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Effect of the Combining Use of Hydrated Lime and Shea Butter Residue as Stabilizers on the Compressed Earth Blocks Physical, Mechanical, Thermal and Hydric Properties

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Abstract

The use of soil as a construction material is limited due to climatic conditions such as rain and wind effects. The valorization of industrial and agricultural by-products in soil-material-based composites for construction materials is an alternative to producing eco-materials for building construction. This study evaluates the effect of Shea Butter residue (SBr) and hydrated lime (HL) as stabilizers on the performance of Compressed Earth Blocks (CEB). For the production of CEB specimens, firstly the dry mixtures were prepared using soil material and 5 wt% HL, 5% - 25% wt% SBr and secondly, the appropriate amount of water was thoroughly mixed with the dry mixtures using the result of the proctor compaction test. All the moistened mixtures were mechanically pressed into CEBs on mold size (29.5 cm × 14 cm × 9.5 cm), cured at ambient temperature in the lab for 0 - 45 days, and dried at 60˚C for 7 days before being tested. The results give for the accessible porosity, bulk density, maximum dry and wet compressive strength, the respective value 31.58%; 1580 kg/cm^2; 3.26 MPa and 0.75 MPa for CEB stabilized with 5 wt% lime without SBr. Moreover, the abrasion coefficient (14.49 cm^2/g), the mass lost (0.08%), the surface depth (3.25 mm/h), the eroded surface (9.12 cm^2), the sorptivity (0.046 g/cm^2·min$^{1/2}$ the absorption by total immersion at 2 h and 24 h (4.06 and 11.94%) are best for the CEBs stabilized with 5/5 wt% HL/SSBr. However, the lower thermal properties were obtained with CEB stabilized with 25 wt% SSBr. We therefore observe the significant reaction between these industrial and agricultural by-products with the earth material, with effects particularly on the hydric, thermal and durability properties. The use of industrial and agricultural by-products such as lime and SBr at an appropriate rate of 5 wt% are suitable to improve CEBs performances.

Keywords

Compressed Earth Block, Shea Butter Residue, Hydrated Lime, Physical and Mechanical Properties, Thermal Properties, Durability

1. Introduction

The demographic boom in most sub-developed countries, such as Burkina Faso, testifies to the growing need for sustainable decent housing for the population [1]. According to a projection in 2022 based on the 5th General Survey of Population and Housing (RGPH), the population and the urbanization rate are respectively estimated at nearly 21 million and 31%, of which 2.8 million live in the city of Ouagadougou [2]. However, construction costs, taking into account all factors including building materials, are very high, making it difficult for the majority of urban and rural population to have access to decent and sustainable housing.

Economic and energy constraints linked to population growth and changing lifestyles have led to research for new alternatives in terms of building materials and technologies. These include earth materials which can be used as a construction material such as cob, daub, wattle, adobe, molded bricks, rammed earth or compressed earth blocks [3]. In fact, despite the evolution of modern materials (cement, reinforcement, sheet metal, etc.) a great deal of research is currently focused on raw earth construction [4] to alleviate housing shortages in developing and industrialized countries alike [5]. However, the raw earth-based construction suffers from a lake ok strength due to climate factors, systematic cracking due to shrinkage and problems linked to their sensitivity to water [6] [7].

Nowadays, scientific research is proposing approaches to reduce these limits of earth-based construction materials limits and this interest in researching CEB is all over the world. Some factors that contribute to the effectiveness of the earth material-based blocks and the performance of the final product or resulting structures. These parameters are: soil granulometry, mixing water content, compaction energy and type and quantity of stabilizers [4]. It is the case of the compaction energy applied in the manufacture of CEB which influences the density, thermal conductivity and mechanical strength [4]. For this purpose, different compositions are proposed, each adapting the type of stabilizer and soil material, varying the quantities used, to understand the effect on the material's properties [8]-[10]. Stabilized earth blocks can be a good alternative to solve the housing problem if the soil typologies, the soil sampling and the appropriate stabilizers/ binder quantities are identified [11]. From the literature, the majority of studies on the development of quality CEB in construction suggested industrial, agricultural, by-products, animals and plant wastes stabilizers used individually or by a combination [12]-[19]. In objective to improve the technical properties of the CEB made from these earth/stabilizer composite materials and to reduce energy consumption during production, provide solutions to avoid the consumption of resources such as aggregates, and decrease reliance on cement [20].

From the analysis of studies on material stabilization, Antoinéti & Azambuja (2021) showed that there is an environmental concern with the use of Portland cement for stabilization, therefore, 18% of the studies used agricultural residues and 25% used mineral by-products, for partial or total replacement of Portland cement [4]. Velenzula *et al.* (2024) concluded that fibers improve tensile and crack resistance while stabilizers enhance the cohesion of mixtures, originating new compounds [19]. The mechanicals strength of bricks can be improved by individual or mixed addition of cement and lime at rates of between 4% - 8% [21]. Also, by amending the soil material with rice straw at an optimum rate, it can improve at 0.2% for flexion and 0.4% for compression [11]. Furthermore, the use of peanut hulls was cut respectively to sizes of 0.33 cm, 1 cm and 3 cm and added to the clay soil matrix at a content rate ranging from 1.8 - 3 wt% [22], the peanut shells powder in the range of 15 to 25 wt% [9] allow to improve the thermal conductivity, water absorption and erosion strength of CEB. Another study conducted by Malbila *et al.* (2020) indicated an improvement in the physical, mechanical, hydric and thermal properties of CEB stabilized with fonio straw and shea butter solid residue (SBSr) [23]. Nshimiyimana *et al.* (2020) noted that the improvement of the structural and thermal efficiency of CEBs by the stabilization with by-product binders is beneficial for load-bearing capacity and thermal performances in multi-story buildings [18]. The comparison of the thermal behavior of house, study by simulations on TRNSYS, revealed that BTC stabilized with slaked lime and canabinus hibiscus fibers offers better thermal temperature comfort than BLT or breeze block [24].

From above, we noted that the selection criteria focused on key parameters including construction method (block type), incorporation of natural fibers or powders, partial or complete cement replacement, pressing techniques, and block preparation methods (adobe or CEB) [20].

The effect of SBr used individually or by combination with fonio straw on the CEB technical properties has been explored [23]. Previous studies indicate the individual effect of Hydrated lime and SBr on CEB properties [23] [25]. The present study aims to explore the possibility of combining HD and SBr as stabilizers of soil material to produce CEB. Few studies on the use of SRr in earth material stabilization have been reported. The Shea butter production process gives a colored [26] [27] solid and liquid residue [28] and some studies indicate the valorization of shea effluents and by-products for biogaz production [29] [30]. Moreover, we can note the production and characterization of an inorganic polymer (geopolymer) employing raw laterite as an aluminosilicate source activated by the alkaline source issued from potassium-rich shea pellet ash (SPA) [31] and the chemical stabilization of compressed earth bricks (CEB) by geopolymer binders [32]. Furthermore, Raharinierana *et al.* (2023) observed that CEB stabilized with a mix of lime/cement are economical materials, the drying time is reduced compared to lime-stabilized material, the release of CO_2 is reduced compared to cement-stabilized material, and the environmental impact is limited [33]. According to Dime *et al.* (2022), the CEB stabilized with 20 wt% of lime residue gives the dry compressive strength from 6 to 9.7 MPa [17].

