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Physico-mechanical Performances of Compressed Earth Blocks Stabilized with Calcined Clay-based Geopolymer

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Abstract

The present study assesses the performances of compressed earth bricks (CEB) stabilized with calcined-clay-based geopolymer. The geopolymer binder was synthesized from local kaolin-rich clay calcined at 700 °C to transform it into amorphous and reactive metakaolin (MK). The lateritic earthen material, which has a grain size of 0/5 mm, was stabilized with 0, 5, 10, 15 % geopolymer binder; and 8% Portland cement for control, with respect to the mass of dry earthen material. The alkali solution of sodium hydroxide (NaoH, 12 M) was added to the dry mixtures for the activation of the MK and production of wet mixtures, which were manually and statically compressed (~35 bar) in mould (295 x 140 x 95 mm^3) of Terstaram machine to produce the CEB. Stabilized CEBs were cured for 14 days (7 days at room temperature 30 ± 5 °C and 7 days in an oven at 60 °C), while those stabilized with cement were cured at room temperature 30 ± 5 °C for 28 days. The CEBs were dried and characterized for their physico-mechanical properties. The results showed a clear improvement in the performance of CEB stabilized with up to 20% geopolymer. The water accessible porosity was 27.4% for CEBs stabilized with 15% geopolymer, against 26% for CEBs stabilized with 8% cement. The dry and wet compressive strength were 9.8, and 4.8 MPa for CEB stabilized with 15% geopolymer, against 6.6 and 4.7 MPa for CEB stabilized with 8% cement. All indicators show that CEB stabilized with geopolymer can be used in modern construction.

Keywords

Calcinated clay, Geopolymer, Compressed earth blocks, Physico-mechanical properties

Introduction

Earth has long been the building material used in various countries due to the availability and accessibility of the raw material. Historically, the construction technology with earth was based on moulded adobe bricks (banco), particularly in sub-Saharan Africa, such as Burkina Faso. However, its use has been shortened by the emergence of clinker-based synthetic cementitious materials. The cultural aspects also hinder the wide acceptance of earthen construction. In Burkina Faso, earthen materials are paradoxically associated with an underprivileged class in society [1]; construction using CEB is mostly observed for the urban elite. Due to their high cost and CO_2 footprint, the cementitious materials remain inaccessible to the vast majority of the population in Burkina Faso [2]. For this part of the population, adobe thus remains an alternative to cement materials. Nevertheless,

adobe is very sensitive to water [3, 4], which affects its structural performance and durability. Stabilisation is, therefore, necessary to improve the performance of earthen materials to water resistance.

Stabilisation can be physical, mechanical or chemical. The chemical stabilisation process consists of mineral or organic additions that strengthen the matrix by reinforcing the bonds between the different particles [5]. Cement is the most popular of the commonly used stabilisers [6] due to its wide availability and ability to significantly improve the mechanical and durability properties of CEB. However, the addition of cement considerably degrades the thermal properties of the CEBs, which impacts the reduction of thermal comfort compared to adobe [2]. Furthermore, clinker production is energy intensive and has a high environmental impact in the current climate context.

Alternative chemical stabilisation techniques, more respectful of the environment, are considered in the literature, particularly those based on geopolymer binders [7, 8]. The different sources of aluminosilicates used as precursors for activating this geopolymer binder are from different origins. Among these, rice husk ash, fly ash, and MK are commonly used depending on their availability, cost, and type of application. However, compared to cementitious admixtures, geopolymers need an activating solution to form stable gels that harden the matrix. The aqueous solutions of NaOH, potassium oxide (KOH), and sodium silicate (Na_2SiO_3) are commonly used to activate the aluminosilicates and stabilise the earthen materials. Earth bricks, stabilised with geopolymer binder, have achieved interesting physical and mechanical properties [2, 8].

However, the durability of these bricks needs to be investigated with the type of climate in which they will be used. Therefore, the present study focuses on evaluating the physical-mechanical properties of CEB stabilised with geopolymer, synthesised from local calcined clay and activated with NaOH.

Materials and Method

Materials

The lateritic earthen material, constituting the main matrix of the CEB, is collected from the locality of Kamboinsin, around Ouagadougou. It is dried and then sieved to 5 mm to obtain a particle size distribution of 0/5 mm, as recommended by ARS 674 [9]. This material was previously characterized for the production of CEB [2]. Calcined clay-based geopolymers are nanoscale materials.

The stabilising agent of CEB comprises a geopolymer binder synthesised from calcined clay of kaolin. The kaolin was collected from the locality of Saaba, around Ouagadougou [2]. It was ground and sieved to 125 µm. Its calcination was carried out at 700 °C for 3 h for the amorphisation of the aluminosilicate and transformation of kaolin into reactive MK. This aluminosilicate was activated using a solution of NaOH (12 M) from the dissolution of NaOH crystals of 99% purity in distilled water. The cement type CEM II/A-P/42.5 N was used as a reference stabilisation binder.

