

# Mechanical, Thermal and Hydric Behavior of the Bio-sourced Compressed Earth Block (B-CEB) Added to Peanut Shells Powder

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**Abstract:** Bio-sourced compressed earth blocks (B-CEB) were manufactured with raw soil material and peanut shells powder to produce building material with feeble environmental impact and better mechanical and hydric performances. The objective of this work is to add value to two local natural raw materials namely earth and peanut shell in the production of B-CEB with low thermal conductivity, better water resistance, and better mechanical strength. Mineralogical studies (by XRD, DTA-TG), chemical and geotechnical studies (Atterberg limits, particle size distribution) carried out on this clay have shown that it is composed of kaolinite (40 wt.%), muscovite (8 wt.%), quartz (34 wt.%), and goethite (10 wt.%). It is a sandy-silty clay of medium plasticity containing no swelling minerals. Its particles are mainly clay (50 wt%), silt (32 wt%), fine and coarse sand (18 wt%). The clay raw material used in this study is referenced BAM. The peanut shells powder, used in range of 10 to 40 wt.% to improve the raw soil, mainly contains the cellulose type I. The apparent density of B-CEB decreases when the peanut shells content increases. By contrast, the porosity increases and was greatly affected by the addition of peanut shells powder. With 20 wt.% of peanut shells powder the porosity of B-CEB increase about 67% compared to the porosity of the reference (untreated B-CEB). Mechanical properties were enhanced with peanut shell content between 15 to 25 wt.% and reached the maximum with 20 wt.%. The B-CEB becomes more ductile when the peanut shells content increases. All the elaborated B-CEB, except the B40, are in the category of the construction of load-bearing wall which is characterized by the strength higher than 4 MPa. With 15 to 30 wt.% of peanut shells powder, the resistance of B-CEB to rain erosion was enhanced. With 30 wt.% of peanut shells powder, thermal conductivity was reduced by about 43% compared with untreated B-CEB. Given the improvement of different properties, the peanut shells powder can be used in the range of 15 to 25 wt.% to stabilize the B-CEB for the construction of habitats with better durability and thermal comfort.

**Keywords:** Bio-sourced Material, Compressed Earth Block, Peanut Shell, Mechanical Property, Thermal Conductivity, Rain Erosion

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## 1. Introduction

In Burkina Faso, the majority of the population does not have access to the durable habitat. The price for construction using the so-called modern building materials, such as cement, steel, is exorbitant. The country does not have the necessary resources to produce these materials at competitive prices making them inaccessible to a large number of populations. The import of raw materials and the lack of energy sources are the main causes of the perpetual increase in the price of these industrial materials.

This makes the majority of the population builds their construction using earth bricks. Earth is a noble material, locally available in abundance, disposable and recyclable [1-3]. Its hygroscopic and thermal properties and facility to use are other advantages linked to earth [4, 5] Earth is an ecological material because it needs less energy for the production and released less CO<sub>2</sub>. The lifespan of earth-based construction is more than 100 years [6]. All these qualities of earth shows that it is a material which takes into account the socio-economic and environmental aspects of the built environment. It is therefore a convenient material for building construction in an arid and hot climate such as in Burkina Faso.

Despite the many advantages of earth, the construction using adobes, molded earth bricks, has low durability linked to their poor resistance to mechanical and water damage [7]. These issues are related the poor cohesion of the clay matrix and the appearance of a large number of pores and eventually cracks during the production of adobe earth bricks. To mitigate these problems, many stabilization methods of earth bricks have been proposed to improve the physical and mechanical properties and especially water resistance and thermal comfort. Compressed earth block (CEB) is the most common product obtained by mechanical (compaction) stabilization of earth bricks.

CEB is a modern evolution of molded earth blocks, more commonly known as adobe blocks [8]. Indeed, the compaction can allow to obtain a material with high mechanical characteristics. However, this material remains sensitive to water. Many researchers have proposed the used of inorganic (mineral) binders such as cement and/or lime to improve (stabilize) the performances of CEB. These industrial binders enhance the physical, mechanical, and water resistance properties CEB; but limits the possibilities to recycle the earth materials and increases its environmental impact. Alternatively, other studies have reported that geo-sourced binders and binders from by-products (wastes) sources improve the performances of CEBs; which at the same time limits their impact to the environnement and the consumption natural resources [7, 9-11].

Furthermore, organic vegetable fibers have been proposed by many researchers, in last few years, to substitute inorganic binders in the stabilization of CEB. CEB was stabilized with date palm fiber [12], banana fiber [13], wood chips [14], alfa fiber, and hibiscus cannabinus

fiber [15, 16]. For many cases of studies, the vegetable was used in fiber form with in content between 1 to 10 wt.%. The vegetable were a rarely used in percentage exceeding 10 wt.%. The stabilized of CEB using vegetable fiber provides a significant energy saving gain in comparison to inorganic binders and reduces the thermal conductivity of B-CEB (bio-CEB). This can improve the thermal comfort of constructions and contributes to the reduction of greenhouse gas production. Many studies on B-CEBs have shown that the incorporation of vegetable fibers reduces the propagation of cracks, improves its durability and tensile strength, or at least decreases the thermal conductivity of composite materials. Also, some contradictory results have been reported about the increase of mechanical properties with the use of natural fibers. Rigassi et al [17] stated that the plant fibers are incompatible with the method of compaction of CEB, because they make the mixture too elastic.

The objective of this work is to add value to two local natural raw materials namely earth and peanut shell in the production of B-CEB with low thermal conductivity, better water resistance, and better mechanical strength. The scientific novelty of this work is to highlight the use of peanut shells powder at a high rate in the elaboration of bio-sourced material for construction. The different results will allow a significant advance in the availability of sustainable construction materials with a low environmental impact and accessible by the rural population of Burkina.

## 2. Materials and Methods

### 2.1. Raw Materials

The clay soil used in this work, referred to as BAM, comes from Kongoussi (13°18'North; 1°30'West) in the north-central of Burkina Faso. This site is heavily exploited by the local population for pottery and the production of construction materials (bricks, roof or wall tiles).

