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Influence of agricultural waste additives on the mechanical performance and water sensitivity of cement-stabilized compressed earth blocks: Case of Parkia biglobosa pods

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ABSTRACT: Cement-stabilized natural clay soils can be combined with agricultural waste decoction to improve the mechanical performance and water resistance of compressed earth bricks. The aim of this study is to investigate the mechanical performance and durability of cement-stabilized compressed earth bricks with the addition of agricultural waste in the form of decoction in order to promote an environmentally-friendly material in the building sector. Based on an experimental campaign, mechanical properties such as modulus of elasticity, flexural strength and compressive strength, as well as durability (open porosity and capillary water absorption), were studied for these bricks. The results show that these properties are influenced by the nature of the soils used, as well as by other parameters studied in this work, such as the percentage of cement and the percentage of Parkia biglobosa pod decoction. Indeed, the addition of 8% cement with at least 10% Parkia biglobosa pod decoction proved beneficial for optimum performance. Moreover, according to criteria such as total open porosity and capillary water absorption, the durability of this material improves with an increase in cement percentage and the addition of at least 10% tannin-rich Parkia biglobosa pod decoction. The use of these waste products (Parkia biglobosa pods) in compressed bricks therefore seems beneficial in terms of improving their mechanical performance, reducing their sensitivity to water and helping to preserve the environment.

KEYWORDS: Clay soil, CEB, pod decoction, sustainability, environment.

1 INTRODUCTION

Raw earth construction is currently enjoying renewed interest as an environmentally-friendly option in civil engineering and the building sector in particular. This readily available, low-cost material is of great interest in today's environmental context, and boasts a wide range of characteristics, including good hygrometric regulation of the rooms it envelops, as well as inertia that ensures thermal comfort. Despite the many known advantages of this material in its compressed form, it still has weaknesses in its current state, such as low mechanical strength and high sensitivity to water. On the other hand, the material's high sensitivity to water can alter its resistance in the presence of excessive capillary rise, or regular weathering, for example. One technique for using earthen materials is in the form of stabilized compressed bricks (CEB) with a regular structure in raw earth masonry. These blocks are increasingly used in modern building construction [1], [2] They are a means of socio-economic and energy adaptation in sub-Saharan African countries, to ensure a satisfactory standard of living and housing for all. The challenge is to find out whether it is possible to improve the mechanical properties of compressed earth bricks by modifying their formulation with agricultural waste additives, a local product collected in Benin. The product in question is Parkia biglobosa pods, known under the scientific name "Parkia biglobosa" [3]. It is the addition of the decoction of Parkia biglobosa pods that is being studied, and containing tannin in particular, they are traditionally used as a natural binder in West Africa to reinforce rammed earth renderings against rainwater infiltration.

Numerous efforts have been made in the literature to improve the physical-mechanical performance and thermal comfort of this material in CEB by adding chemical binders, either cement (5%-12%) or lime (6%-12%). [4] the incorporation of plant fibers [5], [6], [7], [8], [9], [10], [11] in buildings. However, it is important to further explore the question of the durability of CEB and to incorporate natural elements to adopt a more ecological material. We need to characterize the mechanical properties, total open porosity and water absorption by capillary rise of CEB by incorporating the decoction of cowpea pods as mixing water. This work contributes to the valorization of local products such as clay in the construction sector, while preserving the environment through the use of agricultural waste.

2 MATERIALS AND METHODS

The equipment, raw materials used and approach adopted are presented in this section.