The objective of this work is to add value to local natural soil materials and two local industrial and agricultural by-products namely, lime residue (LR) and shea butter residue (SBr) in the production of CEB. It specifically investigates the effect of stabilization with LR and SC on the engineering properties of CEBs such as bulk density, mechanical strength, hygrothermal and hydric properties. The scientific novelty of this work is to highlight the effect of these two by-products (lime and shea cake) in the elaboration and the performance of CEBS as a material for construction. The different results will allow a significant advance in the availability of sustainable construction materials and make a substantial contribution to reducing environmental pollution.

2. Materials and Method

2.1. Presentation of Raw Materials

The raw materials used in this study are presented in **Figure 1** below.

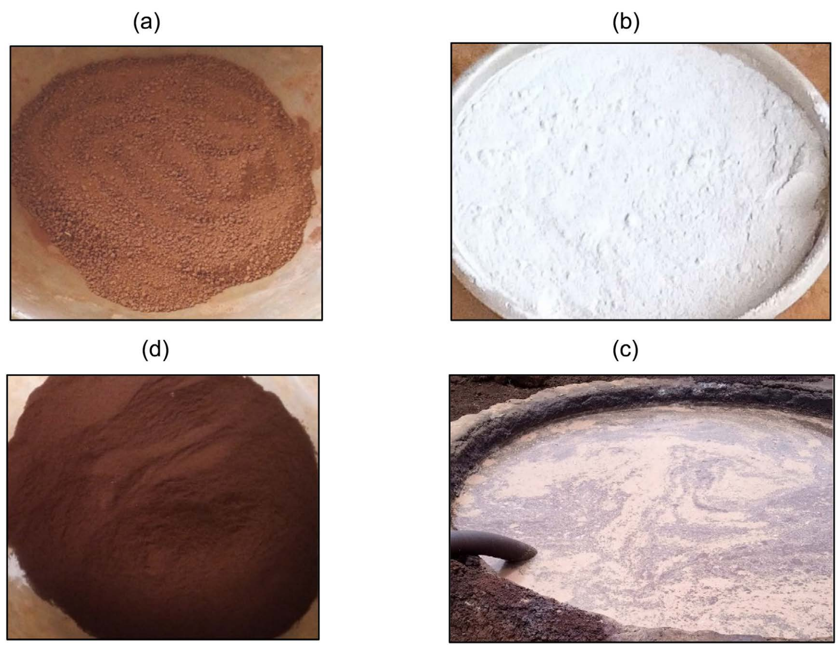

Figure 1. Presentation of raw materials (a) laterite soil, (b) hydrated lime (HL), (c) shea butter liquid residue (SBLr) and (d) shea Butter Solid residue (SBSr).

The laterite comes from the eastern region of Burkina Faso, in the city of Fada

N'Gourma at the GPS coordinates N12.10020 E0.34710.

The Shea Butter residue (SBr) was collected at the Fédération NUNUNA (FN) production center at the coordinates (11˚6'30.64"N; 2˚5'49.40"O) located in central-western region of Burkina Faso, exactly in the city of **Léo**. Shea is a tree native to the savannahs of Africa and in 2011, Burkina Faso became the world's 2nd producer of shea kernels (338,000 tons) and the world's 3rd exporter of shea butter [34].

The hydrated lime (HD) used in the study is an industrial by-product obtained from the production of acetylene by Burkina Industrial Gas (BIG), a company based in Ouagadougou the Kossodo industrial zone at GPS coordinates (N12˚25.935', W001˚29.374') and specialized in the manufacture and distribution of industrial gases.

The laterite soil, the Hydrated Lime (HD) and the Shea butter solid residue (SBSr) were sieved through respectively a 5 mm, 0.8 mm and 0.4 mm sieve (**Figure 1(a)**, **Figure 1(b)**, **Figure 1(d)**) to accommodate their granulometry within the spindle recommended by standard CRATerre.

2.2. Characterization of Raw Materials

For the formulation and manufacture of CEB, the main raw earth materials must comply with some characteristics, in a particular class, which must be included in the grading range, with normative values enabling the correct property to be assessed.

The laterite soil size distribution was performed using two methods. The coarser fraction (>80 μm) was analyzed by wet sieving and the finer fraction (<80 μm) by sedimentation methods according to standards NF EN 933-1 [35] and NF EN ISO 17892-4 [36]. Because the soil particle size distribution is a fundamental step in evaluating the suitability of the soil for earth construction [4]. The Atterberg's limits were determined according to standard NF P 94-051 and the methylene blue value was determined according to standard NF P 11-300-GTR [37].

The laterite soil and the SBr specific weights by air pycnometer test were determined using NF EN 1097-7 standard [38]. The standard Proctor compaction test was carried out on untreated soil, HL stabilized specimens and the specimens with different percentages of SBr for the optimum moisture content (OMC) and Maximum dry density (MDD) under standard **NF P 94-093** [39].

To determine the SBr fat content, we used the Wolff et Castera-Rossignol modified method for liquid sample [40] and the Soxhlet extraction method using hexane as the solvent for solid samples.

2.3. Design, Production and Curing of Stabilized CEBs

2.3.1. Design of CEB Specimens

To make the CEB, we opted for a formulation in which the proportion of earth matrix added to that of stabilizer gives the final mass of the manufactured sample. Previous studies on HL have used mass contents ranging from 0% - 25% [41]-

[43]; on SBSr contents ranging from 3% - 10% [23] on SBLr 25% - 100% [44] in the earth material stabilization. Based on the above, five (05) formulations with stabilization rates by weight (**Table 1**) were selected for the present study.

Table 1. Proportion of SBr, laterite soil and HL in the elaboration of CEB.

Reference	$L_{95}C_5BK_0$	$L_{90}C_5BKS_5$	$L_{85}C_5BKS_{10}$	$L_{70}C_5BKS_{25}$	$L_{95}C_5BKL_{25}$
Laterite soil (wt%)	95%	90%	85%	70%	70%
HL (wt%)	5%	5%	5%	5%	5%
SBSr (wt%)	---	5%	10%	25%	---
SBLr (wt%)	---	---	---	---	25%
Total	100%	100%	100%	100%	100%

For this purpose, raw materials quantities were evaluated to enable the production of 120 CEBs, including 24 CEBs per formulation, as summarized in **Table 2** below.

Table 2. Mixture composition by formulation type.

Reference	$L_{95}C_5BK_0$	$L_{90}C_5BKS_5$	$L_{85}C_5BKS_{10}$	$L_{70}C_5BKS_{25}$	$L_{95}C_5BKL_{25}$
Laterite soil (g)	6745	5985	5440	3640	6745
HL (g)	355	332.5	320	260	355
SBSr (g)	---	332.5	640	1300	---
SBLr (g)	---	---	---	---	275.125
Water (g)	1100.5	1384	1416	1355	825.375

2.3.2. Production of CEB Specimens

The materials are first sieved by hand through various sieves. They are then mixed wet and dry and inserted into the mold (29.5 cm × 14 cm × 9.5 cm) for compaction and followed by demolding (**Figure 2**). Finally, the CEB specimens were hermetically sealed in a plastic bag for 45 days of curing. The curing is one of the parameters that affects the mechanical performance of compressed earth blocks (CEBs) stabilized with calcium carbide residue [45] the oven-dried at 60˚C to a variation of 0.1% in mass for characterization.

2.4. Characterization of Stabilized CEBs

The characterizations were carried out on at least three specimens of CEBs for the consideration of average and standard deviation values.