Experimental methods

Production and curing of stabilised CEB

The stabilisation of earthen materials was carried out on a volumetric basis, considering the absolute densities of the various materials (lateritic earth, MK, and cement [2]. The proportions of the different content of the materials are given in table 1. The geopolymer-stabilised CEB are designated as CEB_0G, CEB_5G, CEB_10G, CEB_15G, and CEB_20G and the cement-stabilised CEB by CEB_8C, respectively, for CEB stabilised with 0, 5, 10, 15, 20% of geopolymer, and 8% of Portland cement as a partial mass substitution to the lateritic earth.

First, the dry materials (Earth + MK or earth + cement) were mixed to ensure homogeneity. The wetting water and the alkaline solution were then mixed, resulting in wet mixtures statically compressed in a prismatic mould (29.5 x 14 x 9.5 cm^3) at a pressure of 35 bar using a manual press model TERSTARAM. The CEB was sealed in a plastic film and kept at the ambient temperature of 30 ± 5 °C. The CEB stabilised with geopolymer binder were specifically cured for 14 days: 7 days at room temperature and 7 days of thermal treatment in an oven at 60 ± 5 °C. CEB stabilised with cement and was cured for 28 days. After curing, CEB was dried at 60 ± 5 °C until reaching the constant mass and characterised for physico-mechanical and durability performances.

Characterisation of the physico-mechanical properties

The bulk density and water-accessible porosity of the samples were determined after hydrostatic weighing, respectively, using the equations (1) and (2). in these equations, ρ is the bulk density of the sample, WAP is the water-accessible porosity (%), ρ_w is the density of water, M_{dry} is the dry mass of the sample (g), $M_{sat.air}$ is the saturated mass measured in the air (g), $M_{sat.wat}$ is the mass of the saturated sample measured in water (g). The compressive strength of the samples is determined on CEB in the dry state and wet state after immersion in water for 2 h, according to the standard XP P13-901 [10]. The test is performed at a constant displacement speed of 0.02 mm/s. The strength, Rc [MPa], is calculated using equation (3), where S (cm^2) is the area of the loaded surface.

Table 1: Content of materials in different mixtures for the production of earth bricks.

Materials	CEB_0G	CEB_5G	CEB_10G	CEB_15G	CEB_20G	CEB_8C
Lateritic earth (%)	100	95	90	85	80	92
Geopolymer (%)	-	5	10	15	20	-
Cement (%)	-	-	-	-	-	8
Water/solid (%)	16.7	17.7	18.5	21.5	22.3	17

$$\rho = M_{dry} \text{ x } \frac{\rho_w}{M_{sat.air} - M_{sat.wt}} \quad (1)$$

$$WAP = 100 \text{ x } \frac{M_{sat.air} - M_{dry}}{M_{sat.air} - M_{sat.wat}} \quad (2)$$

$$R_c = 10 \text{ x } \frac{F_r}{S} \quad (3)$$

The capillary absorption of the samples was determined according to the standard XP P13-901 [10]. The samples must be in constant contact with water to a height of 5 mm. The water absorption coefficient (C_b) is given by equation (4), where M (g) is the mass of absorbed water, and S (cm^2) is the surface area of the immersed face. The samples' water absorption by total immersion was determined according to the standard NF EN 14617, where the samples were entirely immersed in water for 24 h to allow pore saturation. The total water absorbed, TWA (%), is evaluated using equation (5), where M_d (g) is the mass of the dry sample and $M_{sat.air}$ (g) is the mass of saturated samples.

$$C_b = 100 \text{ x } \frac{M}{S \text{ x } \sqrt{10}} \quad (4)$$

$$TWA = 100 \text{ x } \frac{M_{sat.air} - M_d}{M_d} \quad (5)$$

The abrasion resistance test allowed us to simulate the physical dry erosion by constant friction on the surface of CEB using a wire brush. The face of the sample is subjected to 60 rounds of the wire brush loaded with a 3 kg [10]. The abrasion coefficient (C_{ab}) is determined by equation (6). S (cm^2) is the abraded area, m_1 (g) and m_2 (g) are, respectively, the mass of samples before and after abrasion.

$$C_{ab} = \frac{S}{m_1 - m_2} \quad (6)$$

Results and Discussion

Bulk density and water-accessible porosity

Figure 1 shows the bulk densities and water-accessible porosity of the CEBs. The bulk density evolved in 1784 to 1917 kg/m^3 for CEB_0G to CEB_8C, reaching the highest value with CEB_8C, against 1847 kg/m^3 for CEB_15G. The water accessible porosity evolved from 26 to 28.9% for CEB_10G to CEB_8C. The CEB_8C have the lowest water-accessible porosity and the highest bulk density, probably due to the hydration of cement and the densification of its matrix. In addition, the high specific density of the cement (3.1) and the low water demand of the dry mix of CEB_8C contribute to this high bulk density [11]. For geopolymer-stabilised CEBs, the increase in geopolymer binder content induces a decrease in bulk density, probably since metakaolin is lighter than lateritic earth. Therefore, the porosity remains approximately the same for the geopolymer-stabilised CEBs.