2.1 RAW MATERIAL

The clay soils and agricultural wastes (cowpea pods) used in this study are shown in Figure 1. These soils differ in texture, physical and geotechnical characteristics (Table 1). Grain sizes of less than 5 mm [12], [13] and the plastic range [14] of the two clay soils designated Gu and Ma, meet the recommendations of standard XP P13-901 [15] relating to the processing of CEB. Table 1 shows an active clay fraction for the Gu natural earth, while the Ma earth has a very active clay. This difference is due to the nature of the clays present and their affinity with water. The soils are stabilized with CEMI 52.5 N PM-CP2 cement (8%), referred to as **C1** in the presentation of results. In the formulation, the decoction of Parkia biglobosa pods is used as the mixing water, except in the reference specimens (without decoction).

a) b) c)

Fig. 1. clay soil Gu (a), clay soil Ma (b) and cowpea pods (c)

Table 1. Physical characteristics of the soils studied

Land characteristics		Gu	Ma
Granular distribution of soils studied (%)	Clay (d<2µm)	8,3	5,1
	Silt (2µm<d<2mm)	44,3	16,5
	Sand (2mm<d<4mm)	47,4	78,4
Density (Kg/m) ^{3}		2450	2480
Plasticity index Ip		11	17
Clay fraction activity		Active	Very active

2.2 FORMULATION AND STORAGE

To make CEB, clay soils with a particle size of less than 5mm were oven-dried at 60°C±5 to constant mass in accordance with NF EN ISO 17892-12014-12. All the constituents (soil, cement and mixing water) were mixed in well-defined proportions using a mixer. The optimum mixing water contents of the mixture are 17.8% and 16.7% for the Gu and Ma compositions respectively. The water added to the mixture of certain compositions is substituted by the decoction of Parkia biglobosa pods. This decoction is obtained by maceration of the pods in water for 72 hours at ratios of 10% and 20% of the mass of the pods to the total amount of water in the mixture. The wet mixture is molded in a 40x40x160 mm mold^3 and compacted at a loading speed of 2min/mm under a compaction pressure of 5 MPa using a 200 KN capacity Zwick-Roell® press. After compaction, the blocks are immediately removed from the moulds and stored in plastic film (at a relative humidity of 95%±5 and a temperature of T=20°C±1) for the first 7 days. The plastic film is then removed from day 8^{ième} and the blocks are stored at 50% ±5 relative humidity for up to 28 days at the same temperature.

a) b) c)

Fig. 2. Decoction of Parkia biglobosa pods (a), compaction (b) and demolding (c) of CEB.

Table 2. Composition codes and designations

Code	Designation
Nom (**terre**) **-x** % C1, y%G	Compressed earth block stabilized with **x%** (5% or 10%) of cement **C1** mixed with mixing water for ratios of **y%** (0%; 10% or 20%) of Parkia biglobosa **G** pod decoction. For example Gu-5% C1, 20%G

2.3 EXPERIMENTAL METHOD

To gain a better understanding of the mechanisms involved in the addition of cowpea decoction to CEB, the macro-mechanical behavior of CEB is studied through parameters such as dynamic modulus of elasticity, flexural strength and compressive strength. On the other hand, the durability of these blocks in the face of water infiltration by capillary rise and the study of porosity accessible to water.

2.3.1 CHARACTERIZATION OF MECHANICAL PROPERTIES

Experimental methods for determining dynamic modulus of elasticity, flexural strength and compressive strength are presented in this section.

DYNAMIC MODULUS OF ELASTICITY TEST

Dynamic modulus of elasticity E_{dyn} is measured using a non-destructive method based on compression wave propagation. The PUNDIT (Portable Ultrasonic Digital Indicating Tester) device (Figure 4), which measures the longitudinal velocity V_L (m/s) and the time (µs) of wave propagation between two transducers, is used at different times, i.e. at 28 days for both curing modes. Three specimens/composition/hardness are tested at each time point. The dynamic elastic modulus E_{dyn} is calculated using equation 1, assuming that the material is isotropic...

$$E_{dyn}=V_L^2\times\frac{(1-2\nu)\,(1+\nu)}{(1-\nu)}\times\rho \qquad \text{(Equation 1)}$$

Fig. 3. Non-destructive dynamic modulus of elasticity method

FLEXURAL AND COMPRESSIVE STRENGTH TEST

The 40x40x160 mm^3 specimens are first tested in 3-point bending (three specimens per formulation) at 28 days. The half-blocks resulting from the bending are then each crushed in uniaxial compression (six specimens per formulation) at the same age and on the same press in accordance with standard NF EN 196-1 [16].

