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Physico–mechanical and durability performances of compressed earth blocks incorporating quackgrass straw: An alternative to fired clay

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ABSTRACT

In developing countries such as Benin, the use of clay soils to produce fired clay bricks can be confronted with the problems of availability of the energy required for firing. The present study assesses the possibility to use these clay resources to produce compressed earth blocks (CEB) as alternative to fired clay. CEBs were produced by physically stabilizing a highly clayey soil with 0/5 granite dust, followed by chemical stabilization with 8$wt\%$ cement and the incorporation of 0 to 1.5$wt\%$ quackgrass straw. This resulted in dimensional stability of CEB, despite a slight swelling of 16.33 mm/m upon immersion observed only on CEB containing 1 and 1.5$wt\%$ straw. The coefficients of resistance to abrasion are well improved above the standardized minimum threshold of $2cm^2/g$, i.e. 29.7 to $7.72cm^2/g$ for straw contents of 0 to 1.5%. Moreover, the maximum erosion depth of the CEB of $32.6mm/h$, is well below the limit of $120mm/h$, despite using a water pressure 10 times higher than the standard pressure of $50kPa$. These results testify to the durability of stabilized CEB. However, the dry and wet compressive strength decreased from 5.1 to $2.84MPa$ and from 3 to $1.02MPa$, respectively, with the straw content of 0 to 1%. This does not hinder the use of these CEB for sustainable building construction, as the values of their compressive strength in dry and wet conditions were respectively above the required values of $2MPa$ and $1MPa$.

1. Introduction

Building sector has the potential to counter global warming, given its nearly 40% of greenhouse gas emissions. This represents the most polluting sector, ahead of industry (32%) and transport (23%) [1]. Such emissions can be explained by a significant use of energy (35% of the world energy production [1]) for the buildings construction and operation. Knowing that the building envelope is the main factor on which building energy consumption depends [2,3,4], it can therefore be stated that energy and environmental performance of buildings is primarily dictated by construction materials choice. Given the urgency of climate change, it is therefore essential to use construction materials with low environmental impact to ensure the sustainability of buildings. Additionally, the United Nations considers access to sustainable housing as a fundamental right for human security, nutrition and health (SDO 11) [5,6]. These justify the interest of the scientific community for ecological building materials, particularly earthen materials.

Indeed, earth is the oldest building material. It was the main material used in construction before the advent of cementitious materials at the end of World War II. Since then, it has been abandoned [7]. In 2020, only 8–10% of households still live in earthen dwellings worldwide [7]. Such a low use of these economically accessible materials, even in low-income countries, shows the resentment of the populations towards earthen constructions [8]. However these materials have interesting hygrothermal characteristics capable of passively improving the thermal comfort inside buildings [9,10,11,12], with a low impact on the environment [13–16]. According to Niroumand *et al.* [17], the earth is a sustainable building material that fulfills sanitary, thermal comfort and economic criteria. Marsh and Kulshreshtha [7] reported that the rejection of earth is not due to the earth material itself, but rather to its misuse for housing construction. The main criticism of these constructions is their structural durability in terms of poor water resistance [18]. This poor structural performance leads to consider earth as a material for low economic class, in developing countries [19]. For example, Soglo

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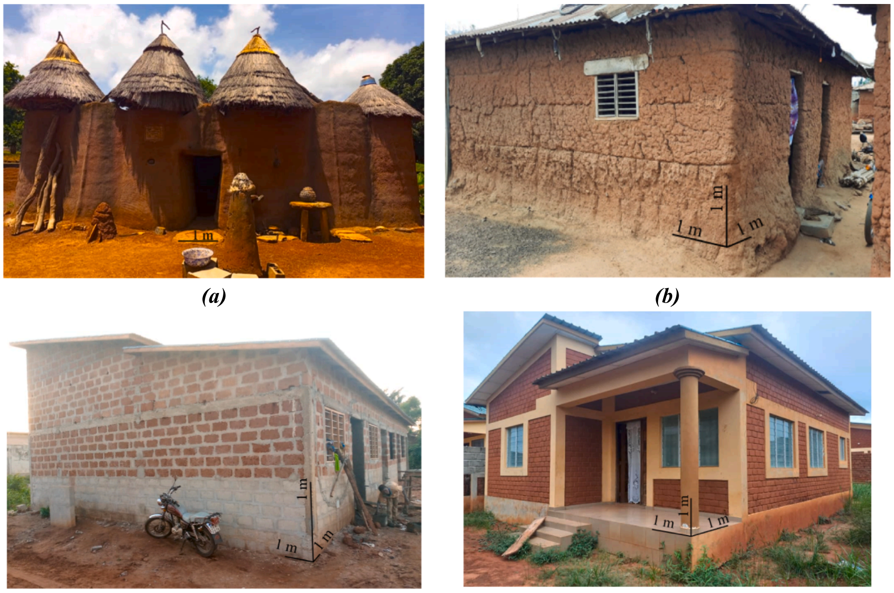


Fig. 1. ***(a)*** Aspect of a Tata Somba; ***(b)*** Cob house in the Zogbodomey region; ***(c)*** Adobe construction with a cement joint mortar in the Zinvié locality; ***(d)*** CEB villa in the Cité Bethel (GCITT) in Abomey-Calavi.

[20] stated that the mentality of the Beninese population is that living in an earthen dwelling reflects a poor social status. This feeling is further reinforced by the lack sufficient scientific/technical data and specific regulations that can guarantee the good quality of earthen constructions in these countries. An earthen building is of better quality if it has a good structural durability performance [7]; a crucial factor for the social acceptance of earthen constructions [21].

The quality of an earthen building also depends on the adopted construction technique. [22] presents an overview of the evolution of raw earth construction techniques, from rammed earth constructions to cob and earth bricks (adobe, cut blocks and compressed earth blocks 'CEB'). Adopting one or other of these techniques offers definite energy savings compared with conventional materials, both in terms of building operation and construction. For example, the production of 1m^3 of concrete requires about 2640kWh against 1140kWh for 1m^3 of fired clay bricks and 10kWh/m^3 for raw earth materials [21]. Furthermore, CEB can allow to save up to 37.5% in masonry wall construction, up to 20% in annual thermal discomfort hours, and up to 10% in air conditioning in a hot, dry climate, compared to cement blocks [23]. Earthen constructions are therefore more energy efficient, less expensive and much more accessible because of the large availability of the earth material.

However, the accessibility of earthen constructions can be questioned in some regions of the world depending on the nature of the available earth and especially on the adopted manufacturing technique. In this respect, the popularization of fired clay constructions can be strongly hindered in developing countries, including Benin, because of the required energy for firing. According to [24], bricks are fired at temperatures between 950 °C and 1100 °C in electric, fossil fuel or wood fuel ovens. This technic requires a significant amount energy with ecological (deforestation), environmental (GHG emissions) and health (respiratory disorders) consequences [25]. Thus, taking into account the realities of a country like Benin where only 53% of the electrical energy needs are ensured, with a very fragile forest coverage [26,27]; it is important to find a sustainable alternative for the valorization of highly clayey soils, otherwise adapted for the production of refractory bricks. Therefore, this research responds to the problem of accessibility to modern earthen constructions by taking into account the energy difficulties of the region and using raw/ non–fired earthen material.

What's more, the soils used to make fired clay bricks are not always suitable for raw earth construction. In most cases, corrections are made to match the nature of the soil to the clay construction technique chosen. Several studies have shown that sand can be used for physical stabilization of highly clayey soils [28–30]. McGregor *et al.* [31] used fine sand to improve the particle size distribution of an highly clayey soil intended for the production of fired clay bricks, to produce CEB. However, the intensive use of construction sands poses many environmental challenges such as coastal erosion, flooding, disturbance of the marine ecosystem, etc. Therefore, there is a need to explore alternative materials to sand, referring to [32] who used 0/3 granite dust to improve the physical properties of the earth material. However, the main defects faced by most earthen dwellings are mainly erosion and crumbling of the envelope surfaces [33]. As a result, chemical stabilization of earthen materials is necessary to ensure their durability [21].

Several authors considered necessary to improve the mechanical strength and ensure better water resistance of earthen materials by chemical stabilization [34,35,36]. Nshimiyimana *et al.* [37] showed that the absence of a chemical stabilizer makes the earthen material crumbly when dry and totally degraded in contact with water. This stabilization is more essential when earth materials are exposed to the outside environment. Despite the introduction of more environmentally-friendly binders such as geopolymers [37,38] or lime [39], cement is still widely used for the chemical stabilization of earthen materials such as CEBs. Although the addition of cement sometimes raises questions about the sustainability of the material, it is important to keep in mind that the embodied energy of a raw earth material stabilized with a low proportion of cement ($<$ 10%) is much lower than that of fired earth brick. Walker [40] stated that the production of earth block stabilized with a low proportion of cement leads to an energy expenditure of about 50% less than that of refractory bricks. Singh *et al.* [41] showed that the production of CEBs stabilized with 5% cement consumes 11 times less energy, pollutes 13 times less and costs 15 to 20% less than fired clay bricks. Therefore, the content of cement proposed for the stabilization of earthen blocks is 5 to 8% [32,42], 5 to 10% [43], 8 to 12% [44] for improving their durability. Mazhoud *et al.* [45] stated that the content of cement of more than 10% makes the material uneconomical and less user-friendly.

In addition to the need to improve the hygrothermal performance of materials [14,36,46–49], the presence of plant aggregates in earth

Fig. 2. X-Ray diffractogram of the clay soil from.

matrices limits cracking, which would mainly result from dry shrinkage [50,51]. Thus, Turco et al. [52] assert that the main reason for incorporating plant fibers into CEBs is their ability to control deformation.

The present study attempts to improve the quality of the local clay soil to produce CEBs by adding a by-product from the local production of granite aggregate, on the one hand. On the other hand, the paper evaluates the influence of the incorporation of quackgrass fibers, an invasive plant, on the physico-mechanical performances and durability of CEBs. The following section 2 provides a brief overview of the earth construction techniques generally used in Benin. Section 3 draws on the literature to justify the use of the proposed materials and process as alternative to producing fired clay bricks. The results obtained were then highlighted and discussed in section 4.