The agricultural waste used of this work is the peanut shells. It is a by-product of a leguminous plant called peanut, *Arachis Hypogaea L.* The peanut belongs to the subfamily of *Papilionaceae* in the family of *Fabaceae*. It is a flowering plant with a height of around 20 to 90 cm, and grows in warm areas due to its resistance to heat and drought. Peanut is a grown mainly for its seeds and oil. It is the sixth-largest source of oil production in the world (FAO 2003). Peanut production in Africa is important according to FAOSTAT data for five countries (Table 1). Peanut shells are generally abandoned in crop fields without a very important recovery. In this study, the raw shells were crushed into powder and sieved to collect the passing on 210 µm, before it used in the production of CEB. Peanut shells powder was referred to as PSP in the rest of the paper.

**Table 1.** Annual production of peanut (FAOSTAT 2020).

Year	Burkina Faso	Ghana	Mali	Sénégal	Tchad
2015	365 887	417 199	421 924	1 050 042	720 138
2016	519 345	425 825	374 318	719 000	871 249
2017	334 328	433 772	301 207	915 000	870 094
2018	329 783	521 032	312 264	846 021	893 940

## 2.2. Methods

### 2.2.1. Characterization of Raw Material

Before The size distribution of raw soil BAM was performed using two methods. The coarser fraction ( $>80\mu\text{m}$ ) was analyzed by wet sieving and the finer fraction ( $<80\mu\text{m}$ ) by sedimentation methods according to standards NF P 94-056 [18] and NF P 94-057 [19]. The Atterberg's limits were determined according to standards NF P 94-051. The methylene blue value was determined according to the standard NF P 94-068 [20].

The chemical composition of the raw soil BAM was determined with X-ray fluorescence. Loss on ignition was obtained by calcining the sample up to a temperature of  $1000^\circ\text{C}$ .

The crystalline phases of raw soil and peanut shells were identified using diffractometer Siemens D5000 equipped with a monochromatic lamp with a cobalt anticathode and using the  $K\alpha$  radiation ( $\lambda = 1.789 \text{ \AA}$ ).

The identification of the phase of the raw material was completed using thermal analysis methods and infrared spectroscopy. Thermal analyses were carried out using SETARAM Setsys 24 at heating rate of  $10^\circ\text{C}/\text{min}$ . The infra-red spectra of a peanut shell were recorded using PERKIN ELMER FT – IR BX operating between  $4000 \text{ à } 500 \text{ cm}^{-1}$ .

The coupling of the results of the X-ray diffraction and those of the elementary chemical analysis allowed us to semi-quantitatively evaluate the composition of the mineral

phases contained in the sample using equation 1, proposed by Yvon et al [21].

$$T(a) = \sum M_i P_i(a) \quad (1)$$

With:  $T(a)$  the percentage of oxide « a » in the raw soil;

$M_i$  the percentage of mineral phase « i »;

$P_i(a)$  the percentage of oxide « a » in the mineral phase « i ».

### 2.2.2. Production and Characterization of B-CEB

The two raw materials were grounded until particle size less than  $210 \mu\text{m}$ . Different mixtures (B0, B10, B15, B20, B25, B30, B40) of BAM and PSP were made with PSP contents varying between 0 to 40 wt.%, according to table 2. A varying amount of water was added until a slightly moist mixture was obtained. The obtained mixture was stored in a hermetically sealed plastic bag at controlled room temperature ( $25^\circ\text{C}$ ) for 48 h to allow ripening. The moistened mixture with constant mass was introduced into a cylindrical of height 160 mm and diameter 50 mm (160 mm x 50 mm) or prismatic (40mm x 40mm x 160 mm) mold and pressed using uniaxial (vertically) mechanical press PRUFSSYSTEME DigiMess M-10. The compaction force used is 10 MPa. The compressed earth blocks were demoulded and then dried on the shade for 21 days at room temperature ( $30 \pm 7^\circ\text{C}$  with an average humidity of  $45 \pm 5\%$ ) to avoid sudden drying and the appearance of cracks. Figure 1 shows the formulated B-CEBs after drying for 21 days.

**Figure 1.** Image of B-CEB after 21 days.**Table 2.** Proportion of PSP and soil in the elaboration of B-CEB.

Reference	B0	B10	B15	B20	B25	B30	B40
Soil (wt.%)	100	90	85	80	75	70	60
PSP (wt.%)	0	10	15	20	25	30	40
Water (wt.% of soil + PSP)	19	21	23	25	26.5	28.5	30.5

Scanning Electron Microscope (SEM) and energy dispersive spectrometry (EDS) analyses of B-CEBs fracture facies was performed using a JEOL 6380 LV device equipped with a backscattered electron (BSE) detector. Direct observations were made using SEM in low-vacuum (LV) mode (no metallization necessary, with a pressure of 60 Pa in the SEM chamber). The elemental quantitative analyses were performed by the energy dispersive spectrometry (EDS) technique using a Brüker X Flash 6/30 detector.

The performed mechanical properties of B-CEBs were compressive strengths. The different tests were made according to standards NF P18 – 406 using a hydraulic press equipped with a 10 kN load cell at a controlled displacement rate of 0.2 kN/s.

The hydric parameters which were tested are water absorption and rain erosion. The water absorption by capillarity of B-CEBs was evaluated according to standards NF EN 1015-18 [22]. The water absorption coefficient ( $C_b$ , g/(cm<sup>2</sup>.min<sup>0.5</sup>)) was calculated using equation 2.  $P_1(g)$  is the weight of B-CEB after capillary water immersion,  $P_0(g)$  the weight of B-CEB before water immersion,  $S(\text{cm}^2)$  the area of immersed face of B-CEB, and  $t(\text{min})$  the immersion time.

$$C_b = \frac{100(P_1 - P_0)}{S\sqrt{t}} \quad (2)$$

The resistance of B-CEBs to rain erosion was evaluated by the spray test. To do so, the B-CEB dried at 105°C was tilted at 30° with respect to the vertical and water was spray onto the surface in fine droplets for 10 min under a pressure of 2 bars. The B-CEB after the test was dried at 105°C for 24 hours and the difference between the mass before and after the test indicates their resistance to rain erosion [23].

The thermal conductivity of B-CEBs was measured using a TR-1 probe (2.4 mm diameter, 10 cm long, working range of 0.1-4 W.m<sup>-1</sup>. K<sup>-1</sup> connected to a KD2 Pro thermal properties analyzer. The probe was introduced into a hole made in the center of the test piece so that it was not in contact with the air. The measurements were done at around 32°C.