2.4.1. Physical and Mechanical Properties

The water-accessible porosity can be used to access the CEB's permeability and mechanical strength. The principle is to determine the dry CEBs mass (Md in kg), the mass of water saturated CEBs after 24 h immersion respectively in water (Msat.wt in kg) and in air (Msat.air in kg), and apparent volume by hydrostatic weighing (**Figure 3**). The specimen for testing is kept in water at 20˚C to be saturated and then placed in the oven at 60˚C until a constant mass is obtained. Water-accessible porosity (Pa), also used as an indicator of block durability, is obtained by applying the following Equation (1). The bulk density (ρ_b (kg/m^3)) of dry CEBs of mass, Md (kg) is determined using Equation (2) after hydraulic weighing [46]. The compressive strength (**Figure 4**) was tested on the stack of two halves of CEBs, in dry and wet conditions after immersion in water for 2 h, using a hydraulic press (Proeti safr, Madrid, Spain) equipped with a 300 kN capacity load cell at a loading rate of 0.2 mm/s, referring to XP P13-901 standard [47]. The CEB's compressive strength, Rc (MPa), was calculated using Equation (3), where Fr (kN) is the maximum load at failure and S (cm^2) is the area of applied surface:

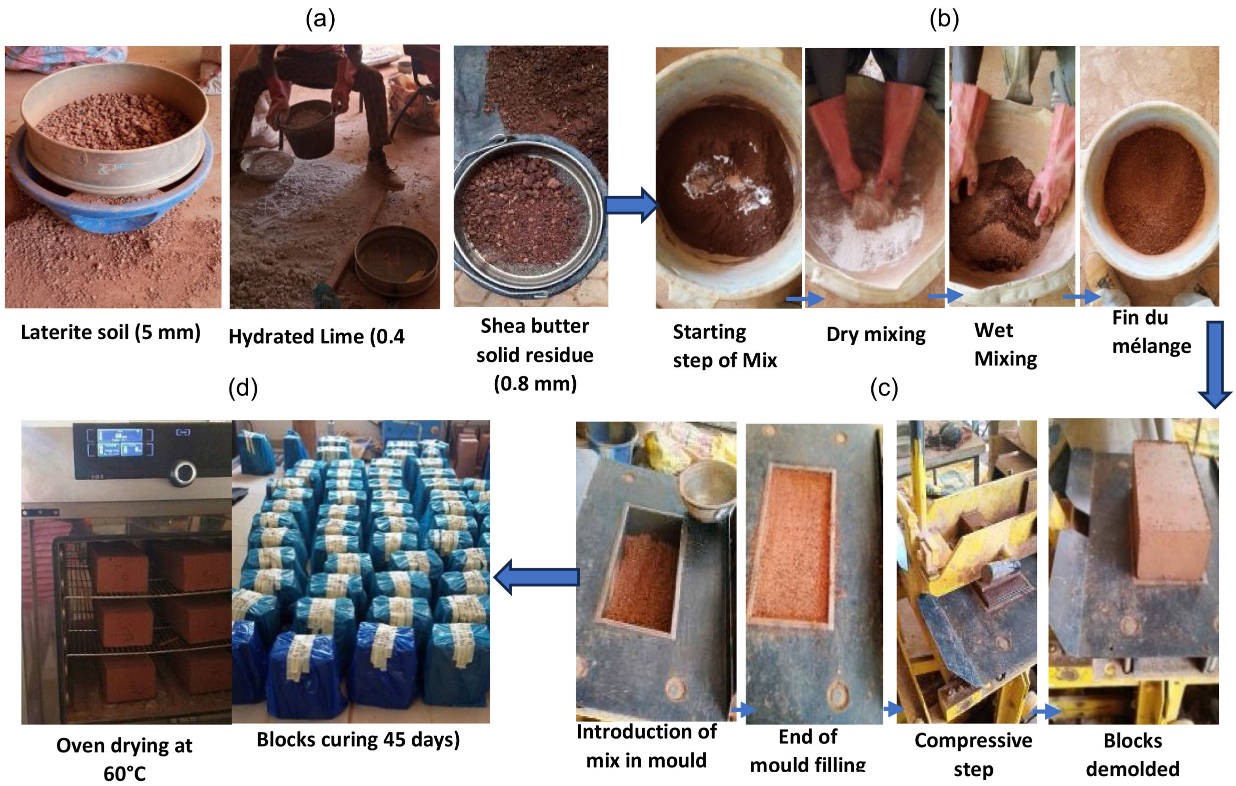

Figure 2. Mains steps in the production of CEBs specimen. (a) Screening process; (b) Mix procedure; (c) Blocks manufacturing step on the manual press; (d) Curing and drying procedure.

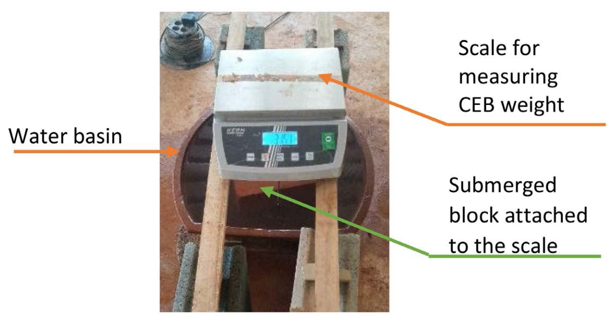

Figure 3. The hydrostatic weighing device.

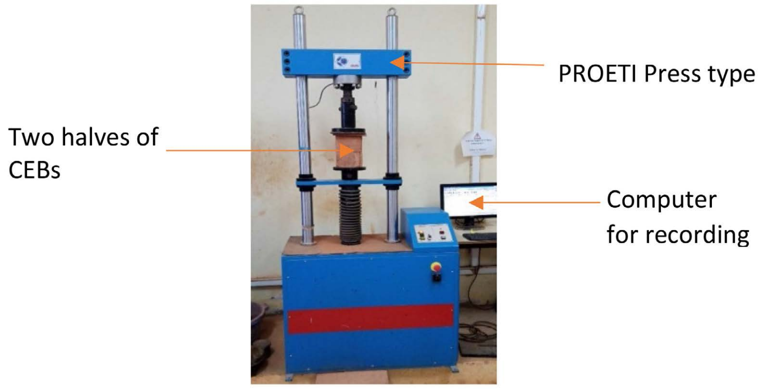

Figure 4. Experimental device for the compression test.