2. Overview of earth construction techniques in Benin

In Benin, raw earth constructions still dominate the architectural heritage, especially in rural areas. The main earthen construction techniques are bauge, cob, adobe and CEBs [20]. Bauge is a well-known ancestral technique whose correct execution guarantees the durability of the constructions. Moreover, it has been adopted for the construction of the most famous earthen constructions in Benin: the *'Tata Somba'* (Fig. 1a), which have been classified as a UNESCO World Heritage Site. Noukpakou *et al.* [53] describe these dwellings, found in Atacora (in the north of the country), as mud constructions composed of several circular huts linked together by curved walls and whose circular or elliptical layout gives the appearance of a fortress house. Cob is one of the most widespread earthen construction methods in the world [54,55]. Cob houses are generally found in the rural areas of southern Benin (Fig. 1b).

Alongside these buildings, adobe is a raw earth construction technique also found in the south of the country. Relatively simple to construct and requiring very little intrinsic energy, it also enables organic waste to be recycled. For example, Brito *et al.* [56] propose adobe blocks containing manure as an alternative to ceramic materials. This solution enabled the authors to avoid significant emissions of CO_2 and SO_2 into the atmosphere by eliminating the calcination process essential to the manufacture of ceramic materials. In the same vein, Millogo *et al.* [48] produce Pressed Adobe Blocks (PAB) containing Hibiscus cannabinus fibers, the use of which guarantees energy savings through the passive improvement of thermal comfort. However, adobe is less common in Benin than the two above-mentioned earth construction techniques [20]. It is sometimes combined with conventional materials in *peri*-urban areas, where soil conditions permit (Fig. 1c). This process is used for the construction of low-loaded sustainable residential buildings [57]. Compared to conventional building materials and fired clay bricks, adobe bricks are mechanically weak. The improvements of adobe can still be achieved through higher densification of the material. For this purpose, a mechanical or manual press is used to perform static, vibrostatic or dynamic compaction of the earth mixture [58]. This approach allows to produce compressed earth blocks (CEBs) that are commonly used for the construction of sustainable and modern buildings. Indeed, CEBs represent an improved version of adobes. Their implementation requires little water and is done with a manual or hydraulic press. The mechanical compaction of the material makes the blocks denser and stronger than adobes. They are a modern, ecological and economically viable alternative to conventional building materials. In Benin, the few buildings made of CEB are found in the main cities of the country (Fig. 1d).

Moreover, Laibi [34] finds that CEBs are better than adobe in terms of mechanical resistance and durability. They offer more design possibilities than cob and have better thermal performance with less embodied energy than fired clay bricks [34]. According to [35] stabilized CEBs represent an alternative to fired clay bricks. Therefore, CEBs were selected in this study as an alternative to fired clay bricks.

3. Materials and methods

3.1. Materials

3.1.1. Earth material as the main matrix

The earth was collected from the Zogbodomey quarry, a region located in the south of Benin, about $112km$ from Cotonou (between $2^{\circ}06'E$ and $2^{\circ}08'E$ and between $7^{\circ}04'N$ and $7^{\circ}06'N$ [59]). This site represents one of the most important quarries of clay material for building construction in the region; with an estimated reserve of $53,198,437 tons$ [60]. Previous works reported that the soil has a very clayey nature and is potentially useful for the production of fired clay bricks [59,60]. In fact, the clayey earthen material has a particle size in the range of $0-5mm$. The clayey nature was confirmed by mineralogical analysis performed by X-ray diffraction (Fig. 2); which shows the dominant presence of clay, essentially kaolinite ($>$ 54%), quartz (44%) and some traces of hematite and k-feldspar.

Because of the clayey nature of the material, Zogbodomey clay could not be used alone to produce CEBs. Moreover, the texture of this clay materials does not fall within the granulometry and plasticity boundaries proposed by the standard XP P 13-901 [61], for the earthen materials appropriated to produce CEB. Therefore, a granular correction, by physical stabilization, of this clayey soil was essential to produce CEB.

3.1.2. Physical and chemical stabilizer

Granite dust 0/5 (particle size range of $0-5mm$) was used as a physical stabilizer for the clay soil. It was taken from the granite crushing site of a road company. It is a by-product of the road construction industry in Benin; an industry in full expansion due to the plan to construct $143,000km$ of bitumous road [62,63]. According to the

Table 1
Composition of the test specimens.

Designation	Earthen matrix		Chemical stabiliser	Reinforcement	Optimal water content			Number of specimens
	Clay (%)	Granite dust 0/5 (%)	Portland cement (%)	Quackgrass straw (%)	Matrix (%)	Quackgrass straw (%)	Total (%)	
CEB$_8$-0	55.2	36.8	8	0	11.50	0	11.5	14
CEB$_8$ −0.5	54.9	36.6	8	0.5	11.44	1.01	12.45	14
CEB$_8$ −1	54.6	36.4	8	1	11.38	2.03	13.42	14
CEB$_8$ −1.5	54.3	36.2	8	1.5	11.32	3.05	14.38	14
CEB$_8$ −1.75	54.15	36.1	8	1.75	11.30	3.56	14.86	2
CEB$_8$ −2	54	36	8	2	11.27	4.07	15.34	2

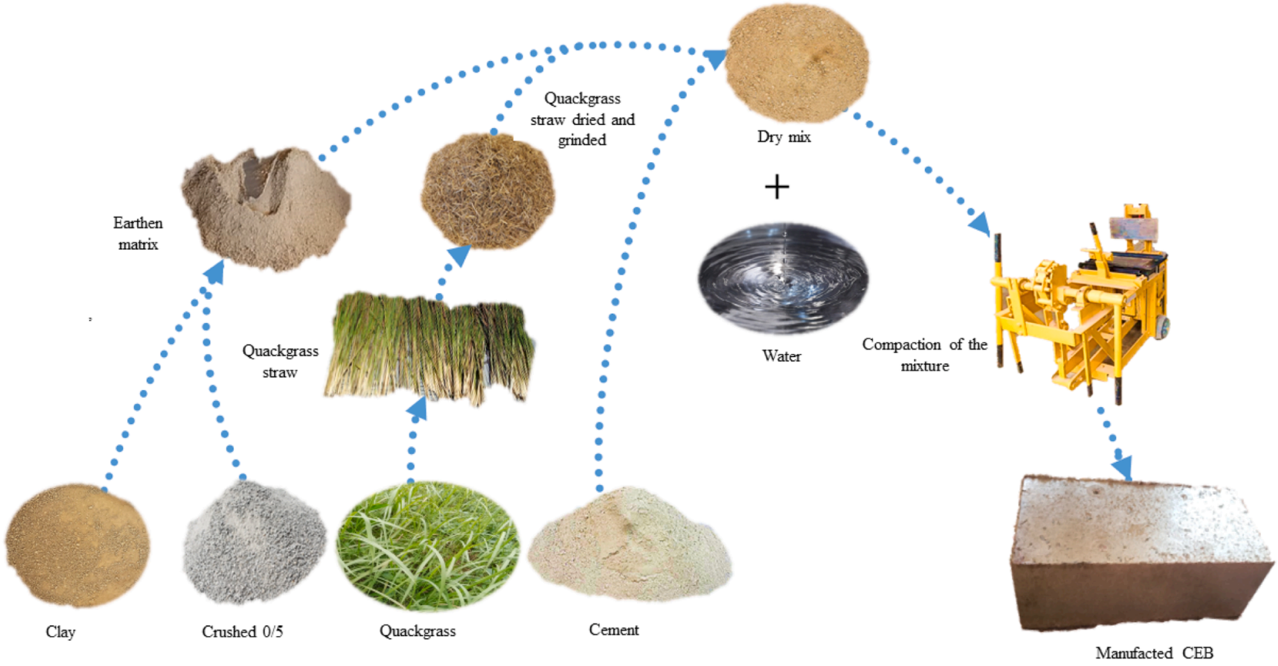


Fig. 3. Conceptual framework for the formulation of the specimens.

feedback from professionals, the construction of one kilometer of 5*cm* thick bitumous concrete generates nearly 380*tons* of by-product (granite dust 0/5). Therefore, the present study attempts to give value this by-product as physical stabilizer of the clayey soil and constitute the main matrix to produce CEBs.

3.1.3. Quackgrass straw for reinforcement

The quackgrass straw, Elytrigia repens, collected on the campus of the Université d'Abomey-Calavi (2°20′ E and 6°24′*N*) was incorporated into the soil matrix. The quackgrass is a perennial and invasive weed of the grass family that generally grows on cultivable soils. It is distinguished by its long, flat, thin-veined, glaucous green leaves and whitish or yellowish underground stems called rhizomes [64]. It is widely present in the humid tropical climate in the south of Benin. The quackgrass straw particles size ranges between 10 and 20*mm*.

3.2. Methods for design and characterization of specimens

3.2.1. Design and production of the specimens

The earth matrix, "clay + granite dust", was mixed with 8% cement and 0 to 2% of quackgrass straw, in weight percentage (Table 1). A total of six (6) designs were proposed each containing 0%, 0.5%, 1%, 1.5%, 1.75% and 2% quackgrass straw content. A dry followed by a wet mixing of the raw materials necessary to produce each block was made for at least 5 min to guarantee a good homogenization of the mixture. The optimum moisture content, determined by Proctor test [65] on the mixtures of earth matrix and cement, was used for wet mixing. The water demand of fibers due their absorption, determined according [66], was also added to satisfy the water requirement for the composite blocks.

Static compaction was then carried out on the different mix designs to produce CEBs. The TERSTARAM manual press (S.P.R.L Appro-Techno), that can generate a compaction load up to 35*bars*, was used to produce CEB of dimensions 29 × 14 × 9.5cm^3. For each design, 14 specimens were produced, except for the designs containing 1.75% and 2% quackgrass, where the first specimens showed significant cracking during production. Fig. 3 presents the conceptual framework to produce stabilized CEB. A total of 60 specimens were produced and packed in airtight bags to cure for 28-day under ambient laboratory conditions (29 ± 3°*C*). The cured specimens were then exposed to the open air in the laboratory for 24 h and then oven-dried at 45°*C* until mass constant (difference of mass <0.5 % between two consecutive weighing in 24 h).