The apparent density of adobe was assessed by hydrostatic

weighting according to the standards NF P 94-053. The closed porosity of adobe was deduced from equation 3. Where,  $\eta$  is the closed porosity,  $d_s$  the density of B-CEB, and  $d_g$  the density of grains (mixture of clay and PSP) calculated according to the equation 4. Where,  $d_{soil}$  is the density of raw soil and  $d_{PSP}$  the density of PSP.

$$\eta = \left(1 - \frac{d_s}{d_g}\right) * 100 \quad (3)$$

$$\frac{1}{d_g} = \frac{\% \text{ Soil}}{d_{soil}} + \frac{\% \text{ PSP}}{d_{PSP}} \quad (4)$$

All results were obtained by averaging four bricks per nuance.

## 3. Results and Discussion

### 3.1. Characteristics of Raw Materials

X-ray diffraction pattern (Figure 2) of soil shows that it consisting of quartz (SiO<sub>2</sub>), kaolinite (Al<sub>2</sub> (Si<sub>2</sub>O<sub>5</sub>) (OH)<sub>4</sub>), goethite ( $\alpha$ -FeO(OH)), and muscovite (KAl<sub>2</sub> (AlSi<sub>3</sub>O<sub>10</sub>) (OH)<sub>2</sub>). The thermal analysis curves (Figure 3) show a large endothermic peak around 95°C associated with weight loss of 2.6% corresponding to the departure of hygroscopic water of the raw soil. The endothermic peak at 394°C associated with weight loss of 1.95% indicates the dehydroxylation of goethite into hematite. The large endothermic peak around 510°C with a weight loss 4.49% shows the transformation of kaolinite into metakaolinite. The small peak at 574°C corresponds to the transformation of quartz  $\alpha$  to quartz  $\beta$ . The only exothermic peak at 934°C corresponds to the reorganization of metakaolinite into spinel or mullite phase.

The main oxides in BAM (Table 3) are SiO<sub>2</sub> (56.60%), Al<sub>2</sub>O<sub>3</sub> (18.69%), Fe<sub>2</sub>O<sub>3</sub> (9.26%) and K<sub>2</sub>O (0.95%). Semi-quantitative evaluation (table 4) indicates that BAM contains quartz (34 wt.%) and kaolinite (40 wt.%) as the main crystalline phases with a significant content of goethite (10 wt.%) and muscovite (8 wt.%).

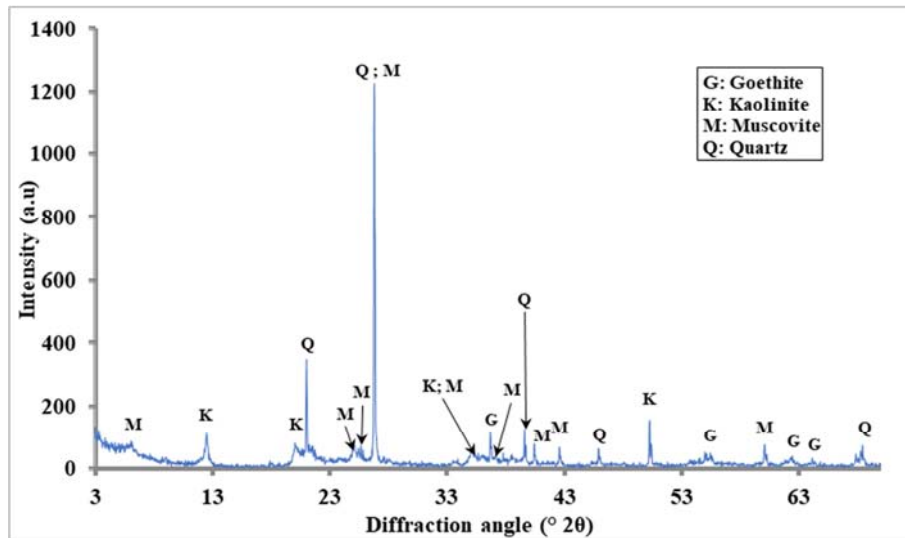


Figure 2. X-ray diffraction of clayey material.

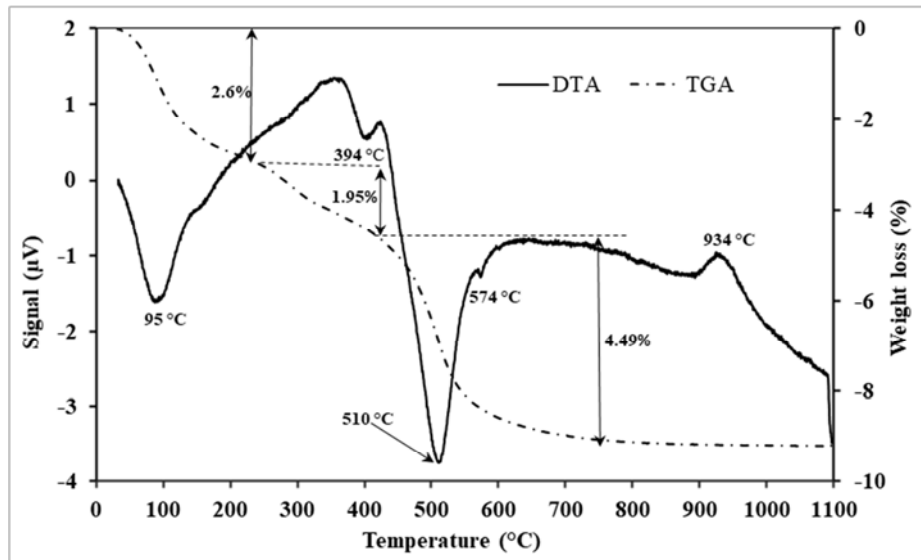


Figure 3. DTA – TGA analyses of clayey sample.

Particle size distribution (Figure 4) shows that BAM is composed of 2 wt.% of coarse sand, 16 wt.% of fine sand, 32 wt.% of silt (2-20  $\mu\text{m}$ ), and 50 wt.% of clay (<2  $\mu\text{m}$ ). The quantity of clay is outside the upper limits of the granular specifications proposed by the standard NF XP 13-901 on CEB [24]. However, these reference curves are indicative data for CEB. The used clay in this study is exploited by the local population for the manufacture of adobes. There are, in fact, other recommendations on soil

granularity in the literature which do not always achieve consensus.

Atterberg's limits: liquidity limit, plasticity limit and plasticity index are respectively  $W_L = 45\%$ ,  $W_P = 23\%$ , and  $I_p = 22\%$ . the plasticity index and methylene blue value (4.44 g/100 g) show that BAM is a silty clay with medium plasticity. According to CRATERre-EAG [24] criteria, the plasticity index and the liquid limit shows that BAM is suitable for the production of CEBs.