$$P_a(\%) = \frac{M_{sat.air} - M_d}{M_{sat.air} - M_{sat.wt}} \times 100 \quad (1)$$

$$\rho_b = \frac{M_d \times \rho_{eau}}{M_{sat.air} - M_{sat.wt}} \quad (2)$$

$$R_c = 10 \times F_r / S \quad (3)$$

2.4.2. CEBs Durability Properties

Water absorption by capillary action was measured according to standard NF XP 13-901 [47]. The principle is to partialize the blocks to a depth of 5 mm and measure their mass for 24 hours. The CEBs capillary absorption coefficient (C_{ac} in g/cm^2) is expressed by Equation (4) where M_h(*g*) *and* M_d(g) *are respectively the CEBs humid mass and dry mass* and S (m^2) the specimen surface:

$$C_{ac} = \frac{M_h - M_d}{S} \quad (4)$$

Absorption by total immersion was carried out following standard NF EN 14617-1 [48] on normalized dimensions of CEB (29.5 × 14.5 × 9.5 cm^3). The absorbed water amount **(H_p in %)** by the CEBs was determined by Equation (5) below:

$$H_p = \frac{M_h - M_d}{M_d} \times 100 \quad (5)$$

The purpose of the abrasion resistance test is to simulate the CEBs' behavior concerning the various erosions eventually caused by human activities or wind. This test is carried out using a steel wire brush loaded with 3 kg to simulate these effects. Brushing is applied on the face of the CEB and along its entire length, at the rate of one return stroke per second for one minute (*i.e.* 60 return strokes) without applying any vertical force to the brush during handling. These effects are simulated and measured and the abrasion coefficient (Cab in cm^2/g) is conventionally determined by Equation (6) where M_0(g) and M_f(g) are respectively the initial and final CEBs mass. The erodibility test presented in **Figure 5** was carried out following the standard NZS 4297:1998 [49]. Samples are subjected to a constant water pressure of 50 kPa for one hour (**Figure 6**). The tested CEBs were placed at a distance of 470 mm and then the depth of water penetration is measured.

$$C_{ab} = \frac{S}{M_0 - M_f} \tag{6}$$

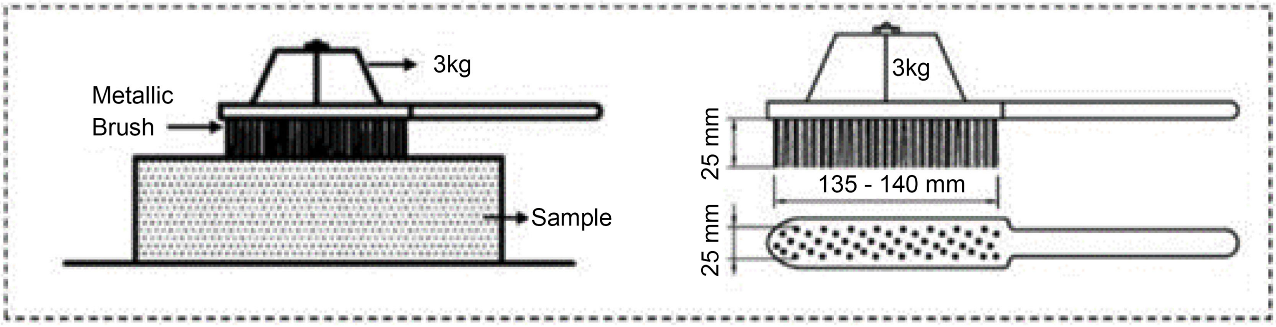

Figure 5. Experimental set-up for abrasion test [50].

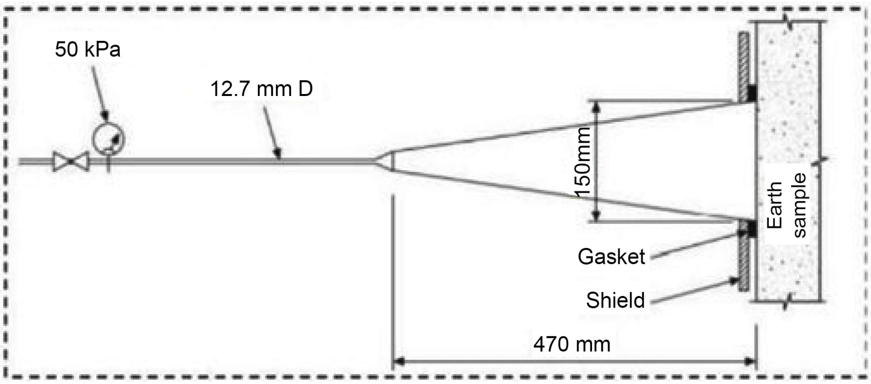

Figure 6. Experimental set-up for erodibility test [8].

2.4.3. Thermal Properties

The thermal properties, such as conductivity, λ (W/m·K), diffusivity, a (m^2/s), specific thermal heat (J/˚C·kg) and specific thermal mass (kJ/kg·K), were measured on dry samples by using the device name "KD2 Pro Thermal Properties Analyzer" (**Figure 7**) Each test take around 5 minutes and when the progress bar has completely darkened, the results are displayed on device screen.

3. Results and Discussion

3.1. Characteristics of Raw Materials

Figure 8 shows the results of laterite soil (LS) particle size analysis and the spindle recommended by the ARS 680 [50]. Theses analyses show that the used LS contains a particle size fraction of around 30% gravel, 40% sand, 15% silt and 10% clay. We also noted that the LS particle curve is within the range recommended by ARS 680, which defines the appropriate particle size for CEB design and production.

Figure 7. KD2 Pro device.

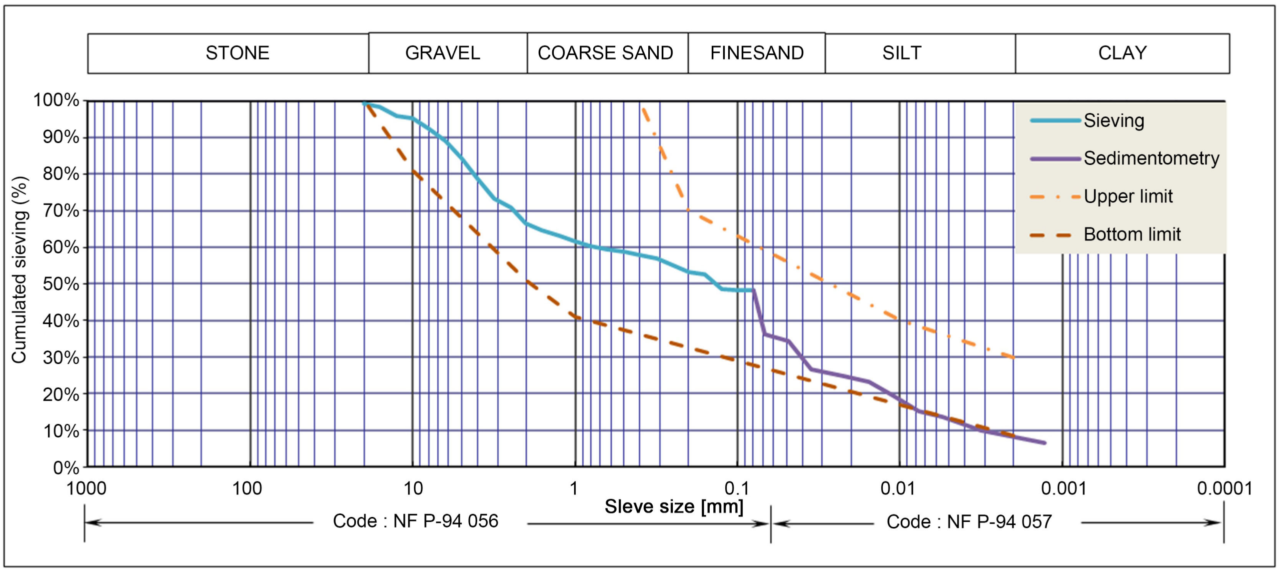

Figure 8. Particle size distribution for raw Laterite material and spindle recommended by standard ARS 680.