3.2.2. Physical characterization

The physical characterization of clay consisted in determining the particle size distribution. A combined analysis by sieving and sedimentometry was carried out in accordance with NF EN ISO 17892-4 [67]. Similar operations were carried out for the granulometric analysis of the 0/5 granite dust and the clay + granite dust mixtures. For these mixtures, the granite dust content varies between 25 and 40% in steps of 5%. The objective was to obtain a granular curve that fits within the granular range proposed by the XP P 13-901 standard [61] for the production of CEB. Other parameters, i.e. the Atterberg limits and the methylene blue value (VBS) of the materials, were determined respectively according to the standards NF EN ISO 17892-12 [68] and NF EN 933-9 + A1 [69]. For the Atterberg limits, the Casagrande method was applied on soil with a grain size of less than $400\mu m$.

The physical characterization of the quackgrass straw consisted of determining the density, initial moisture content and water absorption. In this regard, Amziane *et al.* [66] developed a protocol for characterizing plant aggregates. These tests were carried out on samples of dried quackgrass straw that were crushed with a mini chopper. Straw chopping was carried out to improve the adhesion between the soil matrix and the fibers since the fibers naturally had a smooth surface. The quackgrass straw particles size ranges between 10 and $20mm$.

The physical characterization of CEB containing quackgrass straw consisted in inspection of their appearance, texture and dimensional variations, referring to the standard XP P 13-901 [61]. Each block was visually examined for apparent defects (breaks, cracks, deformations, chips and holes) before and after curing. Specimens with cracks whose width, length and depth were respectively greater than 1 mm, 40 mm and 10 mm were discarded.

The density (ρ_d) and porosity (ε) of CEB were also determined, according to NF P 18-459 [70]. For each sample, three test specimens of unit volume $0.7l$, cut from different CEB, were saturated with water under vacuum at $25mbar$ for about $4hours$. The masses ($M_{sat.wat}$) of the saturated test specimens were measured in water. The measurements were also made on the masses of the water-soaked ($M_{sat.air}$) and dry (M_{dry}) test specimens in the open air. The application of Eqs. (1) and (2) allows respectively to calculate the bulk density and the porosity of the CEB.

$$\text{Bulk density}: \ \rho_d = \frac{M_{dry} \times 1000}{M_{sat.air} - M_{sat.wat}} \tag{1}$$

$$\text{Porosity}: \varepsilon = \frac{100 \times (M_{sat.air} \times M_{dry})}{M_{sat.air} - M_{sat.wat}} \tag{2}$$

Furthermore, Eqs. (3)–(5) allow us to appreciate the magnitudes of shrinkage and swelling and the variation between the extreme states of the specimens. The main parameters l_0, l_1 and l_2 were obtained by measuring the distances between stainless steel studs of $4cm^2$ of surface area each, attached in pairs to 4 specimens of each design with resin. The shrinkage magnitude of the specimens was determined after oven drying at $45^\circ C$ of two specimens. The other two were used to estimate the magnitude of swelling after the specimens were fully immersed in water for $96hours$. In these equations; $\Delta l_r/l$ and $\Delta l_g/l$ respectively represent the magnitudes of conventional shrinkage and swelling (mm/m), $\Delta l_c/l$ is the dimensional variation between extreme conventional states (mm/m), l_0 is the initial inter-pad distance (m), l_2 is the inter-pad distance after drying (m), l_1 is the inter-pad distance after wetting (m), i and j are the specimen numbers.

$$\frac{\Delta l_r}{l} = \frac{1}{N}\sum_{i=1}^{N}\frac{\Delta l_{0i} - \Delta l_{2i}}{l_{0i}} \times 1000 \tag{3}$$

$$\frac{\Delta l_g}{l} = \frac{1}{N}\sum_{j=1}^{N}\frac{\Delta l_{1j} - \Delta l_{0j}}{l_{0j}} \times 1000 \tag{4}$$

$$\frac{\Delta l_c}{l} = \frac{\Delta l_g}{l} + \frac{\Delta l_r}{l} \tag{5}$$

3.2.3. Mechanical characterization

For CEB intended for the construction of sustainable buildings, the XP P 19-901 standard describes two mechanical parameters to be determined. These are the dry compressive strength (DCW) and the wet compressive strength (WCS). They represent the basic universal measurements of the quality of masonry elements [71]. In the present study, both properties were determined by static compaction. The specimens were subjected to a compressive load using Proeti safr hydraulic press which has the capacity of $300kN$ and applied at a speed of $0.2mm/s$. Each CEB was first cut into two half blocks and mounted one on top of the other using a similar mortar [61]. However, the specimens intended for the wet compression tests were previously immersed in water for $2hours$ and then protected from drying for $48hours$, before the test. Three different specimens of each design were tested under the required conditions.

3.2.4. Durability tests

To ensure the durability of the CEB and facilitate their social acceptance, the durability indicators were tested, such as the water absorption test by capillary absorption and total immersion, erosion and abrasion resistance.

The capillary water absorption test was performed in accordance with the XP P 13-901 standard [61]. CEB, oven–dried at $70^\circ C$, were partially immersed in water to a depth of $5mm$. The water level was kept constant. After $10min$, $30min$, $1h$, $2h$, $4h$, $8h$, $16h$, and $24h$ of capillary immersion, the samples were removed from the water, wiped with a damp cloth, and weighed. The tests were extended over a period of $24hours$ (beyond the $10minutes$ recommended by the XP P 13-901 standard [61]) to evaluate the capillary behavior of the blocks in prolonged immersion and to deduce the absorption rate (sorptivity) between 1 to $24h$. Eq. (6) was used to determine the coefficient of water absorption by capillarity (Cb). In this equation; Cb is the water absorption coefficient of the specimen ($g/cm^2.min^{0.5}$), P_1 is the weight of the wet specimen (g), P_0 is the weight of the dry specimen (g), S is the surface area of the immersed face of the specimen ($29.5 \times 14cm^2$) and t is the immersion time (min).

$$Cb = \frac{100(P_1 - P_0)}{S\sqrt{t}} \tag{6}$$

In addition, the total water absorption of the blocks was determined by complete immersion in water. The measurements of the wet masses of the blocks were carried out by time step of $24h$ during the $96h$ of total immersion. The absorption of the blocks was estimated by making a relative difference between the dry and wet masses of the blocks by applying Eq. (7). In this equation, A is the total water absorption of the specimen (%) and M_{dry} and M_{wet} are respectively the dry and wet mass of the specimen after immersion (kg).

$$A = \frac{M_{dry} - M_{wet}}{M_{dry}} \times 100 \tag{7}$$

The abrasion resistance was tested referring to the XP P 13-901 standard [61]. The blocks were subjected to a series of 60 cycles of brushing using a steel carrying a $3kg$ load. Once the initial and final masses (before and after brushing) of the specimens are known, Eq. (8) is used to determine the abrasion coefficient of the material. In this expression, S is the brushed area (cm^2), m_0 is the initial mass of the specimen (g) et m_1 is the final mass of the specimen after brushing (g).

$$Ca = S/(m_0 - m_1) \tag{8}$$

The erosion resistance was tested by spray method which is considered more representative of field conditions and applicable to CEB [72,73]. The test therefore consists in projecting a spray water on a $150mm$ diameter of the face of the specimen. According to NZS 4298:1998 [74], the test specimens were placed $470mm$ from the spray nozzle outlet and subjected to a continuous water jet at a pressure of

Table 2
Physical properties of raw materials.

Properties		Clay	0/5 granite dust	Quackgrass straw
Dry density (kg/m^3)		1405 ± 8	1706 ± 16	141 ± 3
Initial water content (%)		8.46	0.6	4.5
Particle size distribution (%)	$> 4mm$	0.01	3.4	–
	Gravel:$[4; 2mm[$	1	20.5	–
	Sand:$[2; 0.02mm[$	23.3	64.3	–
	Silt:$[0.02; 0.002mm[$	17.5	5.8	–
	Clay:≤ 0.002	58.1	6	–
Atterberg limits (%)	Liquid limit L_l	43	–	–
	Plastic limit L_p	16	–	–
	Plastic indext I	27	–	–
VBS		0.78	–	–

$50kPa$ for $1hour$; which did not have much effect of the CEBs. Therefore, the test was repeated for all specimens, but with a spray pressure of $500kPa$ [75], in order to assess the effect of quackglass fibers on the erodibility of CEBs. The test was interrupted every $15min$ to measure the erosion depth of the blocks. The specification related to the diameter of the water jet ($D = 150mm$) could not be met during the test since the height of the specimens is $95mm$.