2.3.2 DURABILITY INDICATORS

The durability indicators measured are water-accessible porosity, water absorption coefficient and sorptivity coefficient. Durability tests are carried out at 28 days.

WATER-ACCESSIBLE POROSITY

The test is performed on 40x40x160 mm^3 samples, referring to the NF P18-459 standard. It consists in totally immersing the CSB in water for (44 ±1) hours (vacuum sealing with water), preceded by a pre-conditioning under vacuum for 4 hours (vacuum sealing without water), which is considered sufficient for a complete saturation of water in their pores at the pressure below 25mbar in vacuum sealing. The mass of the saturated sample was weighed in water $m_{satwater}$ (g) (hydrostatically weighed), and in air, $m_{sat.air}$ (g) and then dried in an oven set at 60°C to the constant mass, this dry mass is noted m_s. The total porosity to water (P_0) is calculated by the Equation 2.

$$P_0=100\times\frac{m_{satair}-m_s}{m_{satair}-m_{satwater}} \quad \text{(Equation 2)}$$

CAPILLARY WATER ABSORPTION

Capillary absorption is measured in accordance with experimental standards XP P13-901 [15] on 40x40x160 mm^3 samples 28 years old. The principle is to partially immerse one face (surface: 40x40 $mm^{2,}$ Figure 5) of the brick to a depth of 5 mm and determine the absorption coefficient (Cb in $g/cm^2.m^{0.5}$). This coefficient makes it possible to evaluate the absorption rate corresponding to a time equal to 10 minutes (0.17h), as recommended in standard XP P13-901. Like sorptivity S, which shows a material's capacity to absorb and retain water in its pores, it is interesting to exploit this coefficient to characterize pore filling according to their size [17]. The Cb coefficient is expressed by the formula in equation 3:

$$C_b=\frac{100\times(m_h-m_s)}{S\times\sqrt{t}} \quad \text{(Equation 3)}$$

m_h-m_s: mass of water absorbed by the block during the test, in g;
S: Cross-section of immersed face, in cm^2;
t: is the immersion time of the test piece corresponding to 10 min.

Fig. 4. Capillary water absorption of CEB

3 RESULTS AND DISCUSSION

This section looks at the mechanical performance and durability (water sensitivity) of mud bricks with the addition of Parkia biglobosa pod decoction.

3.1 EFFECT OF DECOCTION OF COWPEA PODS ON MECHANICAL PROPERTIES

The results obtained on mechanical properties such as dynamic modulus of elasticity, flexural strength and compressive strength at 28 days are presented in this section.

DYNAMIC MODULUS OF ELASTICITY

Figure 6 shows the dynamic modulus of elasticity (Edyn) of CEB at 28 days. The parameters examining this mechanical property of CEB are soil type, cement percentage and decoction percentage. For stabilized natural clay soils, increasing the cement percentage from 5% to 8% leads to an increase of 4 GPa and 2 GPa respectively in the dynamic modulus of elasticity of the Gu and Ma compositions at 28 days. However, the presence of decoction led to a slight decrease in Edyn for Gu compositions and a slight increase for Ma compositions at this age. This difference in results can be attributed to the cohesive behavior between soil and cement particles, as well as to the granular structure. The Ma composition, being denser with highly active clays, exhibits better cohesion between particles than the Gu soil. The increase in modulus with the addition of the decoction shows a good interaction between the clays and the tannins in the Parkia biglobosa pods.