The raw laterite material studied has a liquidity limit of 41.19%, a plasticity limit of 24.2% and a plasticity index of 17%. These properties are close to those of the Morinda soil with a plasticity index of 17.4%, and are already used as a matrix for CEB stabilization with industrial and agricultural waste [16]. Antonelli and Azambuja (2021) mentioned that soils with plasticity indexes between 15% and 30% have a stabilization success rate of 69% [4]. With a plasticity index from 10% - 20% the stabilization with cement is preferable, and according to standard CRATerre the higher the IP, the higher the material strength [51]. The studied raw LS is within the plasticity diagram recommended by standard ARS 680 (**Figure 9**) and constitutes an appropriate raw material for construction. In addition, the methylene blue value (VBS = 0.68) is range [0.2 - 1.5], so the studied sample is a sandy-loam soil sensitive to water according to the standard GTR 92.

The raw LS specific weight results gave for raw LS 28.345 ± 0.36 kN/m^3, so around double that of Shea butter solid residue (SBSr) which is 14.8 ± 0.57 kN/m^3

and for Hydrated lime (HL) 27.15 ± 0.64 kN/m^3. This means that LS has a higher solid grain density than SBSr. Table 3 shows the Optimum Moisture Contents (OMC) and the Maximum Dry Density (MDD) of the different composites formulated. The OMC ranges from 19.5% to 26.3% and the MDD from 1.79 g/cm^3 to 1.31 g/cm^3 depending on the type and the rate of stabilization. We noted that the addition of SBr, especially the SBSr results in lower CEBs densities and higher water requirements for the different formulations. This could be explained by the SBr low density compared to raw LS.

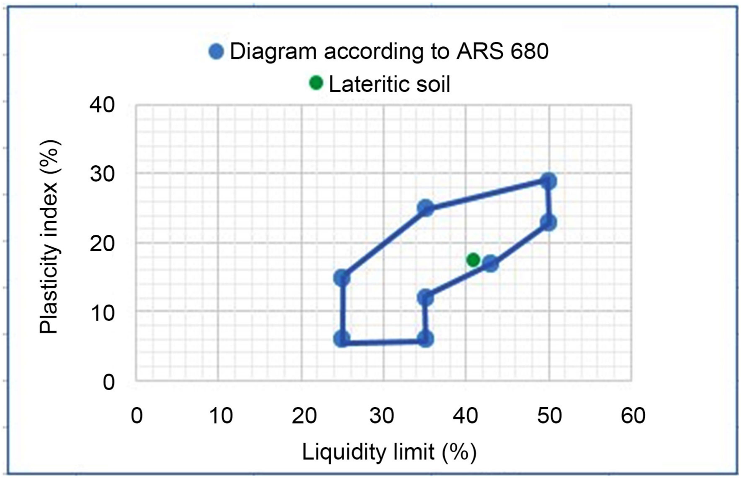

Figure 9. LS in standard ARS 680 plasticity diagram.

Table 3. Results of standard Proctor compaction test.

Sample type	OMC (%)	MDD (g/cm^3)
$L_{95}C_5BK_0$	19.5	1.79
$L_{90}C_5BKS_5$	20.4	1.63
$L_{85}C_5BKS_{10}$	24.1	1.55
$L_{95}C_5BKS_{25}$	26.3	1.31
$L_{95}C_5BKL25$	19.8	1.71

The fat content of the Shea Butter residues (SBr) sampled was 0.461 g/L for Shea butter solid residues (SBSr) and 0.586 g/L for Shea butter liquid residue (SBLr).

3.2. Physical and Mechanical Properties of Stabilized CEBs

The physical properties as well as mechanical strength were affected by the stabilization with by-product binders such as HL and SBr. However, the stabilized CEBs with 25 wt% SBSr were friable and completely degraded in contact with water; so, it was impossible to quantify their water-accessible porosity, due to their high sensitivity to water.

3.2.1. Accessible Porosity and Bulk Density

The addition of 5 - 25 wt% SBr decreases the bulk density of CEB in the range of

1580 - 1370 kg/m³ following the increase of the porosity accessible in the range of 31.58% - 41.47% (**Figure 10**). The increased accessible porosity with the addition of SRSr in the range of 8.04% - 31.31% can be related to the OMC for the production of stabilized CEB and the organic nature of the stabilizer. The partial substitution of 25% LS by the SBLr slightly decreased the bulk density from 1580 to 1540 kg/m³ and the accessible porosity from 31.58% to 32.53% (*i.e.* 3.01%). This indicates that the SBSr affect strongly the stabilized CEB densities and the accessible porosity than the SBLr. Moreover, the stabilized CEB with HL is less porous (31.58%) and denser (1580 Kg/m³) than the HL and SBr combined stabilized CEB. The results of stabilized CEBs with HL could be mainly due to the good cohesion and the different physical and chemical reactions between the LS and the HL stabilizer [52]. These results corroborate those of Zoma *et al.* (2020) [12]. The low density and high-water-accessible porosity observed with the addition of SBr could be explained by the poor cohesion between LS and SBr and also the formation of lumps during the mixing with the water added.

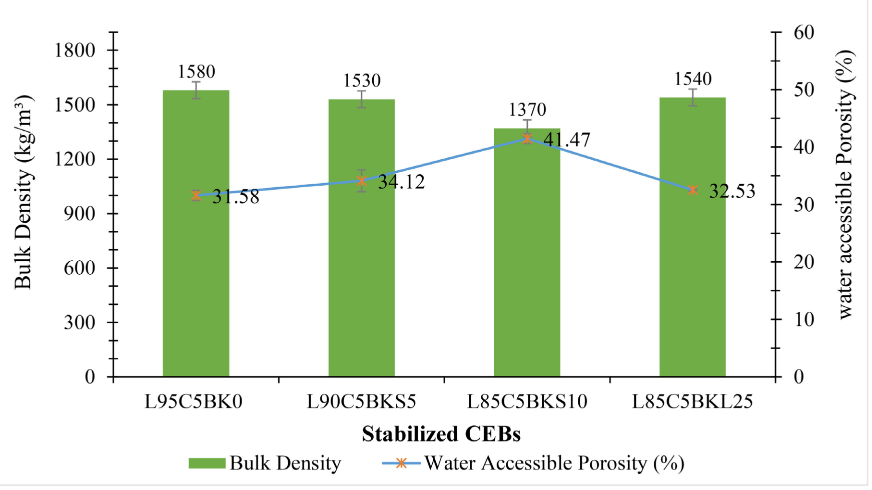

Figure 10. Bulk density and water-accessible porosity of Stabilized CEBs.

3.2.2. Compressive Strength in Dry and Wet Conditions

Figure 11 details the evolution of compressive strength in dry and wet conditions of CEBs stabilized with HL and SBr. The average dry compressive strength significantly decreased by the addition of SRSr from 3.26 MPa (Stabilized CEBs with HL) to 0.3 MPa (25 wt% SBSr) and 2.3 MPa (25 wt% SBLr). Additionally, the wet compressive strength of stabilized CEBs also decreased with the addition of SBr from 0.75 MPa (Stabilized CEBs with HL), to 0.10 MPa (10 wt% SBSr) and 0.60 MPa (25 wt% SBLr). The wet compressive strength of stabilized CEBs with 25 wt% SBRs could not be determined as they immediately degraded in water.

For the stabilized CEBs with 5 wt% HL, the optimum values obtained may due to the creation of bonds between the earth particles and the ions in solution during the hydration of the hydrated lime. These results are in agreement with 1.33 MPa [53] and 1.48 MPa [54].