Table 3. Chemical composition of clayey raw material.

Oxides	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	LOI	Total
wt. %	56.60	18.69	9.26	0.08	0.65	0.44	0.21	0.95	1.32	12.29	100.48

Table 4. Semi-quantification of mineral phases of raw clayey material.

Mineral	Kaolinite	Quartz	Goethite	Muscovite	Balance	Total
wt. 1%	40	34	10	8	8	100

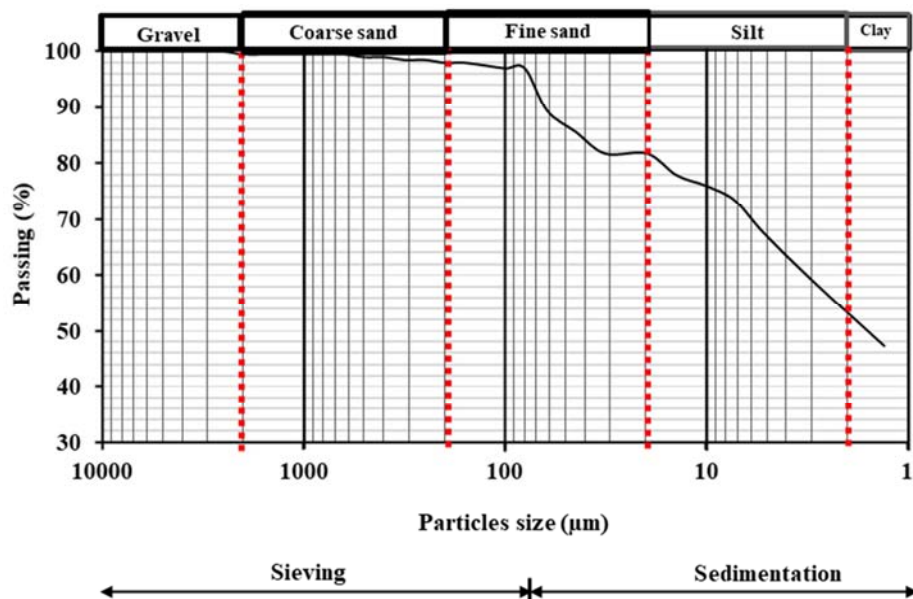


Figure 4. Particle size distribution of raw clay material.

The infrared (IR) spectra of PSP is reported in Figure 5. The stretching O-H bond and C-H bond respectively around 3345 and 2922  $\text{cm}^{-1}$  were assigned to cellulose [25, 26]. The stretching C=O bond at 1603  $\text{cm}^{-1}$  was related to the acetyl group in hemicelluloses or the ester and carboxylic acid in hemicelluloses, lignin, or pectin. The C-O stretching at 1165 and 1029  $\text{cm}^{-1}$  were attributed to the aryl group in lignin [27-29]. The IR of used peanut shells seems to be similar to previous spectra obtained with peanut shells from another zone of Burkina Faso [30].

The diffractogram of PSP (Figure 6) shows the principal peak at  $26.58^\circ 2\theta$ , which corresponds to  $d_{002}$  of cellulose type I, showing that cellulose of type I is the main crystalline phase in the PSP. The presence of a large peak at  $12.30^\circ$ ;  $23^\circ$ ;  $26.58^\circ$ ;  $34.84^\circ$ ;  $40.40^\circ$  and  $50^\circ 2\theta$  corroborates the fact that cellulose type I is the main crystalline phase in peanut shells. The peaks at  $21^\circ$  and  $23^\circ 2\theta$  respectively for a plan  $(1\bar{1}0)$  and  $(110)$  are very distinct and show that the cellulose of peanut has high crystallinity [31]. The crystallinity index of cellulose is estimated in equation 5, from the empirical formula of Segal [32]. Where,  $I_{002}$  the intensity of diffraction peak at  $2\theta = 25.8^\circ$

and  $I_{am}$  the intensity of the diffraction peak at  $2\theta = 18.68^\circ$  [33].

$$I_C = \frac{I_{002} - I_{am}}{I_{002}} \times 100 \quad (5)$$

The determined index of 70% is very high and indicates that cellulose is very ordered, which justifies the best quality of the X-ray diffraction pattern. This result is different from the index found with the peanut shell in previous study of Bobet and al.[30], and this value was of 28.47%. The difference can be explained by the difference between the variety in cultivating the peanuts in the two-zone.

### 3.2. Microstructure of B-CEBs

The SEM image of the fractured surface of B-CEBs, after the compression test, is given in Figure 7. The reference B0, without PSP, shows a homogeneous and dense material.

However, micro-cracks are observed either due to the departure of water or to the applied force during the compression test. B15 is also homogeneous with some microfibers soaked in the soil matrix.

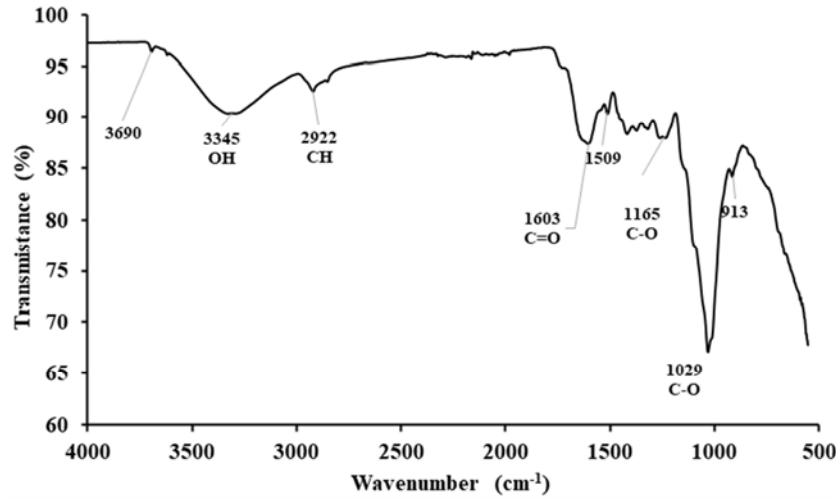


Figure 5. FTIR of peanut shells powder.