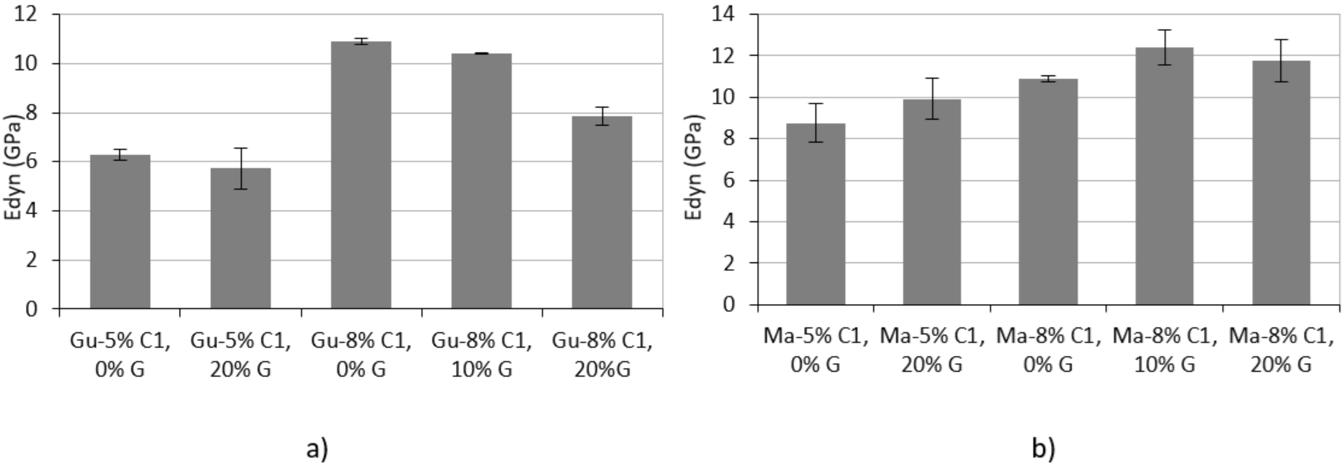


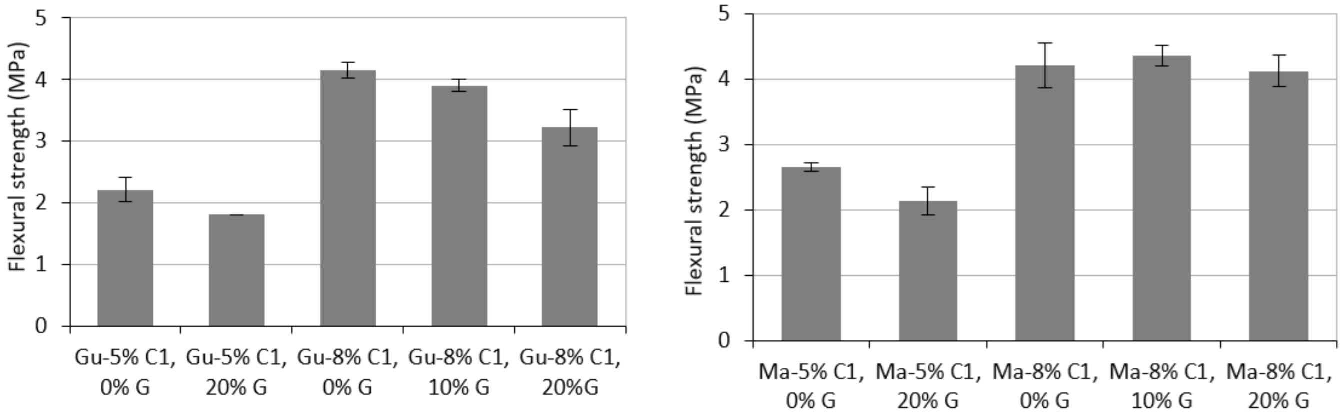
Fig. 5. Effect of decoction and cement content on the dynamic modulus of elasticity of CEB: Gu (a) and Ma (b) compositions.