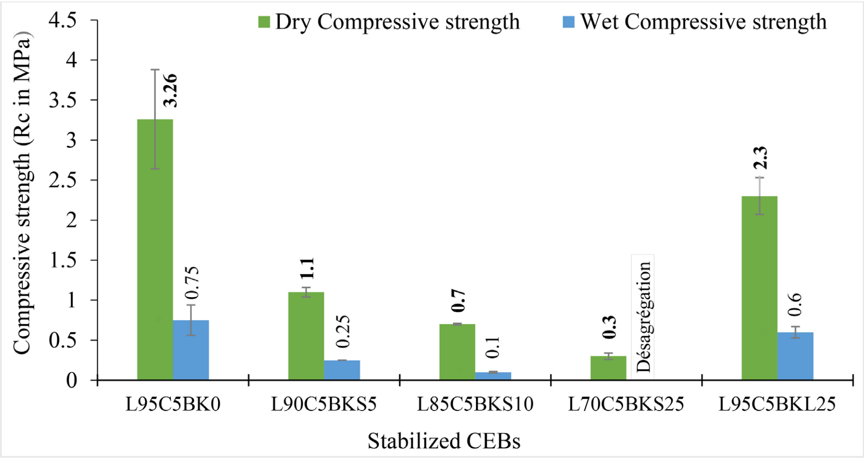

Figure 11. Dry and wet compressive strength of stabilized CEBs.

The sharp decrease in the strength of CEBs with 5 - 25 wt% SBSr and the slight decrease in strength of stabilized CEBs with 25 wt% BLr could be due to their high-water accessible porosity and low density.

However, these results present similar dry compressive strength with previous studies using 3 - 10 wt% SBSr [23]. According to previous studies, most standards recommended the minimum dry compressive strength of 2 MPa for CEBs-based construction. According to African Standards **ARS 674** [55], the stabilized CEBs with 5 wt% HL and stabilized CEBs with 25 wt% SBLr with dry compressive strength in the range of 2 - 4 MPa, could be used for non-load bearing walls. However, the other stabilized CEBs with dry compressive strength of less than 2 MPa did not meet this standard for each construction and should be excluded.

3.2.3. Structural Efficiency of Stabilized CEBs

The construction materials are used for structural or envelope components in one or multiple-story buildings, taking into account their structural efficiency. The coefficient of structural efficiency (CSE) is an important physical-mechanical parameter to assess the contribution of the strength and density of CEBs toward the load-bearing capacity in building construction [18]. The CSE of the stabilized CEBs is obtained by the ratio between the dry compressive strength and the bulk density. The stabilization with SBr did not improve the CSE which decreased by 34.84%, *i.e.* from 2063.29 Pa·m^3/kg (J/kg) for CEBs stabilized with 5% HL to 718.95 Pa·m^3/kg (J/kg) for CEBs stabilized with 5 - 25 wt% SBSr (*i.e.* 52.5%) and 1493.506 Pa·m^3/kg (J/kg) for CEBs stabilized with 25 wt% SBLr (*i.e.* 27.6%). This indicates also that the shea butter liquid residue had more effect than shea butter solid residue on CEBs structural efficiency by around 1.9 times. Finally, this suggests that the decrease in bulk density has negative effect on the structural efficiency of stabilized CEBs.

3.3. Durability of Stabilized CEBs Specimens

3.3.1. Abrasion Resistance

Figure 12 shows the evolution of abrasion coefficients (**Figure 12(a)**) and the mass loss (**Figure 12(b)**) of stabilized CEBs with HL and SBr. The abrasion coefficient (Ca) ranges from 14.49 cm²/g - 3.9 cm²/g depending on the addition rate of SBr and is 13.1 cm²/g for stabilized CEBs with 25 wt% SBLr versus a value of 13.03 cm²/g for stabilized CEBs with 5 wt% HL. The highest Ca (14.49 cm²/g) is obtained on the stabilized CEBs with 5 wt% HM and the lowest Ca (3.9 cm²/g) for stabilized CEBs with 25 wt% SBSr. We noted that the addition of SBr improved the Abrasion resistance of the stabilized CEBs with 10 - 25 wt% SRr. According to standard XP P13-901 concerning the normative value of Ca, the stabilized CEBs with (5 wt% HL, 5 wt% - 10 wt% SBSr and 5 wt% HL - 25 wt% SBLr with Ca > 7 cm²/g, are classed as CEB 60 used for external wall [47]. However, the stabilized CEBs with 25 wt% SBLr which Ca > 2 cm²/g are classed CEB 20 used for internal walls.

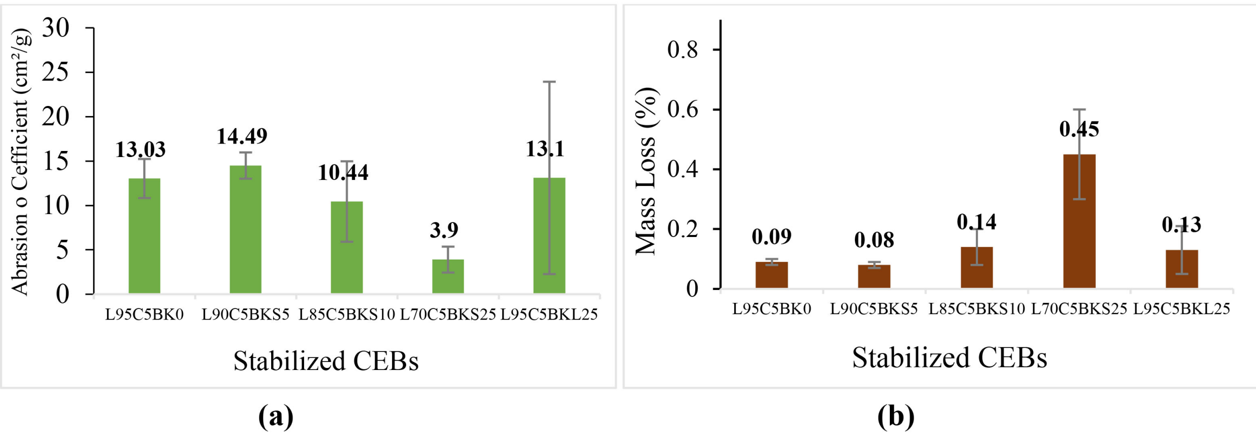

Figure 12. Evolution of Abrasion resistance (a) Abrasion coefficient (b) Mass loss of stabilized CEBs.

Furthermore, the mass loss of studied stabilized CEBs ranges from 0.45% to 0.08% depending on the type and the rate of stabilizer. The stabilized CEBs with 5 wt% HL - 25 wt% SBSr have the highest mass loss while the stabilized CEBs with 5 wt% HL - 5 wt% SBSr have the lowest, so the mass loss is inversely proportional to SBr rate in the mix. From these results, the mass loss is less than 10%, and then all the stabilized CEBs reach the recommendation limits of the standard ARS 675 [56].

3.3.2. Resistance to Erosion

Figure 13 shows the evolution of erodibility of stabilized CEBs, in particular depth (**Figure 13(a)**) and eroded surface (**Figure 13(b)**). We noted that the stabilized CEBs with 5 wt% HL-10 wt% SBSr, 5 wt% HL, and 5 wt% HL - 25 wt% SBLr have the greatest depths respectively 4.37 mm/h; 3.25 mm/h and 3.12 mm/h versus the lowest value of 2.88 mm/h for stabilized CEBs with 5 wt% - 5wt% SBSr. The stabilized CEBs 5 wt% - 25 wt% SBSr could not be tested due to their sensitivity to water. The literature, previous studies of stabilized CEB with 7 wt% cement, 5/7 wt% cement/lime and 1 wt% fibers found respectively eroded depth of 1 mm/h, 20 mm/h and 55 mm/h [57]. According to standard NZS 4298 [58], the limit value of erosion depths must be less than 120 mm/h [42]. Consequently, the studied stabilized CEBs can be classified as non-erodible blocks except the stabilized CEBs with 5 wt% HL - 25 wt% SBSr.