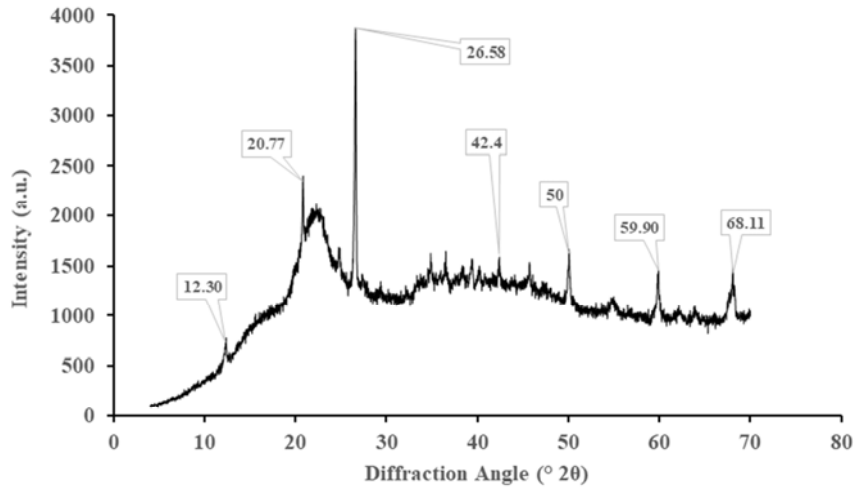


Figure 6. X-ray diffraction of peanut shells powder.



With 25 wt.% of PSP, the material (B25) becomes heterogeneous with microfibers well adhered to the soil matrix. With 35 wt.% of PSP, the obtained material (B35) is highly heterogeneous with microfiber stacking per location.

The SEM image (Figure 8) of B-CEB containing 30 wt.% of PSP at magnification  $\times 100$  shows a better adhesion between the soil matrix and the microfiber of PSP. However as shown the material B35, the obtained material B30 has a less dense aspect. The elementary chemical analysis (Table 5) for two-zone of the fractured surface of B30 did not present a significant difference. The principal element are Si, Al and Fe. The presence of sulfuric element S at relatively high content in the zone referenced '53' compared to zone '52' is interesting. The element S provided by peanut shells can participate in the

formation of bonds between molecules which can improve the mechanical properties of B-CEB [34].

### 3.3. Physical Properties of B-CEBs

Open porosity and apparent density of B-CEB (Figure 9) varied in an opposite directions as expected. According to Sore et al [8], the more porous a sample is, the lower its density and vice – versa. The density of B-CEB varied from 2010 to 1240  $\text{kg/m}^3$  with the PSP content increasing from 0 to 40%. When the content of PSP increases, the density of B-CEB decrease.

The substitute of raw soil (density 2570  $\text{kg/m}^3$ ) by the peanut shells (density 1400  $\text{kg/m}^3$ ), which are less dense, justifies the reduction of density.

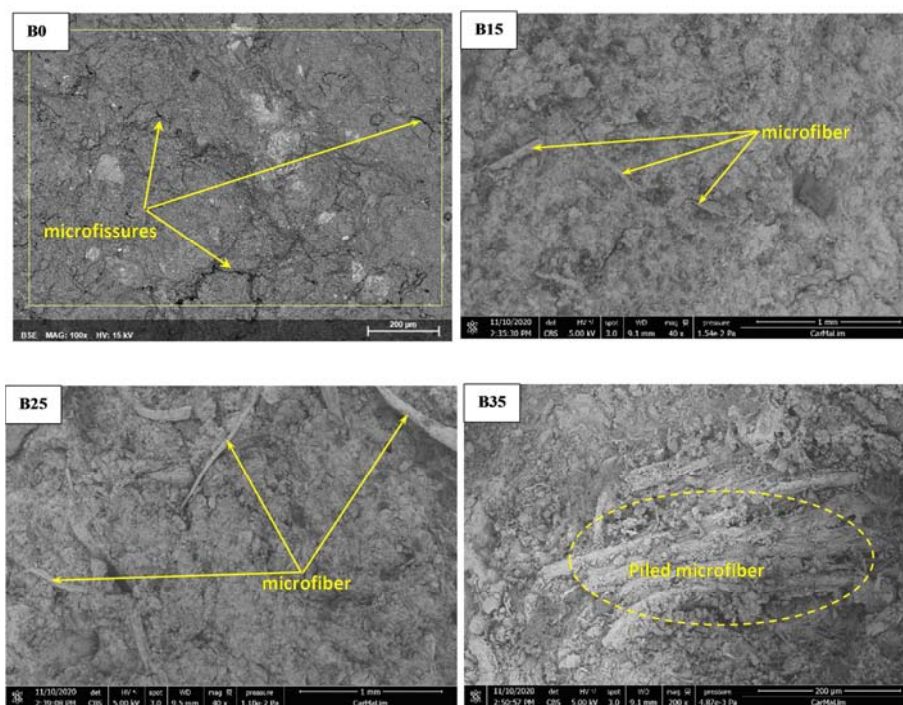


Figure 7. SEM image of fractured surface of B-CEB: B0, B15, B25, B35.

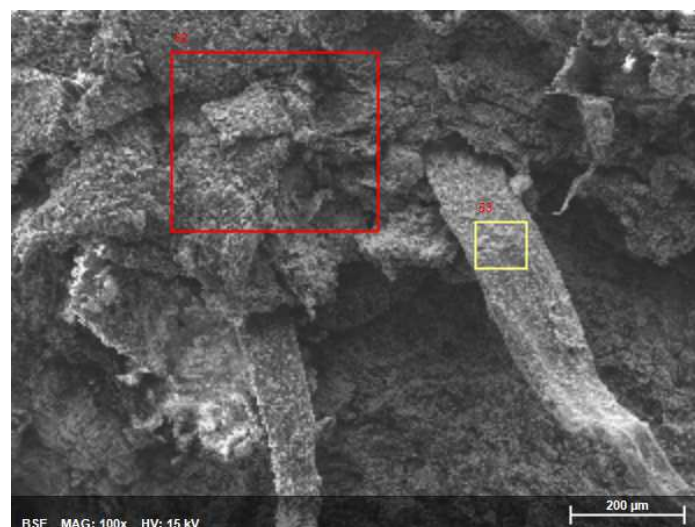


Figure 8. SEM image of B30.