FLEXURAL STRENGTH

Flexural strength is determined at 28 days and shown in Figure 7 with Gu and Ma earths.

The average flexural strength of CEB improved 1.8 times with increasing cement percentage: 2.2 MPa and 2.6 MPa with Gu-5% C1, 0% G and Ma-5% C1, 0% G; and 4.16 MPa and 4.21 MPa with 8% C1 at 28 days (Figure 7). This is due to the formation of C-S-H/C-A-S-H and CaCO3 cement gels around the particles, which increase the contact points and thus improve the microstructure of the CEB.

For 5% C1, the addition of 20% of the decoction led to a decrease in flexural strength for all compositions. Like the dynamic modulus of elasticity, flexural strength with 8% decreased for Gu compositions while it increased slightly for Ma ones. This result suggests a difference in interaction between the clays in the natural soils and the tannins contained in the decoction of Parkia biglobosa pods. So, the nature of the soil, the percentage of cement and the decoction of Parkia biglobosa pods influence the material's flexural strength.



a) b)

Fig. 6. Effect of decoction and cement content on the flexural strength of CEB: Gu (a) and Ma (b) compositions.

COMPRESSIVE STRENGTH

Figure 8 shows the results for compressive strength at 28 days. We analyze the effect of the percentage of cement, the nature of the soil and the percentage of Parkia biglobosa pod decoction.

The average compressive strength of 3 specimens improved for CEB as the cement percentage increased. Compressive strength was better at 28 days with Ma soil (approx. 17 MPa) than with Gu (13.58 MPa), which had the same compressive strength regardless of the percentage of cement incorporated. Soil stabilization with cement is particularly effective on clay soils with relatively coarse particles, enabling cement grains to be incorporated homogeneously. This process ensures uniform hydration of the particles, promoting their bonding and the multiplication of their contact points. This is in line with the results obtained by Walker [18] which indicate that the compressive strength of C1-stabilized compressed earth block decreases with increasing clay mineral content. The increase in mechanical strength depends on the number of contact points between particles, which is influenced by particle size.

Nevertheless, the addition of pod decoction caused a slight decrease in compressive strength, with a difference ranging from 0.4 MPa to 2 MPa between reference specimens (Gu-8% C1, 0%G and Ma-8% C1, 0%G) and specimens with decoction (Gu-8% C1, 10%G, Gu-8% C1, 20%G, Ma-8% C1, 10%G and Ma-8% C1, 20%G). For all compositions, the addition of 5% C1 and 20% G reduced the compressive strength of CEB. This result could be explained by the fact that the presence of the decoction would have disrupted the hydration of the incorporated cement due to the organic matter in the cowpea pods (plant matter).

We can deduce that decoction of the pods was beneficial in improving the tensile strength of Ma-based bricks, but had the opposite effect on Gu clay soil.