4. Results and discussion

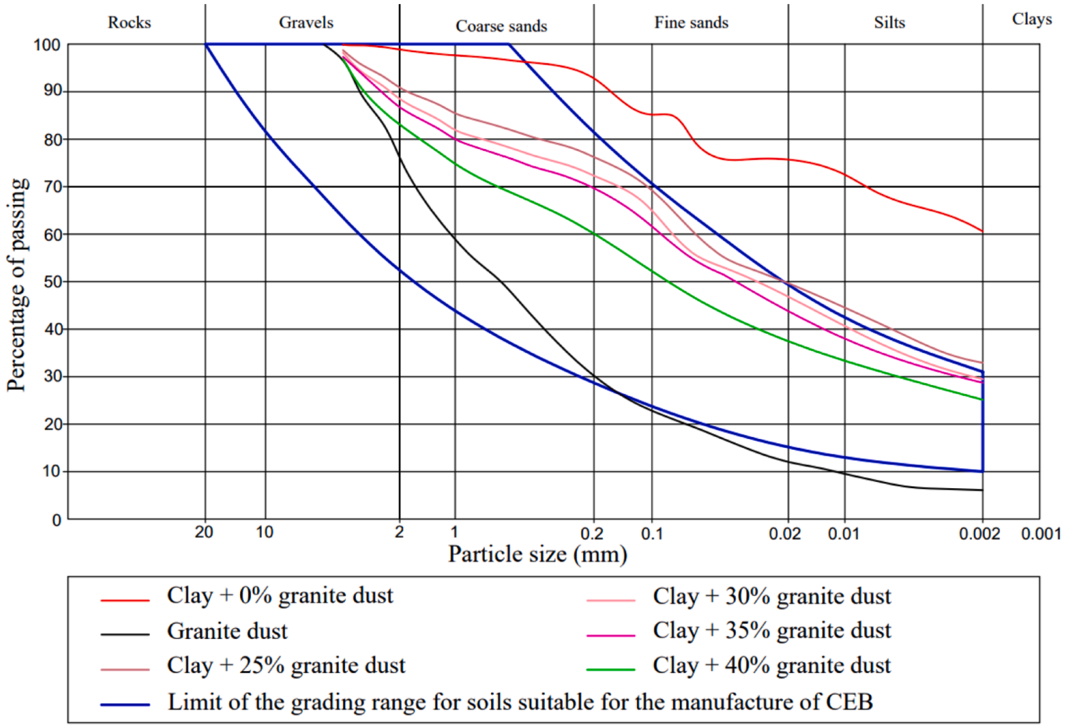
4.1. Physical properties of raw materials

Table 2 presents the physical properties of the raw materials. The values of the bulk density are respectively $1405 \pm 8kg/m^3$, $1706 \pm 16kg/m^3$, and $141 \pm 3kg/m^3$ respectively for clay, 0/5 granite dust and quackgrass straw; the initial water contents of 8.46%, 0.6% and 4.5%. The results on the particle size of the soils (clay and granite dust) and the Atterberg limits of the clay are summarized in Table 2. It shows that the clay soil has a high proportion of fines (72%) compared to the recommended proportions of 8 to 30% [76]. Fig. 4a shows that the particle size distribution of the clay soil is completely outside the granular boundaries defined by the XP P 19-901 standard [76] for soils intended for the production of CEBs. However, the correction of the granulometry of the soil can be achieved by adding different proportions of 0/5 granite dust. The granulometry curve of the matrix was corrected to fit into the recommended boundaries by adding 40% of 0/5 granite dust. Therefore, the matrix composed of 60% clay soil and 40% of 0/5 granite dust was selected to produce the CEBs.

The plasticity index ($PI = 24\%$) and methyl blue value ($VBS = 0.28$) of the composite matrix (60% clay + 40% of 0/5 granite dust), shows that it is in soil category A1 containing slightly too many fines (Fig. 4c and 4b). However, it can be used for the production of CEBs given that its plasticity index is well within the range recommended by the XP P13-901 standard [61].

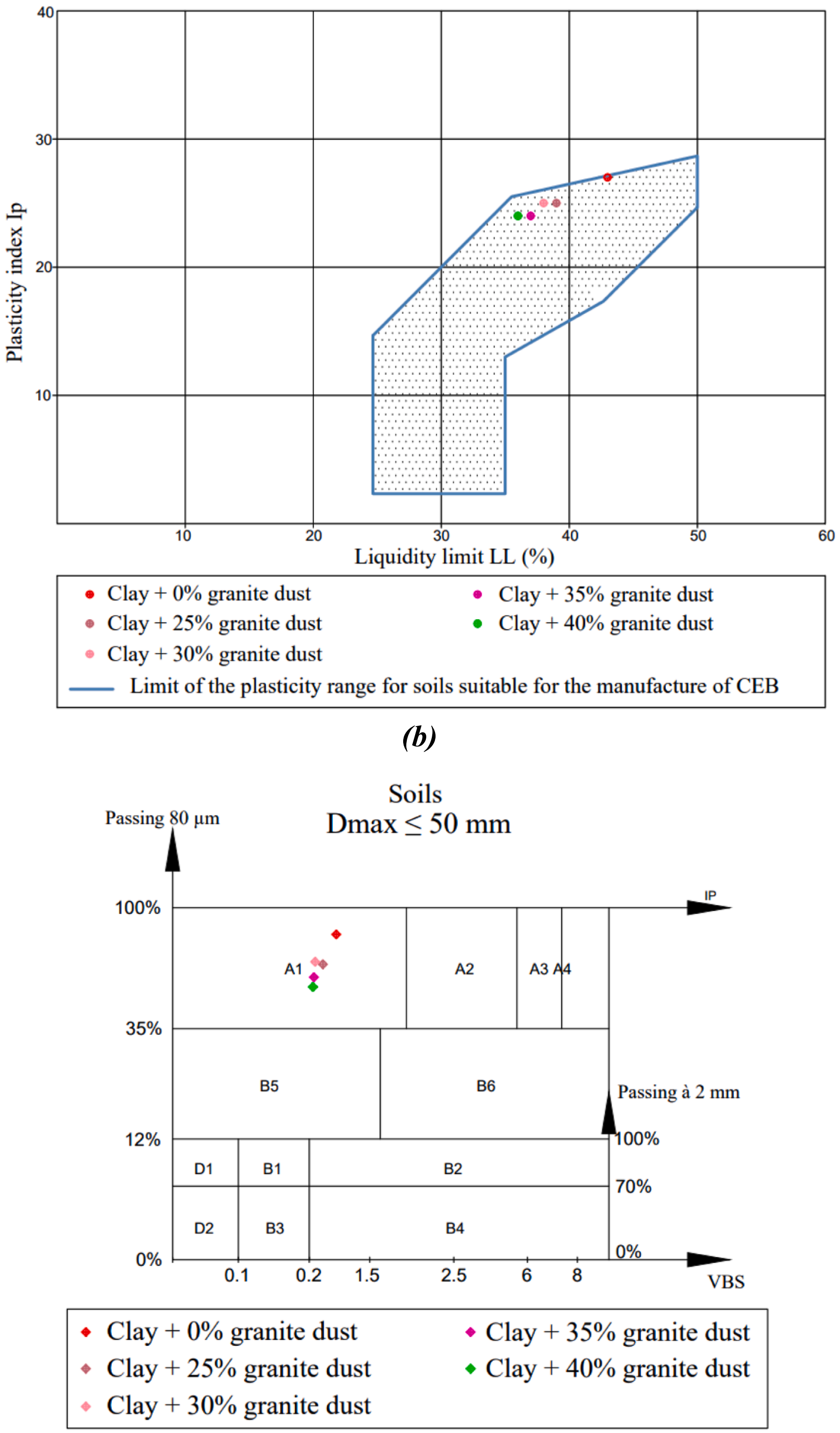
Table 1 presents the physical properties of the raw materials used to produce the specimens. For each of the three materials, i.e., clay, 0/5 granite dust and quackgrass straw, the bulk densities are respectively $1405 \pm 8kg/m^3$, $1706 \pm 16kg/m^3$, $141 \pm 3kg/m^3$ for initial water contents of 8.46%, 0.6% and 4.5%. The results on the particle size of the soils (clay and granite dust) and the Atterberg limits of the clay are summarized in the same table. It can be observed that the clay soil has a high proportion of fines (72%) compared to the recommended proportions (8 to 30% [76]). This is even more evident in Fig. 4a where the particle size distribution of the clay soil completely falls outside the granular range defined by the XP P 13–901 standard [61] for soils intended for the manufacture of CEBs. However, by adding different proportions of 0/5 granite dust, a correction of the granulometry of the soil can be observed. At 40% of 0/5 granite dust, the granulometry curve of the matrix shows a similar shape to that of the recommended boundaries. Referring to [76], the matrix composed of 60% clay soil and 40% of 0/5 granite dust was selected for the manufacture of the CEBs.

Looking closely at the plasticity index ($PI = 24\%$) and methyl blue value ($VBS = 0.28$) of the composite matrix (60% clay + 40% of 0/5



(a)

Fig. 4. (a) particle size distribution curves of the mixtures of clay – 0/5 granite dust; (b) plasticity limits of the mixtures, (c) classification of the mixtures; adapted from XP P 13-901 [61].



(b)

(c)

Fig. 4. (*continued*).

granite dust), it is in soil category A1 containing a little too many fines (Fig. 4c and 4b). However, it can be used for the manufacture of CEBs given that its plasticity index is well within the range of the XP P13-901 standard [61]. The different proportions of raw materials used to manufacture the specimens are presented in Table 2.

4.2. *Physical properties of CEBs*

4.2.1. *Visual inspection*

The appearance and texture of the CEB revealed the presence of significant cracks on the specimens containing 1.75% and 2% quack-