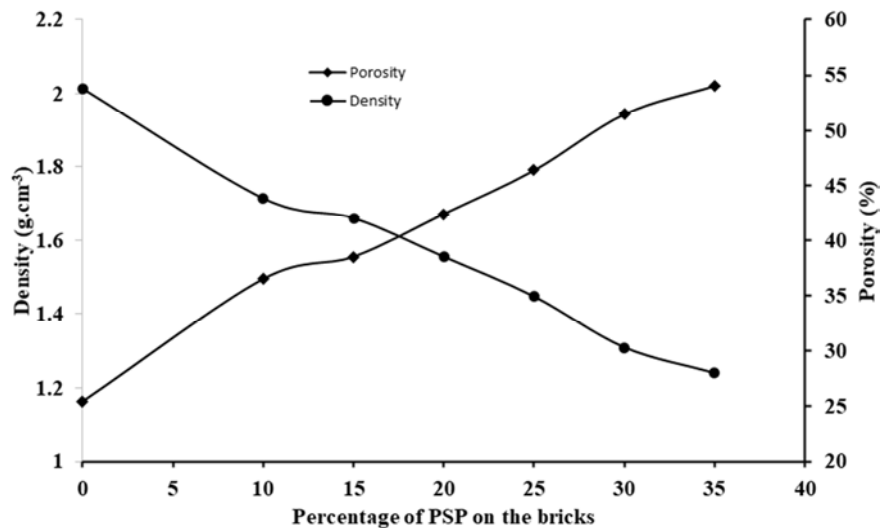
**Table 5.** Mineralogical analysis of some B-CEB areas.

Zone	Si	Al	Fe	K	Ti	Ca	Mg	S	Na	O
52	19.94	10.39	3.01	1.47	0.45	0.59	0.51	0.12	0.28	63.23
53	17.64	11.74	3.43	1.81	0.76	0.99	0.31	0.29	0.55	62.48

Commonly, the density of CEB varied between 1500 and 2000 kg/m<sup>3</sup> [35]. Beyond 20 wt.% of PSP, the density of B-CEB was slightly feeble than the common values. It should be noted that the use of 20 wt.% of PSP significantly reduces the density of B-CEBs at 23%. A similar reduction (around 25%) was reported by Khoudja et al [36] during the stabilization of adobe with 10% of date palm waste. Sore et al [8] stabilized CEB using cement and geopolymer and found the density ranging in 1600 – 1900 kg/m<sup>3</sup>. Mansour et al [37] obtained CEB characterized by density varied between 1320 to 2190 kg/m<sup>3</sup> when the compaction pressure varied from 0.39 to 3.16MPa. The density of CEB according to previous studies depends on the applied pressure for the compaction, the nature of the soil, and the nature of the additive. The use of peanut shells in the powder form and at a relatively high percentage explains the low values of obtained density compared to those found in the literature.

Open porosity of B-CEB increase with the increase of PSP

content and ranges from 25.40 to 54.07%. As for the density, the values of porosity of B-CEB corroborates with those reported in previous study, for PSP content less or equal to 20%. Lawane et al [38], in their study about the mechanical and physical properties of stabilized compressed coal bottom ash blocks with the inclusion of lateritic soils, have obtained a CEB characterized by porosity between 33 and 40%. Sore et al [9] reported the porosity of 37.63% for CEB stabilized with 15% of geopolymer. The increase of porosity is attributable to the intrinsic porosity of PSP and its air-entraining effect during formulation which contributes to increasing the number of open pores accessible by water. According to Ouattara et al [39], the stabilization of CEB with 10 wt.% of sawdust creates more interconnected pores which facilitate the flow of water. With 20 wt.% of PSP, the porosity of B-CEB increase by about 67% and for 35% of PSP, the porosity of B-CEB is slightly greater than twice that of the reference.

**Figure 9.** Porosity and density of B-CEB.

### 3.4. Mechanical Properties of B-CEBs

The simple compression test is an important test for predicting brick quality. Mechanical compressive strength of B-CEBs was given by table 6. Compressive strength increases with the increase of PSP up to 20%. The use of 20% of PSP as an additive in B-CEB increases the mechanical strength by around 23%. After this percentage, the compressive strength decreases until it reaches the value less than the strength of the reference (B0). The increase of compressive strength is due to the combined filling effect of the finer particle of PSP and the reinforcement effect of the microfiber contained in the PSP. The filler effect of the finer particle of powder participates in the reduction of porosity of the B-CEB. The microfiber

supports one part of the applied force during the compressive test and improves the mechanical performance of B-CEB. For high contents of PSP, the microstructure of the B-CEB becomes very heterogeneous with piling up or bundling of the PSP in places as indicated in the SEM image and creating a high porosity and a low density which causes a reduction in mechanical resistance.

According to African Standard ARS 674 [40], all the elaborated B-CEB, except the B40, are in the category of the construction of load-bearing wall which is characterized by the strength higher than 4 MPa. The strength of all the B-CEB corroborated with the previous study which indicates that the strength of compressed earth block is in a range of 0.4 to 5 MPa. The obtained resistance is interesting because they are in the same order as the resistances obtained for CEB stabilized



with cement. Bahar et al [41] obtained the strength between 4.5 and 6.5 MPa with 10 or 20% of cement as additive. In the same order, Touré et al [42] obtained strength around 2.5 to 3.5 MPa with 8% of cement.

The load-displacement curves of the different bricks were recorded (Figure 10) to assess the influence of peanut shells powder on the behavior of brick during the compressive test. The curves have shown that PSP influenced the B-CEB behavior before and after failure. The shift of the load-displacement curves with the addition of PSP indicates that the mechanical behavior of the bricks is strongly influenced. Two zones can be observed on the curves with the addition of powder. The first zone corresponds to the elastic behavior of B-CEB and the second zone corresponds to the plastic behavior of B-CEB. It is found that the breakage of the non-admixed BTC (without peanut shell powder) is very rapid and almost without warning. In contrast, in the case of BTCs with peanut shell powder, it was noted that after the breaking load was reached, the samples further deformed. This may be due to the distribution of internal forces from the soil matrix towards the reinforcing peanut shell powders. We also note that the introduction of fibers into the mixture reduces the fragility of the block, therefore they increase its ductility. This is explained

by the fact that B-CEB without PSP has a certain brittleness because it exhibits an abrupt rupture without recovery just after it has reached maximum stress. This rupture occurs after a catastrophic propagation of cracks resulting from defects (Figure 7 B0). With the incorporation of peanut shells, there is a first breaking peak corresponding to a partial breaking of the clay matrix accompanied by a second peak corresponding to the total breaking of the clay matrix. This phenomenon is greatly increased with high content of peanut shells (10 to 30%) in B-CEB manifested by at least one breaking peak after that of the clay matrix. Thus, in addition to increasing the final compressive strength, the peanut shells give the C-CEB a certain ductility which will allow it to hold up a little after significant shocks [43]. With increasing of PSP, the rigidity character of B-CEB reduces to gives ductile material. The ductile character of B-CEB allows to have a gain of residual strength. The ultimate strain (0.92 - 8.49 mm) increase with increasing of PSP and shows an increase of elastic properties of B-CEB when the content of PSP increases (Figure 10). The B-CEB shows an important displacement before the failure. The different behavior corroborate the result of many researchers such as Khoudja et al [35], Omrani et al [44].