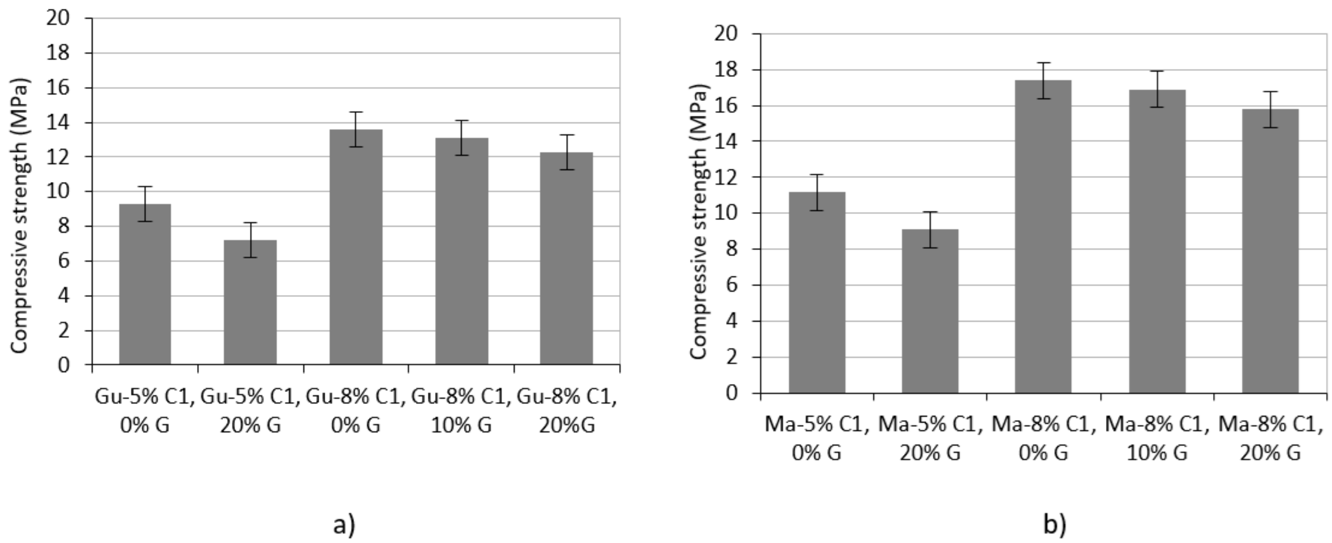


Fig. 7. Effect of decoction and cement percentage on the compressive strength of CEB: compositions of Gu (a) and Ma (b).

3.2 EFFECT OF DECOCTION OF COWPEA PODS ON CEB DURABILITY

The parameters for assessing the water-sensitivity of CEB in terms of its durability against weathering are water-accessible porosity and water absorption by capillary action. The effect of cement percentage and pod decoction will be analyzed, as will the effect of soil type.

WATER-ACCESSIBLE POROSITY

Bricks formulated with natural clay soils did not resist contact with water, so it was necessary to incorporate cement as a stabilizer to improve their durability. Figure 9 shows that the porosity of CEB is respectively 34% and 29% with 5% C1, and 33% and 27% with 8% C1 for Gu and Ma stabilized earth at 28 days. This result shows that the porosity of CEB decreases with increasing cement percentage and also depends on the type of soil used. This result can be explained by the slight improvement in CEB microstructure due to the cement hydrates formed. When water is substituted in the formulation with 10%G and 20%G of Parkia biglobosa pod decoction, the total open porosity determined shows values of the same magnitude for all compositions. This means that the decoction of the pods does not influence the total porosity of the CEB. In any case, the lowest total porosity values are obtained with Ma soil compositions. This result on porosity with Ma soil is mainly linked to its intrinsic properties (granulometry, fraction activity and clay nature). We can deduce that the nature of the soil influences the porosity of CEB.