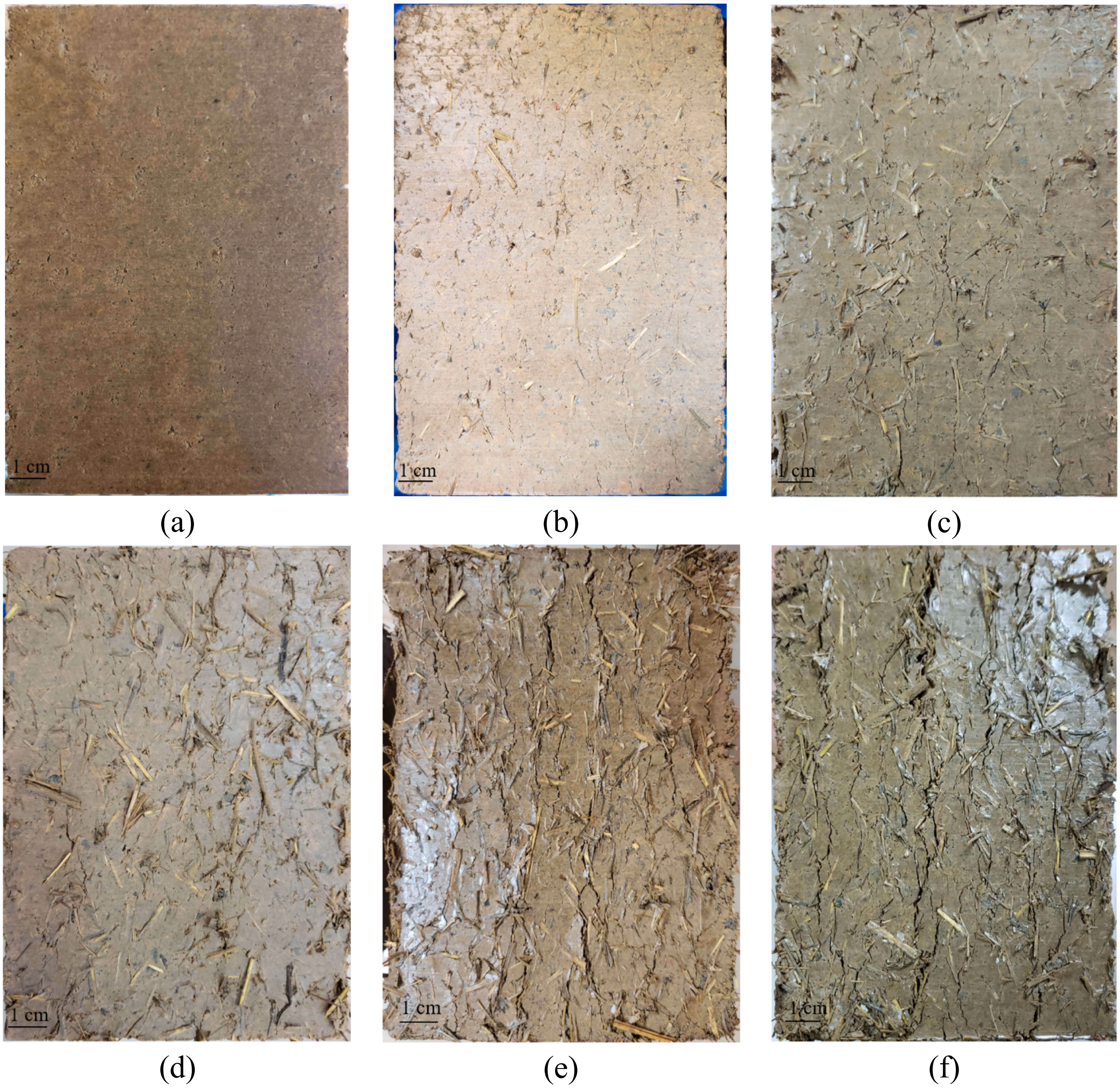


Fig. 5. Appearance of specimen: **(a)** $CEB_8 - 0$; **(b)** $CEB_8 - 0.5$; **(c)** $CEB_8 - 1$; **(d)** $CEB_8 - 1.5$; **(e)** $CEB_8 - 1.75$; **(f)** $CEB_8 - 2$.

grass (Fig. 5). This led to stopping their production. The CEBs containing 0 to 1.5% of quackgrass straw were compact and in agreement with the requirements of the XP P 13-901 standard [61] in terms of appearance and texture (Fig. 5a and 5d). Therefore, these four designs ($CEB_8 - 0$, $CEB_8 - 0.5$, $CEB_8 - 1$ and $CEB_8 - 1.5$) were retained for the continuation of the work.

4.2.2. Density and porosity

Fig. 6 shows the evolution of the density of the specimens with the content of quackgrass straw. The density of the blocks decreases when the content of straw increases due to the substitution of part of the soil by a lighter biosourced material. The values varied from $1932 \pm 6kg/m^3$ for the specimens without straw ($CEB_8 - 0$) to $1835 \pm 3kg/m^3$ for $CEB_8 - 0.5$, $1753 \pm 7kg/m^3$ for $CEB_8 - 1$ and $1692 \pm 5kg/m^3$ for $CEB_8 - 1.5$. Compared to typical values observed in the literature, only the density of $CEB_8 - 1.5$, does not fall within the ranges defined by [77] and [52], i.e. 1700 to $2200kg/m^3$ and 1700 to $2000kg/m^3$ respectively. However, this does not constitute a criterion for eliminating the material, since the literature reports very satisfactory work on CEBs with densities outside the above defined ranges [37,46,78].

The decreasing evolution of the density with the straw content increases the porosity of the blocks. The porosity evolves from 27% for the $CEB_8 - 0$ to 33% for the CEB containing 1.5% of straw (Fig. 6). This is justified by the incorporation of more porous fibrous material in the soil matrix. The strong correlation between density and porosity is illustrated in Fig. 7; with the correlation coefficient $R^2 = 0.96$. Similar observations was reported by [52].

4.2.3. Dimensional variation

The shrinkage and swelling tests highlighted the dimensional stability of the blocks in the absence or presence of water. For the drying test, the distance initially measured between the 2 studs fixed on each of the blocks ($100mm$) did not change. However, the swelling test reveals a very small variations in the range of 0 to $16.33mm/m$ (Table 3). For the blocks without straw ($CEB_8 - 0$), the absence of dimensional variation can be explained by the presence of the 0/5 granite dust (not very

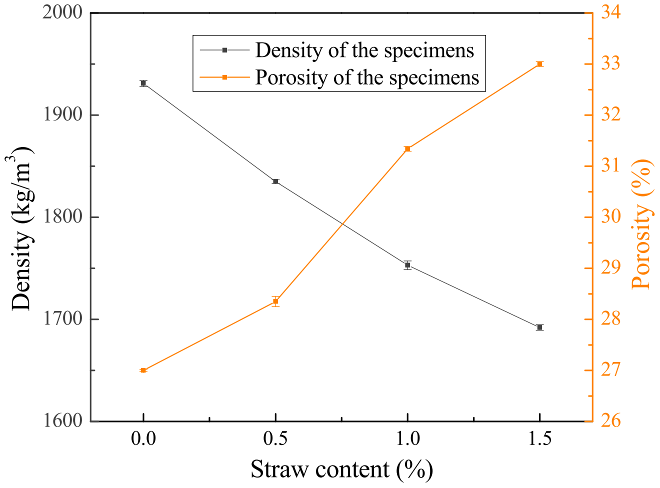


Fig. 6. Evolution of density and porosity with the content of straw.

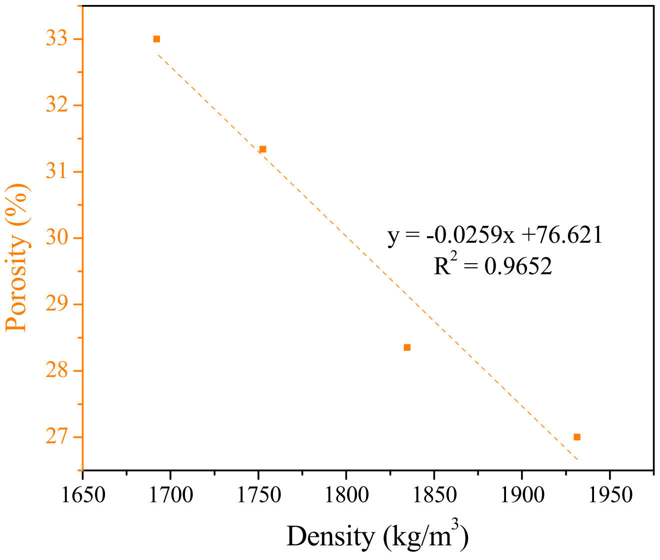


Fig. 7. Relationship between porosity and density of CEBs.

Table 3
Dimensional variation of the specimens.

	CEB-0	CEB-0.5	CEB-1	CEB-1.5
$\Delta l_r/l$(mm/m)	0	0	0	0
$\Delta l_g/l$(mm/m)	0	8.33	16.66	16.66
$\Delta l_c/l$(mm/m)	0	8.33	16.66	16.66

sensitive to water) in the soil matrix and the non–swelling mineralogical composition of the Zogbodomey clay. Indeed, the predominance of kaolinite (more than 50%) in the clay offers a good resistance to dimensional variations. This is due the small interfoliar space between the layers of kaolinite clay, giving it low potential for swelling/shrinking due to the absorption/drying of water molecules [79,80]. Moreover, the addition of granite dust and cement reinforces the rigidity of the bonds between different earth particles of the material.

The presence of a hydrophilic vegetable aggregate such as quackgrass straw did not change much in the dimensional stability of the blocks. The cohesion of the clay and the cementation of cement allows the formation of rigid cavities around the straw particulates. Therefore, the absorption or withdrawal of water from the straw particles is done within these cavities without any variation in their volume.

4.3. Mechanical properties of CEBs

4.3.1. Compressive strength

The evolutions of the dry compressive strength (DCS) and wet compressive strength (WCS) are presented in Fig. 8. The highest values of the strength were obtained with the specimens without straw, i.e. 5.1 ± 0.5 MPa for DCS and 3 ± 0.1 MPa for WCS. These values respectively decreased to 3.85 MPa and 1.82 MPa for $CEB_8-0.5$; 2.84 MPa and 1.02 MPa for CEB_8-1 and 1.76 MPa and 0.56 MPa for $CEB_8-1.5$. Such a reduction can be justified by the incorporation of a biobased material such as quackgrass straw into the earth matrix. This bahavior has also been observed in several other studies. For example, [51] found a 45% reduction in the dry compressive strength of when 2% jute fiber was incorporated in the blocks. Reductions of 76.7% and 5.6% were also observed respectively by [81] and [82] when 4% Afzelia sawdust and 0.25% coir fiber were added to the soil matrix.

Indeed, the addition of biobased material to an earth matrix leads to a reorganization of the particles within the blocks. Thus, the addition of quackgrass straw to the 'clay + granite dust' matrix modifies the initial 'clay – granite dust' bonds into 'clay – granite dust – straw' bonds. As the calcium silicate, calcium aluminate and calcium aluminosilicate hydrates from the hydration of cement are more effective for cementing the soil particles [58,83], the occurrence of new, less solid soil-straw interface weakens the cementation and structure of the material. Moreover, the addition of quackgrass straws results in additional void in the material. Therefore, the material becomes more vulnerable under the action of a certain load. Furthermore, [84] states that the evolution of the mechanical properties of fiber/soil/cement mixtures depends mainly on the dimensions, the surface conditions and the amount of fiber. Therefore, the incorporation of a larger amount of straw mechanically weakens the material. Hence, the compressive strengths of the blocks decrease continuously as the straw content increases.