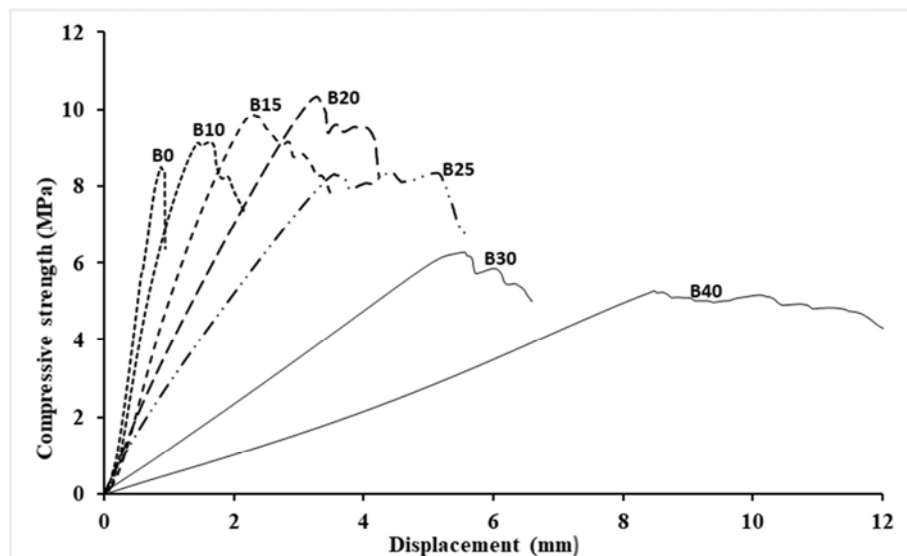


Figure 10. Compressive strength versus displacement of bricks.

Table 6. Compressive strength and Elastic modulus of B-CEB.

B-CEB	Compressive strength (MPa)	Ultimate strain
B0	4.21 ± 0.06	0.92
B10	4.62 ± 0.08	1.53
B15	4.90 ± 0.05	2.31
B20	5.19 ± 0.03	3.28
B25	4.44 ± 0.04	3.60
B30	4.21 ± 0.02	5.56
B40	2.35 ± 0.04	8.49

### 3.5. Hydric Behavior of B-CEBs

The hydric behavior of B-CEBs is an important aspect of their acceptability in construction. B-CEB can undergo more

or less severe disintegration depending on its quality under the effect of rain. The impact of rain on the B-CEBs was assessed by the erosion test called the "spray test". Figure 11 presents the mass loss of B-CEBs after the spray test. Excepted for B10, all the amended B-CEB with PSP show a feeble weight loss than that of the reference. This result is linked to the microstructure of the B-CEBs. With the lower content of PSP, the microstructure of B-CEB is homogeneous. With high content of PS, the material is heterogeneous with a strong peanut shell network which confers on brick significant resistance to erosion, given its stickiness properties and the possibilities of bond formation by hydrogen bridge between celluloses, hemicelluloses, polyphenols in the PSP with soil mineral phases (kaolinite, muscovite) or ions ( $\text{Fe}^{2+}$  or  $\text{Fe}^{3+}$ )

[45]. The dispersion of the powder throughout the matrix of the brick constitutes a barrier or supports reducing the degradation of the brick due to the presence of fine particles and microfibers.

The photo of B-CEB after spray test (Figure 12) has shown a better contribution of PSP on the water-resistance of elaborated B-CEB. The coefficient of water absorption by capillarity ( $C_b$ ) of the B-CEBs as a function of the content of the PSP is presented in table 7. The coefficient varied between 15.5 and 38.3  $\text{g}/\text{cm}^2 \cdot \text{min}^{1/2}$ . According to standard NF – XP 13-901 [24], the B-CEB B0 and B10 have a very low capillarity ( $C_b \leq 20 \text{ g}/\text{cm}^2 \cdot \text{min}^{1/2}$ ), and the others B-CEB have a low capillarity ( $C_b \leq 40 \text{ g}/\text{cm}^2 \cdot \text{min}^{1/2}$ ). In general, the coefficient of capillary absorption increases when the content of PSP increases in the brick. The increase of coefficient with the PSP content is due to the increase of cellulose content on

one hand and the increase of voids created by the fibers on another hand. Cellulose has a hydrophilic character, which induces an increase in the absorption of water by capillarity following the increase in the quantity of peanut shells powder. Also, the increase in porosity following the addition of the powder is another cause of the increase in the coefficient of water absorption. According to Limami et al [46], the high content of PSP in the soil matrix causes more flocculation which increases the interlayer spacing in the brick and increases the porosity.

Erosion occurs generally at the surface of bricks, but can occur by infiltration of water through cracks and outer pores. The addition of peanut shells is highly beneficial for B-CEB, improving its resistance to erosion. They should, however, be used in the range of 15 to 30% by the weight of earth.

Table 7. Coefficient of capillary water absorption of B-CEBs.