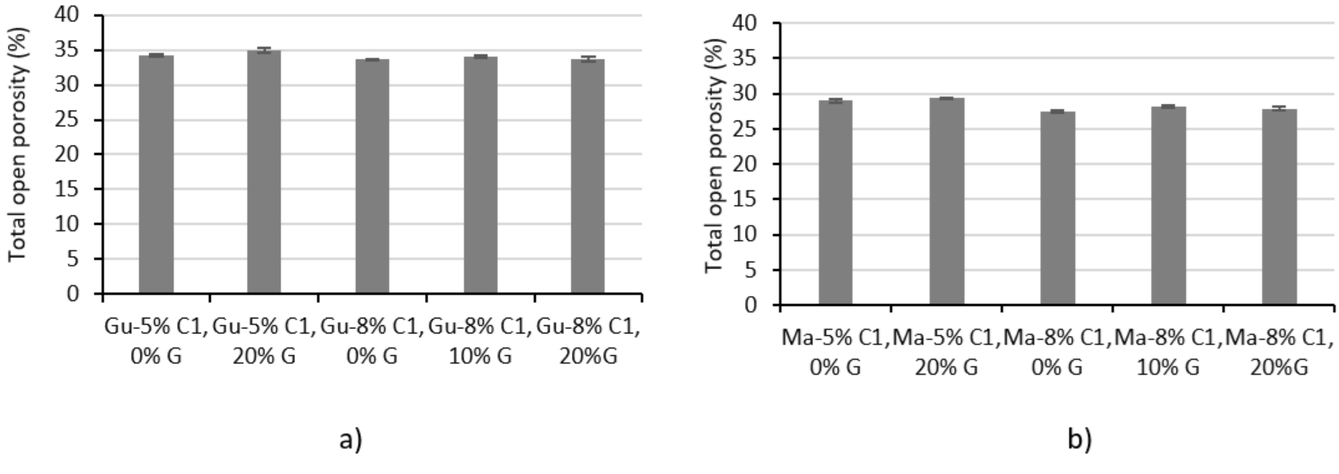


Fig. 8. Effect of decoction on the total open porosity of Gu-based (a) and Ma-based (b) CEB.

CAPILLARY WATER ABSORPTION

The results in Figures 10 and 11 show the coefficient of water absorption by capillarity of Gu- and Ma-based CEBs, as well as sorptivity at 28 days. These coefficients are determined by examining the effect of cement percentage (5% and 8% of C1), Parkia biglobosa pod decoction (10% G and 20% G) and soil type. The water absorption coefficients C_{b10min} of CEB without decoction are determined and are respectively for Gu and Ma with the addition of 5% C1: 5.28 g/cm^2.mn^{0,5} and 8.5 g/cm^2.mn^{0,} and with 8% C1: 4.6 g/cm^2.mn^{0,5} and 7 g/cm^2.mn^{0,5} at 28 days are lower than 20 g/cm^2.mn^{0,5} (Table 3), so CEB are qualified as weakly capillary ($C_{b10min<20}$ g/cm^2.mn^{0,5}, AFNor 2001) [15]. The presence of 10%G and 20%G of Parkia biglobosa pod decoction in CEB led to a decrease in C_{b10min}. This can be explained by the presence of tannins in the Parkia biglobosa pods, which establish bonds with clay constituents such as iron oxides and albumin to reinforce the cohesion of the material, making it watertight.

The linear correlation between capillary absorption (g/cm^2) and the square root of time (mn^{0,5}) of Gu- and Ma-based CEB with the addition of 5% and 8% C1 between 1 and 24 hours is shown in Fig. 10 and Fig. 11). The sorptivity coefficient S (g/cm^2.mn^{0,5}) derived from this correlation provides a qualitative assessment of the absorption rate in the capillary pores: the lower the coefficient S, the smaller the pore radius. [7], [17]. The mean values of the capillary sorptivity of CEB range from 0.0379-0.0664 g/cm^2.mn^{0,5} reaching its minimum value with Ma-8% C1, 10% G. The lower value of sorptivity accompanied by the reduction of the total absorption coefficient suggests that CEB with the composition Ma-8% C1, 10% G present the smallest average pore radius with the presence of the cement hydrates formed.