However, the incorporation of quackgrass straw in proportions of 0 to 1% of the mass of the earth matrix does not compromise the usage of the blocks in building construction. Indeed, one of the main criteria that justifies the choice of a building material is its compressive strength. According Falceto *et al.* [85], the minimum dry and wet compressive strength required for the use of CEB in building envelopes are $2MPa$ and $1MPa$ respectively. In addition, [12] defines three structural categories of CEB depending on their compressive strengths. Thus, CEBs with DCS and WCS between $[2MPa;4MPa[$ and $[1MPa;2MPa[$ are classified in category 1 ($CEB20$). This is the case for $CEB_8-0.5$ and CEB_8-1 (Fig. 8). For CEB_8-0 whose DCS and WCS are respectively $[4MPa;6MPa[$ and $[2MPa;3MPa[$, they are classified in category 2 ($CEB40$) (Fig. 8). Above 6 and 3 MPa, the CEBs would be considered in category 3 ($.CEB60$) Following this classification, $CEB_8-0.5$ and CEB_8-1 can therefore be used as filling elements in building envelopes, while CEB_8-0 can be used as a structural element in the construction of two-storey buildings. Although, none of the CEBs proposed in this study possess the strength required for structural elements in the construction of three or more storey buildings, as the case of fired clay bricks [86,87,88], they have the advantage related to their relatively low embodied energy and environmental impact [25,89].

Furthermore, Kinuthia [90] states that unlike well-designed concrete, the presence of water significantly affects the mechanical properties of earthen building materials. Heathcote [91] therefore suggests evaluating the mechanical durability of earthen blocks by calculating the loss of compressive strength after soaking in water. This is highlighted by the ratio of wet to dry compressive strengths of blocks (WCS/DCS). According to the author, a material can be qualified as durable when it has a ratio WCS/DCS higher than 0.33 [91]. In the present study, the values of the ratios WCS/DCS of 0.58, 0.47, 0.36, and 0.31 were obtained for the CEB_8-0, $CEB_8-0.5$, CEB_8-1, and $CEB_8-1.5$, respectively. This shows the good structural and durability performance of the first three mixes. For example, the ratio WCS/DCS of CEB_8-0 and $CEB_8-0.5$ is higher than that of the CEB stabilized with 8%

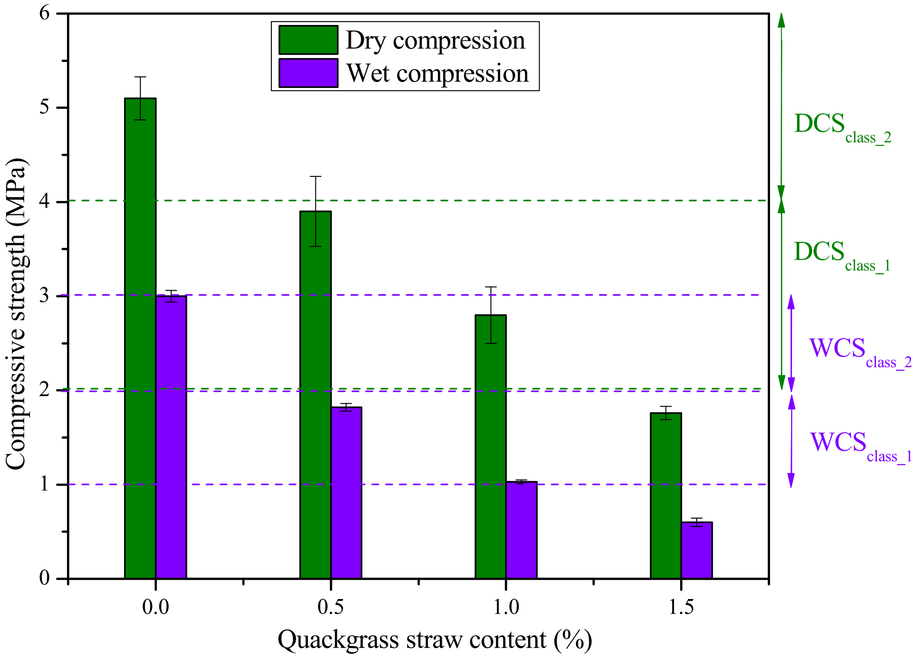


Fig. 8. Dry and wet compressive strengths of specimens with straw content; structural catergory are referred to [12].

($WCS/DCS = 0.42$) reported by [92]. As for the CEB_8-1, it has better mechanical durability than the CEB stabilized with 4% cement and 4% lime ($WCS/DCS = 0.33$) [92].

4.3.2. *Structural efficiency*

To evaluate the influence of the decrease of the bulk density and compressive strength caused by the addition of the quackgrass straw on the over all structural performance of the blocks, the coefficient of structural efficiency (CSE) of the CEBs was determined. Akinyele *et al.* [93] define this parameter as an indicator of the load capacity that a material can support in relation to its weight. It is the ratio of the dry compressive strength of the material and its density. For the CEB_8-0, the CSE is estimated to be $2640N.m/kg[J/kg]$. The incorporation of 0.5% quackgrass straw in the blocks resulted in a 20.53% reduction in the CSE of the blocks. This value decreased by 38.64% and 60.6% respectively with straw contents of 1 and 1.5%. This behavior can be explained by a simultaneous decrease in the density and compressive strength of the blocks. This is in agreement with [93] when the authors added plastic waste in the production of clay bricks. In that study, the addition of 1% plastic waste caused a 65% decrease in the structural efficiency. Moreover, the addition of 0 to 0.8 wt% of plant fiber and polymeric fiber to the CEBs stabilized with lime residu respectively resulted in evolution of the CSE in the ranges of 2544 to $2298J/kg$ and 2544 to $1853J/kg$ [78].

4.4. *Durability indicators of CEBs*

4.4.1. *Water absorption*

The coefficient of capillary absorption of CEB increased from $6.43g/cm^2$ to $22.65g/cm^2.s^{0.5}$ after $10min$ on capillary immersion when the straw content increases from 0 to 1.5%. These values make it possible to consider the blocks as very weakly capillary, except for $CEB_8-1.5$ whose capillarity exceeds the threshold value of $20g/cm^2.s^{0.5}$ for weakly capillary absorption CEB [61]. The increase in capillary absorption can be justified by the presence of the quackgrass straw, which is hydrophilic nature and creates additional porosity, and promote the capillary rise of water in the blocks through preferential passages. A linear regression between the coefficient of capillarity (Cb) and the porosity of the blocks shows the close relationship between both parameters ($R^2 = 0.98$). This relationship was also reported by [94] who found a decrease in the water absorption of the blocks following a reduction of their porosity by compaction.

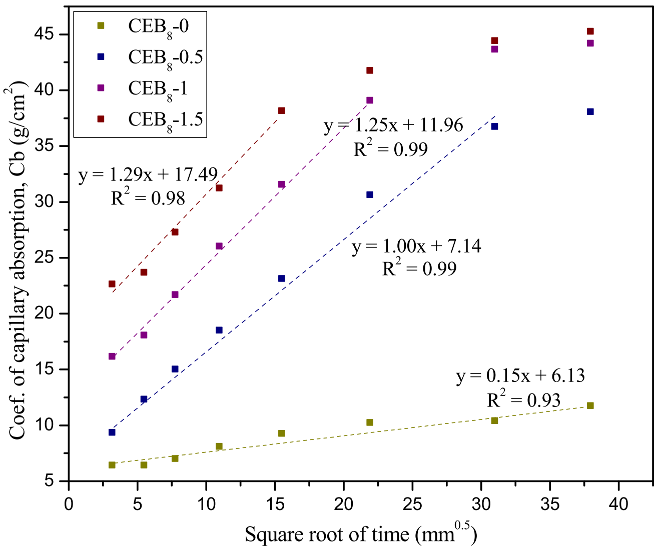


Fig. 9. Capillary water absorption of CEBs exposed to prolonged partial immersion.

Fig. 9 present the evolution of the coefficient of capillary absorption over the square root of time. CEB_8-0 shows lower absorption kinetics with respect to that of CEB with straw. For these blocks the capillary absorption over the square root of time (sorptivity) range of $1-24h$ of immersion is equal to $0.15g/cm^2.s^{0.5}$. This “sorptivity” represents the rate of absorption in the capillary pores. In contrast, a higher increase of the sorptivity can be noticed for the blocks with straw. This is shown by sorptivity values of $1g/cm^2.s^{0.5}$ for $CEB_8-0.5$, $1.25g/cm^2.s^{0.5}$ for CEB_8-1 and $1.29g/cm^2.s^{0.5}$ for $CEB_8-1.5$ and therefore suggesting the increasing effect of the straw on the diameter of the capillary pores of CEB.

Concerning the total water absorption of the blocks, all the blocks were resistant to water after immersion for 96*hours*. This behavior is

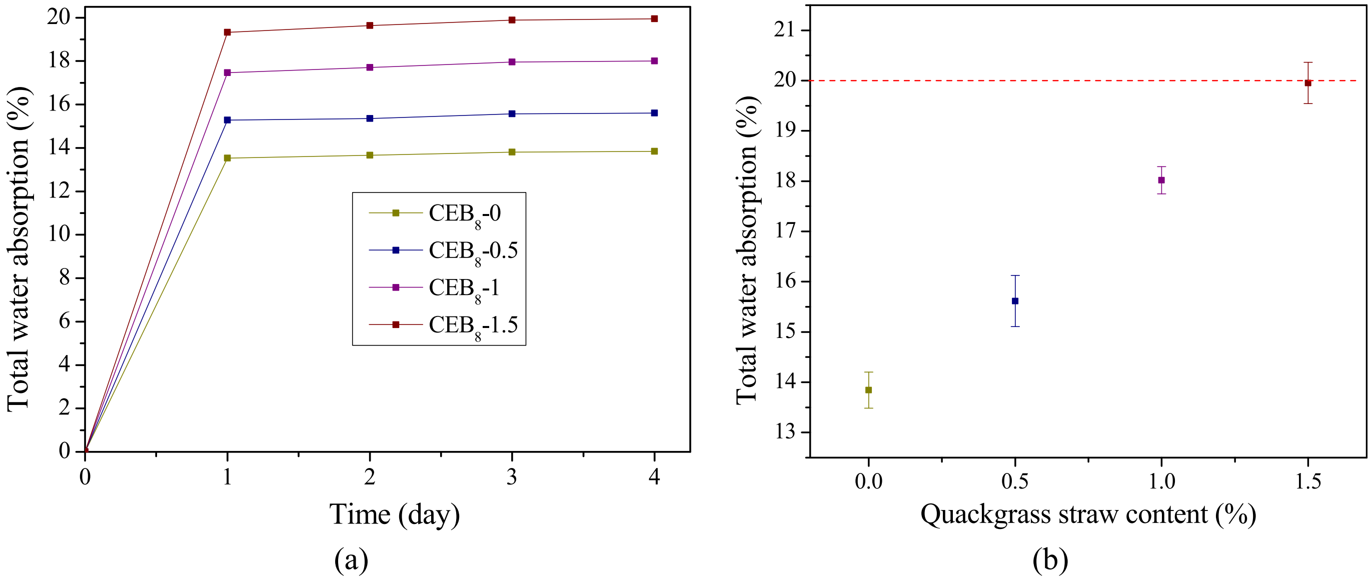


Fig. 10. Evolution of total water uptake with: **(a)** time; **(b)** straw content.