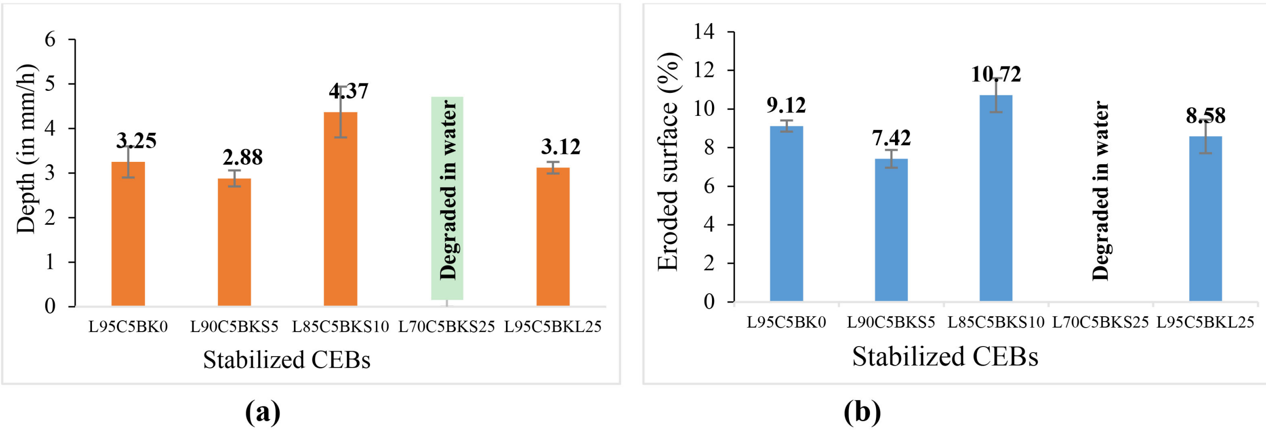

Figure 13. Evolution of stabilized CEBs erodibility (a) erosion depth, (b) eroded surface.

On the other hand, the eroded surface areas are 7.42; 10.72 and 8.58 cm^2 respectively for the various stabilized CEBs with 5 wt% HL - 10 wt% SRSr, and 5 wt% HL - 25 wt% SBLr, versus stabilized CEBs with 5 wt% HL (9.12 cm^2). These results testify the addition of SBr increases the stabilized CEBs erodibility. Despite this finding, the stabilized CEBs with 5 wt% HL - 10 wt% SRSr have higher eroded depth and surfaces (*i.e.* 17.5% more than stabilized CEBs with 5 wt% HL). So, the rate of stabilizer SBr influences the stabilized CEBs erodibility resistance. This could be explained by the poor cohesion between LS-HL-SBr, and also the rougher surfaces of these stabilized CEBs and the areas of brittleness displayed during their manufacture.

3.3.3. Capillary Absorption

Figure 14 shows the evolution of stabilized CEBs capillary absorption as a function of the square of time. We noted that the absorption varies according to the nature and the rate of the stabilizer. The slope, line gave us the sorptivity, which represents the rate of water absorption by capillary. Sorptivities range from 0.046 - 0.097 $g/cm^2 \cdot min^{1/2}$ for stabilized CEB with 5% HL - 5 - 25 wt% SBr, versus 0.077 $g/cm^2 \cdot min^{1/2}$ stabilized CEB with 5% HL. The low sorptivity is attributed to stabilized CEBs with 5% HL - 5 wt% SBr (0.046 $g/cm^2 \cdot min^{1/2}$) and the greatest for stabilized CEB with 5% HL - 10 wt% SBr (0.097 $g/cm^2 \cdot min^{1/2}$. This CEB behavior is probably linked to the water-repellent (moisture-preserving) properties of Shea butter residue. Thus, it is the presence of flat in shea butter that makes stabilized CEB more or less impermeable [41]. The results of durability studies on geomaterials with shea decoction have shown similar trends [44].

3.3.4. Total Immersion Absorption

Figure 15 shows the stabilized CEB water absorption by total immersion after 2 hours and 24 hours. It can be seen that the stabilized CEB with 5 wt% - 5 wt%

SBSr have lower water absorption of 4.06% and 11.94 % versus 6.26 et 24.52% for stabilized CEB with 5 wt% - 10 wt% SBSr. However, the ratio Ab_{2H}/Ab_{24H} of stabilized CEB varies from 0.26 - 0.46. Consequently, more than 26% - 46% of the porous microstructure is highly water accessible over a short period. Izemmouren *et al.* (2019) carried out studies on stabilized CEB with 6 - 10 wt% lime and presented a water absorption by total immersion from 10.1% - 13.5% [59]. Moreover, similar values (13.6% - 16.5%) were observed for stabilized CEB with 8 wt% cement and 4/4 wt% cement/lime by Bogas *et al.* (2019) [60].

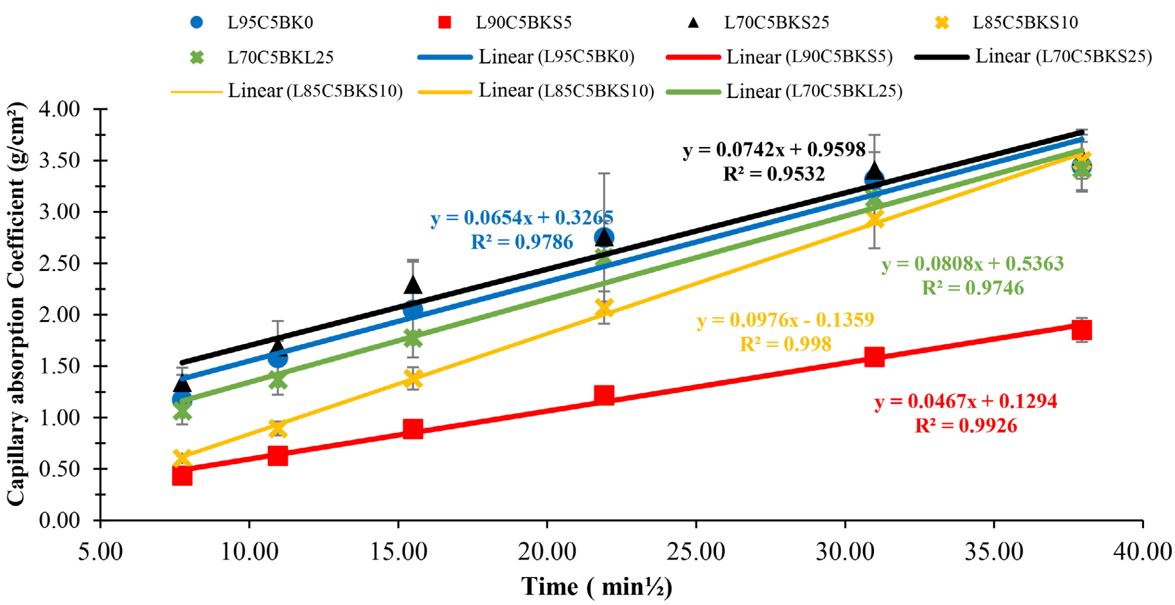

Figure 14. Capillary Absorption of stabilized CEB.

