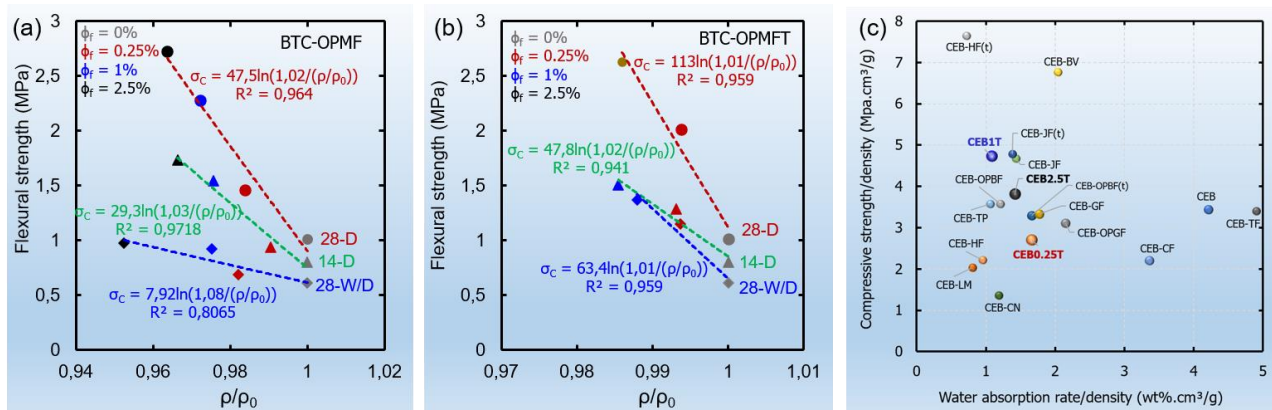


Fig. 3. (a) Theoretical behaviour of compressive strength and the densification index; (b) Changes in hygroscopic properties as a function of fibre content; (c) Correlation between specific mechanical properties and specific water absorption. The suffixes associated with the acronym CEB (Compressed earth brick) indicate the type of fibres incorporated: DP, doum palm [4]; AS, sisal [3]; RC, Rhectophyllum camerunense [3]; TF, Typha [12]; OPBF, oil palm rachis [13]; CN, coconut fibre [14]; CF, cotton [15]; HF, hemp [16]; BV, bamboo [17]; TP, Triumfetta pentandra [18]; JF, jute [19]; LM, sheep's wool [20]; DPF, date palm [21]; OPGF, palm sheath [22]; GF, glass [22]. The symbol (t) indicates alkaline treatment of the fibres.

Table 4 - Fitting parameter values for Schiller's theoretical models of compressive strength.

Model	Paramter	CEB-OPMF			CEB-OPMFT		
		14-D	28-D	28-W/D	14-D	28-D	28-W/D
Schiller [23] σ $= k \ln \left(\frac{\beta_0}{\left(\frac{\rho}{\rho_0} \right)} \right)$	k	53,8	98,2	11,68	227,6	570,7	197,1
	β_0	1,02	1,01	1,06	1,01	1,003	1,004
	R^2	0,999	0,973	0,942	0,996	0,997	0,994

There is an inverse correlation between mechanical performance and water-related indicators. An increase in water absorption and the capillary coefficient is accompanied by a rise in fibre content, whilst alkaline treatment simultaneously mitigates this adverse effect on water behaviour and optimises strength. The optimal balance is achieved for CEB1T (Fig. 3c), which combines a compressive strength of 9.70 MPa, a flexural strength of 2.73 MPa, water absorption limited to 9.3 wt% and a capillary coefficient of 8.5 g/cm².min^{0.5}.

This optimisation results from the morphological changes induced by the alkaline treatment. The removal of waxy and oily layers, combined with a slight dimensional contraction of the fibres, promotes mechanical anchoring and reduces water transport pathways. Similar mechanisms are widely used in technical yarns and textile composites based on plant fibres, where control of the interface is the key factor in simultaneously increasing specific strength, hygrometric stability and structural efficiency.

5. CONCLUSION

This study demonstrates that oil palm mesocarp fibres can effectively reinforce unstabilised compressed earth bricks when incorporated at low contents. Although fibre addition induced a slight reduction in bulk density of less than 4%, it substantially improved the mechanical performance. After 28 days of curing, the compressive strength reached 9.70 MPa for bricks containing 1 wt% alkali-treated fibres, compared with 1.62 MPa for the control, while the flexural strength increased by more than twofold. Alkali treatment also reduced the increase in water absorption and improved strength retention after capillary water conditioning, indicating a more efficient fibre–matrix interface. Among the formulations investigated, the brick reinforced with 1 wt%

treated fibres provided the best compromise between mechanical performance and hydric behaviour. These findings highlight the potential of valorising oil palm mesocarp residues as reinforcement for compressed earth bricks intended for sustainable construction without cement-based stabilisation. Nevertheless, the conclusions remain limited to the experimental conditions investigated and to short-term capillary water conditioning. Further work should address long-term natural weathering, cyclic environmental exposure, microstructural characterisation of the fibre-matrix interface, and validation at the masonry element scale to further assess the suitability of these materials for construction applications.

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