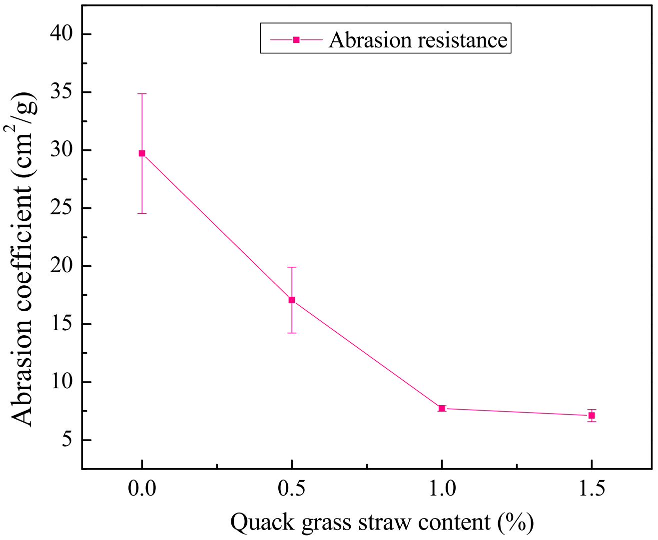


Fig. 11. Evolution of the abrasion coefficient as a function of the straw content of the specimens.

undoubtedly due to the presence of cement in the mixes. However, the total absorption of the blocks was mostly increased by the presence of quackgrass straw as it was the case with other biosourced materials such as coconut fibers and aloe vera mucilage [95], banana fibers [96] or bagasse and oil palm fibers [50]. The results from the present study show that the blocks reached the maximum absorption after three days of immersion. The evolution of the total absorption of the blocks over time is presented in Fig. 10a. It shows that the most important quantity of water was absorbed during the first 24*hours*, approximately 97% of the total absorption. Moreover, a very small increase ($\approx$ 3%) was observed up to the saturation after 76*h*. A comparison made between the blocks a difference of more than 6% the water absorption between the blocks without and with 1.5% of quackgrass straw. Thus, water absoption increases from 13.84% for the $CEB_8 -0$ to 19.9% for the $CEB_8 -1.5$ (Fig. 10b). Once again, this can be related to the influence of the quackgrass straw through the increase in porosity and their water absorption capacity. However, none of the blocks had a water absorption exceeding the 20% threshold recommended in the literature [97]. Nevertheless, considering the measurement uncertainties, the acceptability of $CEB_8 -1.5$ in the recommended range can be questioned.

4.4.2. *Abrasion resistance*

Fig. 11 presents the evolution of the coefficient of resistance to abrasion (*Ca*) of the block with the content of straw. This coefficient decreases from $29.7\mathrm{cm}^2/g$ to $7.11\mathrm{cm}^2/g$ with the increase of the content of straw. [98] explain this change by the weakening of particle adhesion of composites due to the addition of plant aggregates to the soil matrix. As stated above, the incorporation of fibers into the soil matrix weakens the cohesion between the particles of the composites and therefore promotes their loss. Despite this decrease, the values of *Ca* remain higher than the minimum thresholds set by the XP P13-901 standard [61]. According to the [61], blocks of class *CEB*40 must have the coefficient of abrasion resistance of at least equal to $5\mathrm{cm}^2/g$.

Referring to the literature, the evolution of abrasion resistance of earthen material following the incorporation of plant aggregate cannot be predicted. Indeed, the addition of biobased materials to an earth

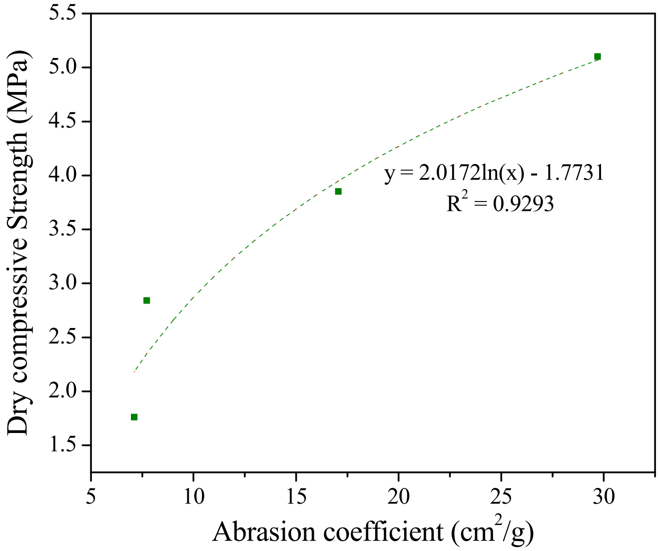


Fig. 12. Relationship between dry compressive strength and abrasion coefficient.

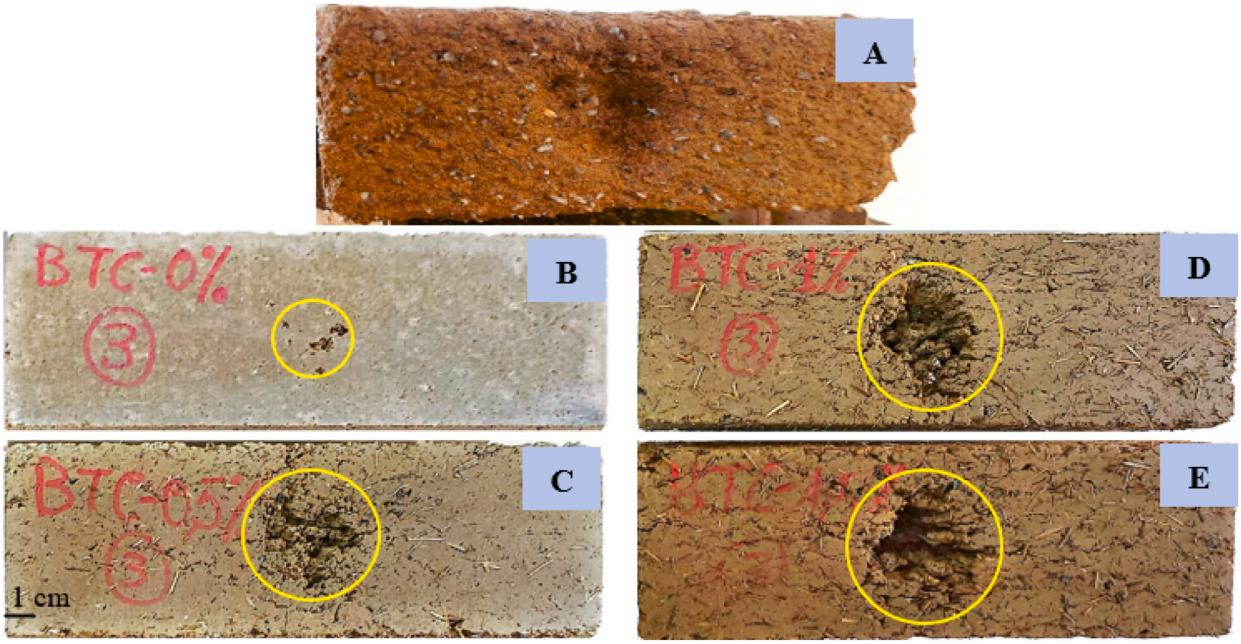


Fig. 13. View of blocks after erodibility test at 500*kPa*: **(A)** unstabilized $CEB-0$; **(B)** CEB_8-0; **(C)** $CEB_8-0.5$; **(D)** CEB_8-1; **(E)** $CEB_8-1.5$.

matrix can strengthen or weaken its abrasion resistance. For instance, [99] observed 52.9% and 17.6% of reductions of the resistance to abrasion respectively after the addition of 3% barley straw and rice husk to the soil matrix. In contrast, [14] reported an increase of the abrasion coefficient from 3.4 to $8\text{cm}^2/\text{g}$ with 3% lavender straw in the soil matrix. This was explained by the morphology of the plant aggregates. For barley straw, the particles are broad and short with a smooth surface while the lavender straw particles are fine, elongated, and rough on the outside. Such a morphology for the lavender straw strengthens the bond between its particles and the soil matrix [14]. This contrast in the literature shows that biobased materials do not exert the same influence on soil matrices. In addition, [100] established a relationship between the abrasion coefficient and dry compressive strength of CEBs. According to the authors, compressive strength is an important factor on which the abrasion coefficient depends. This is shown in Fig. 12. By analyzing the evolution of the compressive strength and the abrasion resistance as a function of the straw content, it is obvious that materials with a better compressive strength are more resistant to external actions that can cause particle detachment.