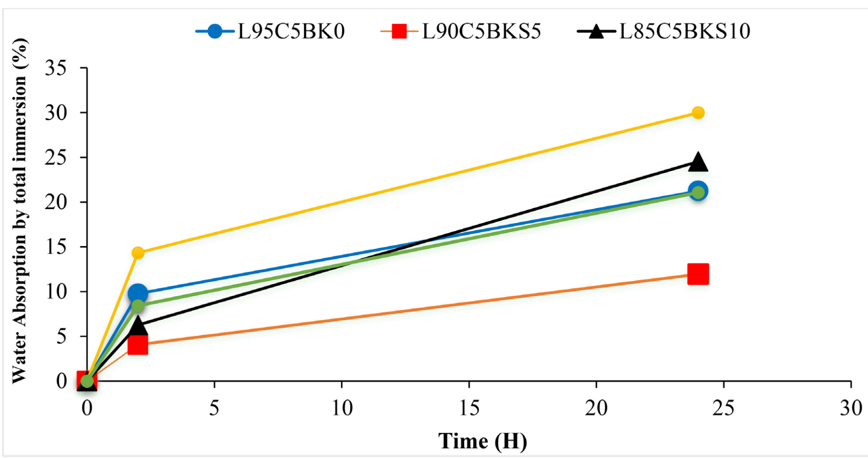

Figure 15. Water Absorption by total immersion of stabilized CEBs.

3.4. Thermal Properties

The thermal properties of CEBs were also improved by the stabilization with by-product Shea butter residues. Figure 16 shows the stabilized CEB thermal parameters results.

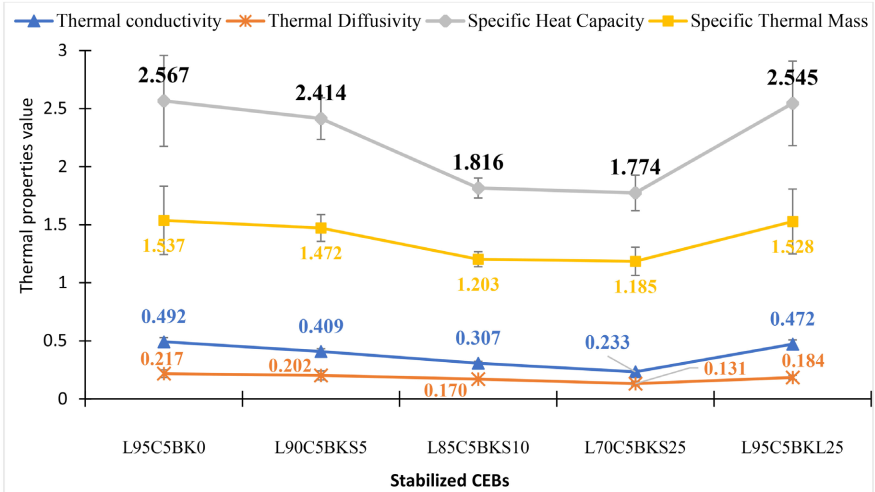

Figure 16. Graph of the thermal properties of stabilized CEBs.

The average value decreased in the range of 0.492 to 0.233 W/m·K, for thermal conductivity (*i.e.* 52.64%), 0.217 to 0.131 mm^2/s, for thermal diffusivity (*i.e.* 39.63%), 2.567 to 1.774 $MJ/m^3 \cdot K$, for specific heat capacity (*i.e.* 30.89%), 1.537 to 1.185 kJ/kg·K for specific thermal mass (*i.e.* 22.91%), measured on CEB stabilized with 0 - 25 wt% SBr. These results indicated that the CEB stabilized with HL/SBr has excellent thermal parameters than CEB stabilized only with HL, so the Shea butter residue improve the CEB thermal properties.

The thermal properties change with the rate of HL in the mix and their values decrease inversely proportionally to the HL rate. This could be due to these stabilized CEB low density and the porosity. The effect on the agricultural by-products gave similar conclusion on CEB stabilized with (1 wt% fiber + 1 wt% lime) and (1 wt% fiber + 3 wt% lime) with the respective value of 0.80% ± 0.30% W/m·K and 0.69% ± 1.73% W/m·K for thermal conductivity and 708.97% ± 0.24% and 876.29% ± 0.60% J/˚C·kg for specific heat capacity [12]. It's the case of similar values of thermal conductivity range from (0.667 to 0.798 W/m·K), thermal diffusivity range from (2.24×10^{-7} m^2/s to 3.055×10^{-7} m^2/s) and the specific thermal mass (1.508 to 1.584 kJ/kg·K) obtained on CEB stabilized with 3 - 10 wt% SBSr [23].

4. Conclusions

This paper investigated the technical properties of CEBs resulting from the stabilization of laterite soil with industrial and agricultural by-products. The object was to determine the Stabilized CEBs properties with locally available raw materials such as laterite soil (LS), hydrated lime (LS) and shea butter residue (SBr). The identification test previously carried out revealed that the raw laterite soil is not very clayed according to standard LPC classification. The various tests performed show that the HL and SBr affected the stabilized CEBs properties and behavior. The main conclusions were as follows:

- Concerning the physical properties, the maximal value of porosity (41.47%) and minimum density (1370 kg/m^3) were observed on CEBs stabilized with SBr.
- In terms of mechanical resistance, despite the reduction of compressive strength due to the addition of SBSr, the CEBs stabilized with 5 wt% HL and 25 wt% SBLr present a dry compressive strength superior to 2 MPa recommended for earth-based constructions of one-story buildings. However, these CEBs should not exposed to a wet environment, using a coating or technical protection system, because the wet compressive strength failed around 75.5%. The structural efficiency was not evidenced by the decreased bulk density and the dry compressive strength which is accompanied by the decrease of the CSE of stabilized CEBs.
- The durability properties of stabilized CEBs were evidenced by the improvement of the abrasion coefficient, mass loss, erodibility and water absorption using an appropriate stabilization rate. All the stabilized CEBs studied have an Abrasion coefficient of more than 7 g/cm^2 except CEBs stabilized with 5/25 wt% HL/SBSr and the low mass loss is obtained with CEBs stabilized with 5/5 wt% HL/SBSr. Furthermore, for the erodibility test, CEBs stabilized with 5/5 wt% HL/SBSr are more resistant by the lowest eroded depth and surface than the overs stabilized CEBs. In terms of water properties, the CEBs stabilized with 5/5 wt% HL/SBSr had the lowest sorptivity and the lowest absorption by total immersion for 2 hours and 24 hours.
- The thermal efficiency of the stabilized CEBs can be observed by the decrease in thermal properties measured. And the lowest values are obtained with the CEBs stabilized with 5/25 HL/SBLr.

To complete these results, further investigation should be carried out on the hydric and water-repellent and engineering properties of a coating formulated based on shea butter residues.

Authors' Contributions

Conceptualization: E.M., O.Y., C.H, A.M.; methodology: E.M., O.Y., C.H, A.M.; formal analysis and investigation: E.M., O.Y., C.H., M.N., A.M.; writing—original draft preparation: E.M. O.Y; writing—review and editing: E.M., C.H., A.M.; All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

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

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