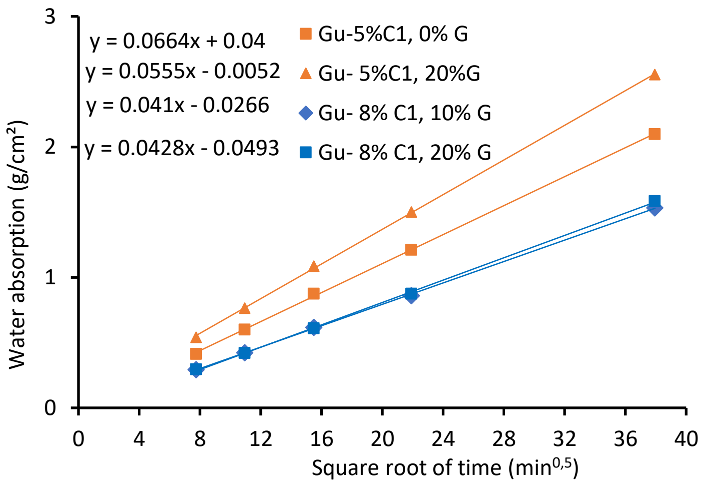


Fig. 9. Effect of decoction on the sorptivity of Gu-based CEB

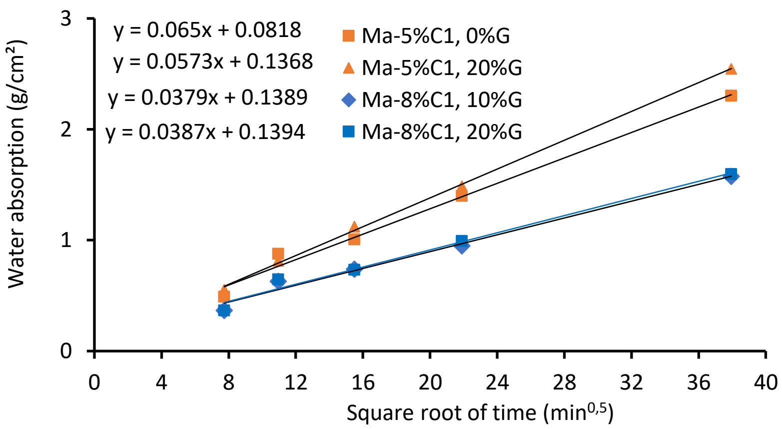


Fig. 10. Effect of decoction on the sorptivity of Ma-based CEB

An analysis of Table 3 also shows that the addition of pod decoction reduced the sorptivity of CEB, i.e. their capacity to absorb and retain water by capillary action, and the effect was more marked with Ma soil. The addition of Parkia biglobosa pods decoction appears beneficial for the durability of CEB in terms of their sensitivity to water.

Table 3. Capillary water absorption coefficients and sorptivity of CEBs

Compositions	S ($g/cm^2.min^{0,5}$)	C_{b10min} ($g/cm^2.min^{0,5}$)	Total porosity (%)	Qualifications [15]
Gu-5% C1, 0%G	0,0664	5,28±1,26	34,28±0,19	Weakly capillary
Gu-5% C1, 20%G	0,0555	7,29±1,08	34,94±0,34	
Gu-8% C1, 0%G	0,0487	4,61 ±0,01	33,60±0,16	
Gu-8% C1, 10% G	0,0410	3,39±0,07	34,07±0,20	
Gu-8% C1, 20% G	0,0428	3,76±0,96	33,64±0,35	
Ma-5% C1, 0%G	0,065	8,5±1,73	29,00±0,28	
Ma-5% C1, 20%G	0,0573	6,6±0,33	29,38±0,12	
Ma-8% C1, 0%G	0,0405	7,0±0,57	27,48±0,15	
Ma-8% C1, 10% G	0,0379	4,7±0,86	28,11±0,15	
Ma-8% C1, 20% G	0,0387	6,1±0,74	27,89±0,20	

4 CONCLUSION

This study highlights the importance of several parameters in understanding the performance of a cement-stabilized raw earth brick building material with the use of Parkia biglobosa pod decoction. The results of the mechanical properties analysis show that the dynamic modulus of elasticity and flexural strength are improved by the addition of the decoction for a soil with specific physical characteristics, including a less fine granulometry, a high proportion of active clay and a chemical composition favorable to the tannins contained in dene pods. However, no significant influence was observed on compressive strength. Optimum mechanical performance was achieved using 8% cement and 10% decoction.

In addition, it was found that stabilizing natural soils with 8% cement and at least 10% Parkia biglobosa pod decoction had a beneficial effect on water sensitivity, thanks to the tannins present in the pods. The use of this agricultural waste improves the durability of mud bricks against water infiltration.

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