4.4.3. *Erosion resistance of the blocks*

The erodibility tests carried out at a water pressure of 50*kPa* showed a good resistance of the clay – quackgrass blocks. For all the specimens, no sign of major erosion was observed. The highest erosion depth was

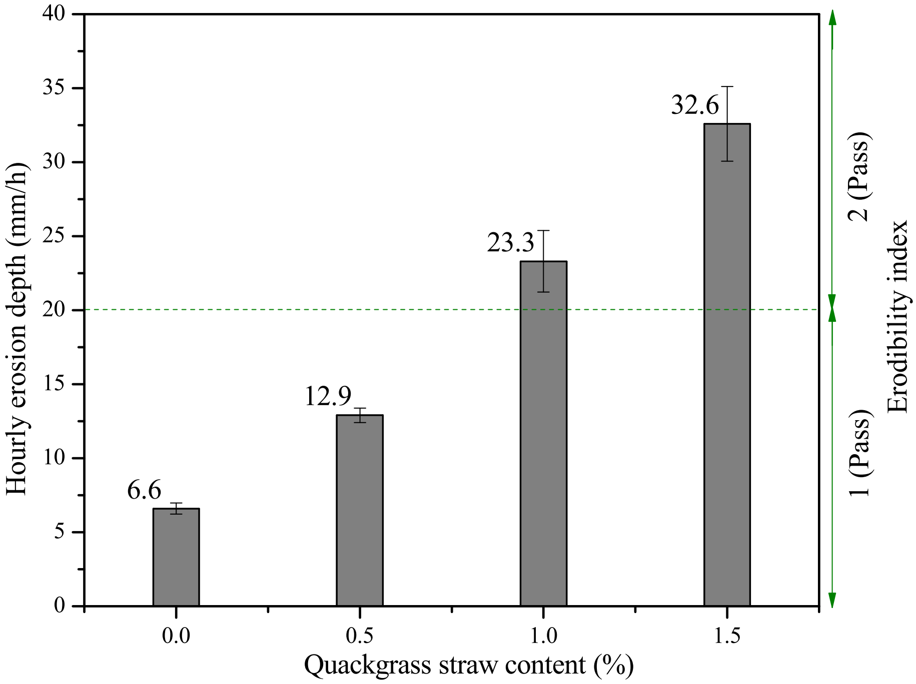


Fig. 14. Erosion depth with straw content in CEBs.

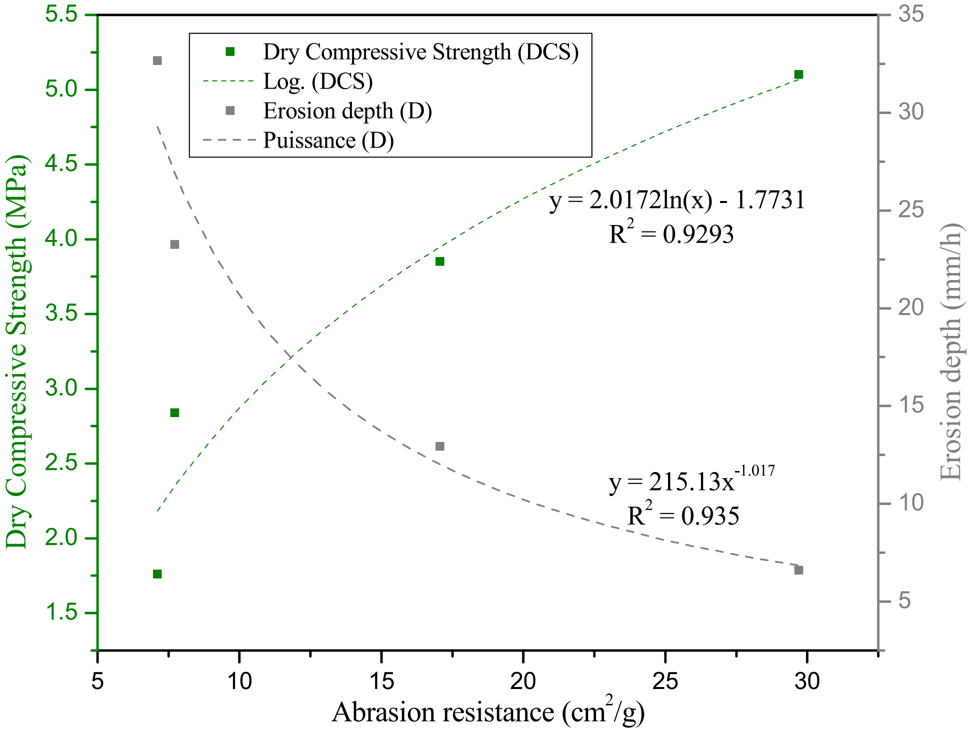


Fig. 15. Relationship between dry compressive, erosion resistance with abrasion resistance.

measured at $CEB_8 -1.5$ and was only $2mm$. Thus, the erosion index of CEB_8 in clay-grass straw is 1, for the erosion depth (D) less than $20mm/h$ [74]. In contrast, significant degradation was observed when an unstabilized control block ($CEB -0$) was subjected to the same test (Fig. 13A). This experiment once again highlights the positive impact of cement stabilization of the blocks. Similar conclusions were drawn for CEBs stabilized with cement [100], lime, or by-products [75]. The highly clayey nature of the soil has also contributed to the improvement of the resistance to erosion. Danso [72] states that high clay soils offer better resistance to erosion because of the good cohesion between the particles.

However, by applying a water pressure of $500kPa$ as suggested by Nshimiyimana *et al.* [75] for stabilized blocks, the erosion index of some blocks increases from 1 to 2($20mm/h \leq D < 50mm/h$ [74]), i.e. the class of low erosive materials. This is the case of $CEB_8 -1$ and $CEB_8 -1.5$ which have erosion depths of $23.3mm/h$ and $32.6mm/h$, respectively. This increasing evolution of erosion depth with the content of straw reveals the negative influence of straw on the erosion resistance of blocks (Fig. 14). [52] emphasized the uncertainty that exists around the influence of fibers on the erosive behavior of CEBs. For example, [101] found a reduction in the erosion resistance of CEBs with increasing content of natural fiber. However, [72] and [102] reported an improvement of this resistance when vegetable fibers (coconut husk, sugarcane bagasse and oil palm nut fibers) and animal fibers (pig hair) were incorporated in the blocks. This difference is related to the mechanical behavior of the CEBs in the presence of biosourced materials, reinforcing the hypothesis of a dependence between the mechanical and durability properties of biosourced earth materials. This was further confirmed by Fig. 15 which presents the regression correlation between the dry compressive strength and abrasion resistance following a logarithmic law. This correlation was also established between erosion and abrasion resistance with an inverse power law (Fig. 15). Thus, the evolution of the compressive resistance and abrasion resistance follows the same trend. This suggests that biobased earth materials with good mechanical properties offer better durability.

Fig. 13(A, B, C and D) shows the appearance of the eroded blocks. On the latter, it can be observed an increase in the erosion area as the erosion deepens in the specimens. For the $CEB_8 -0$, the erosion surface is limited to a few spots of less than $1cm$ in diameter. Given the surface area covered by water spray on the specimen ($D \approx 9.5cm$), these spots could only have been due to the most vulnerable points on the surface. The good surface condition of $CEB_8 -0$ was due to the good cohesion of the clay particles and cementation with cement which limited the presence of the vulnerable spots. On the contrary, the cracks formed due to the incorporation of quackgrass straw in the soil matrices increases the erosion surface of the composite CEBs (Fig. 13). The ratio of eroded surface over sprayed surface are estimated at 30% for the $CEB_8 -0$, 52% for the $CEB_8 -0.5$, 65% for the $CEB_8 -1$, and 69% for the $CEB_8 -1.5$.

5. Conclusion

In this study, clay - quackgrass straw CEBs were proposed as an alternative to fired clay bricks in the south of Benin; where energy availability for firing clay bricks is a problem. The material consists of a matrix of earth (clay + 0/5 granite dust) stabilized with 8% cement and incorporating 0 to 1.5% of quack grass straw. The physical characterization showed the impact of quackgrass straw on the density, porosity and capillary and total water absorption of blocks.

- The incorporation of quackgrass straw in the CEBs results in a 12.42% decrease in density. The porosity, capillarity and total water absorption also increased from 27 to 33%, 6.43 to $22.65g/cm^2.s^{0.5}$, and 13.84 to 19.95% respectively with 0 to 1.5%.
- The incorporation of straw in CEBs also affected the mechanical and durability performance of the blocks. There was a 65% and 81% reductions of the dry and wet compressive strengths, respectively, which led to the disqualification of $CEB_8 -1.5$ for use in building construction. The latter has a compressive strength of $1.76MPa$ in dry and $0.56MPa$ in wet conditions which are below the normative thresholds of $2MPa$ and $1MPa$. Other CEB can be used for the construction of modern and sustainable building envelopes. $CEB_8 -0$, $CEB_8 -0.5$ and $CEB_8 -1$ can be used as filling elements as well as structure elements in two-storey buildings ($CEB_8 -0$) and single-story buildings ($CEB_8 -0.5$ and $CEB_8 -1$). The structural durability

especially achieved for the CEB_8 -0 can be attributed to the stabilizations (addition of 0/5 granite dust and addition of cement) that respectively created and strengthened the skeleton of the blocks. These CEBs made of clay - quackgrass straw are a good alternative to fired clay bricks.

- The abrasion and erosion resistances of the blocks were weakened by the addition of straw; but remained good enough to allow the use of all the CEBs in the construction of sustainable buildings.

This effectively shows that earth blocks can be produced without firing, to achieve the sustainability in the building sector. These blocks contribute to meeting the expectations of populations reconciling socio-cultural, economic, modernity and environmental aspects. The impact of the use of the CEB, made of clay - straw of quackgrass, on the energy consumption of the buildings and the thermal comfort of the occupants must be evaluated. Future study should therefore aim the evaluation of the hygrothermal and energy performances of the CEBs made of clay - straw of quackgrass.

CRediT authorship contribution statement

Gratien Kiki: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Philbert Nshimiyimana:** Writing – review & editing, Visualization, Methodology, Data curation. **Clément Kouchadé:** Writing – review & editing, Data curation. **Adamah Messan:** Writing – review & editing, Visualization, Resources. **Aristide Houngan:** Writing – review & editing, Supervision, Funding acquisition. **Philippe André:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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