B-CEB	B0	B10	B15	B20	B25	B30	B35
$C_b (\text{g}/\text{cm}^2 \cdot \text{min}^{0.5})$	15.5	19.5	27.8	22.8	22.7	38.3	

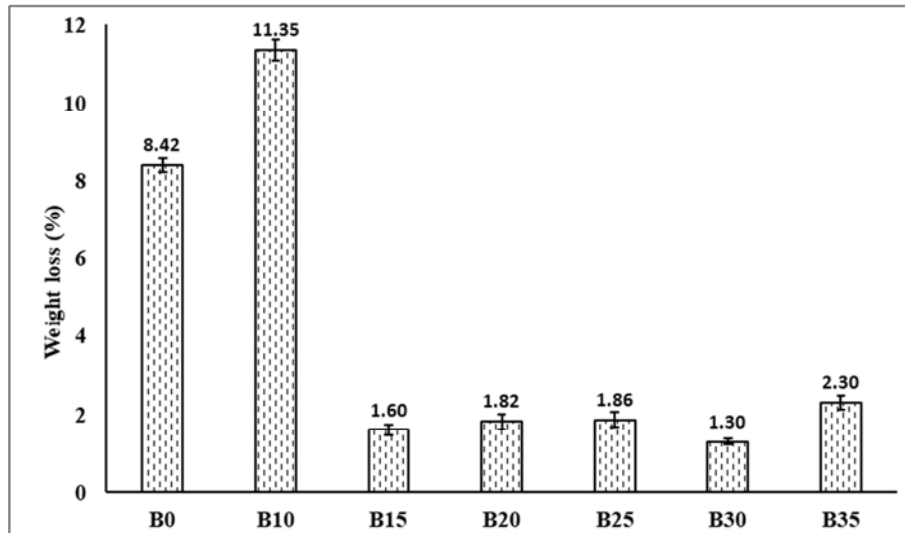


Figure 11. Weight loss after spray test.



Figure 12. Image of brick after spray test.

### 3.6. Thermal Behavior of B-CEBs

Figure 13 shows the influence of peanut shells on the thermal conductivity of B-CEBs. The thermal conductivity decreases (1.44 - 0.76 W/m.K) when the amount of peanut shells powder increases (0 - 40 wt.%) in the B-CEB. This decreasing phenomenon of the thermal conductivity is due to the intrinsic property of cellulose of peanut shells which has a

thermal insulating character. The substitution of a part of soil by peanut shells, less dense, contributes to the decrease of thermal conductivity. This decrease in thermal conductivity correlates perfectly with the increase of the porosity in the B-CEB. Heat conduction was slowed down by the presence of air-filled voids inside the specimens and consequently lowered the thermal conductivity.

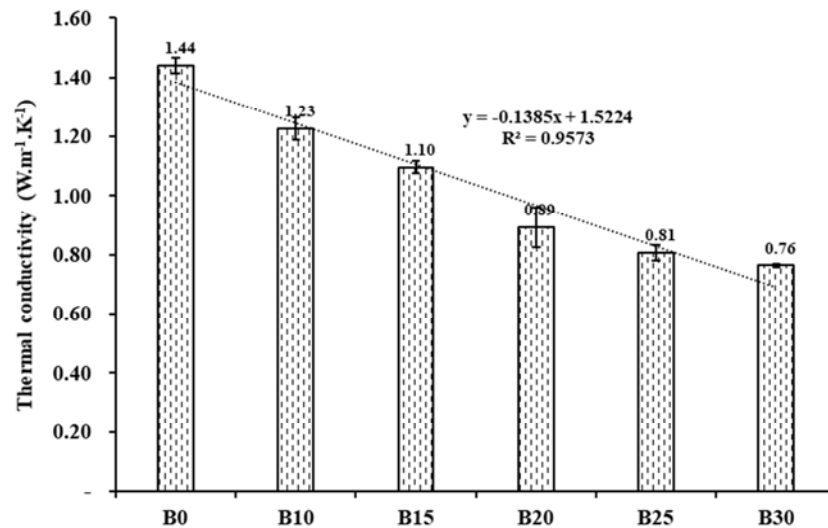


Figure 13. Thermal conductivity of CEB.

Similar result was observed by Khedari et al, [47] in the stabilization of compressed earth blocks reinforced with coconut fibers. The thermal conductivity values are lower than those reported by Laibi et al (2.2 - 1.8 W/m.K) [5], on the compressed earth blocks stabilized by kenaf fibers from Benin. This difference may be related to the compaction force used and the nature or size or the used percentage of the fibers. Furthermore, the thermal conductivity results obtained in this study are higher than those of adobes containing fibers obtained by several researchers such as Bobet and al [48] and Ouedraogo and al. [49]. This is due to the fact that CEB are less porous than adobes, given the application of compaction pressure which increase the bulk density and thus increasing the thermal conductivity. Overall, the values of thermal conductivity are in the same range as the values reported in the literature on raw bricks or bricks reinforced with plant fibers [10]. The use of 20 wt.% of PSP reduces around 38.1% the thermal conductivity of B-CEBs with respect to the reference CEBs (0% PSP).

## 4. Conclusion

The influence of peanut shells powder (10 to 40% by mass) on the microstructural characteristics of compressed earth blocks produced with the raw soil material was studied. The additions of peanut shells did not lead to the formation of new mineralogical phases, but contributed to enhancing some properties of compressed earth blocks like mechanical resistance, water resistance, and thermal conductivity. The followings conclusion can specifically be drawn:

1. The addition of peanut shells powder increases the open porosity (25.40-57.07%) of compressed earth brick and reduce considerably its density (2.01-1.24 g/cm<sup>3</sup>). Beyond 20% of peanut shells powder the microfibers of peanut shells powder are stack and contributes to increasing the porosity by the increasing the amount of voids in the bricks.
2. The addition of peanut shells powder (up to 20%) to the raw soil improves the compressive strength of bricks. Beyond this percentage, the strength decreases. The mechanical behavior is related to the microstructure of the soil matrix after addition of the peanut shells powder. The enhance of strength results from the combined filler effect of finer particles and the good adhesion between the microfiber and soil matrix. The decrease in strength (beyond 20% PSP) is related to the stacking and heterogeneous distribution of microfiber in the soil matrix. The use of peanut shells powder improves the ductility properties of compressed earth brick.
3. The resistance to water of bricks is improved by the addition of peanut shells powder. When the peanut shells content increases, the loss of mass due to erosion decreases, given the creation of a network of peanut shells which prevents the erosion of soil.
4. The water absorption by capillarity of compressed earth block increases when the content of peanut shells increases due to the hydrophilic character of cellulose contained in the peanut shells.
5. The thermal conductivity of compressed earth block

decreases when the content of peanut shells powder increases due to the good thermal insulation of cellulose in the peanut shells powder.

From the point of view of mechanical resistance, thermal conductivity, and water resistance, the B-CEB are suitable for the construction of sustainable habitats and can potentially provide better thermal comfort. The content of peanut shells should however be used in the range of 15-25%. This type of construction would limit the energy consumption for the ventilation of buildings with the aim of reducing atmospheric pollution linked to the high production of cement or the overconsumption of energy to cool the buildings.

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