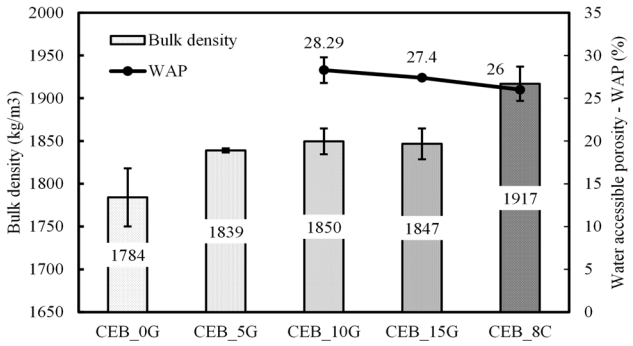


Figure 1: Physical properties of CEBs.

Compressive strength and structural efficiency

Figure 2a presents the dry and wet compressive strengths of the CEBs. The dry compressive strength ranges from 0.8 to 9.8 MPa for CEB_0G to CEB_15G, against 6.6 for CEB_8C. The wet compressive strength reached 4.84 MPa for CEB_15G and 4.7 MPa for CEB_8C. The unstabilised CEBs show the worst dry compressive strength and disintegration during the 2 h immersion before testing the wet compressive strength. CEB_8C shows the lowest decrease between dry and wet compressive strength. The water resistance coefficient is the ratio between the wet and dry compressive strength, which is 0.49 for CEB_15G against 0.71 for CEB_8C. That could be related to their high bulk density and low water-accessible porosity. That would be related to the small water absorption during the 2 h of immersion before the wet compression test. The stabilisation of CEB_10G has a compressive strength in the dry state of 5.33 MPa against 6.6 MPa of CEB_8C. CEB_15G has a higher value of wet compressive strength (5.84 MPa) than CEB_8C (4.7 MPa). Thus, stabilising with 15% geopolymer would make CEBs as strong as CEB stabilised

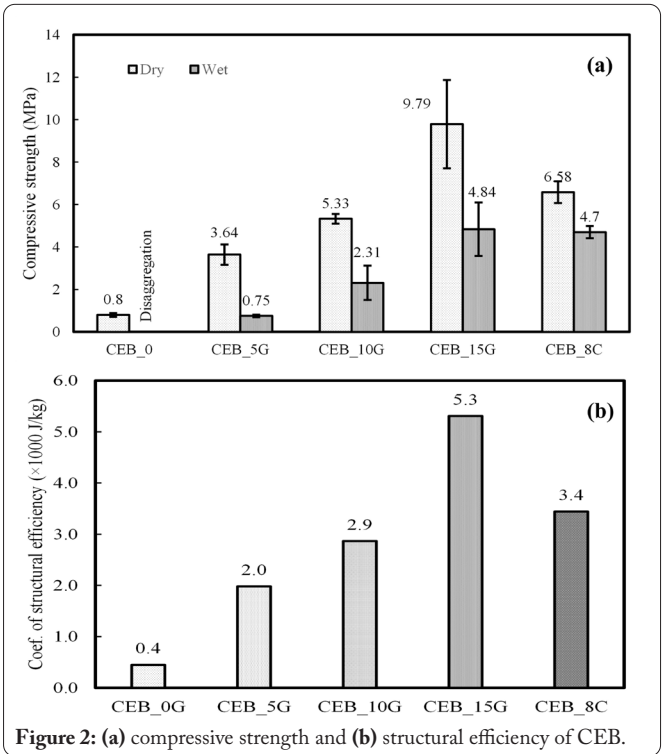


Figure 2: (a) compressive strength and **(b)** structural efficiency of CEB.

with cement in the wet state. CEB_10G allows reaching a value of dry compressive strength of 4 MPa required for the construction of wall masonry of a building [9].

These results agree with Idriss et al. [8], where stabilisation of CEBs with 15% geopolymer resulted in a wet compressive strength of 11 MPa. The considerable loss observed between wet and dry strength is probably due to the hydrolysis affecting the cohesion between the particles. Furthermore, the earthen materials from Kamboinsin have medium to high cohesion [12], with a fraction of fine particles (50 - 80%). According to Preethi et al. [13], it is preferable to use clayey soil with a fraction of fines below 30% for activation using an alkaline solution with high molarity in order to avoid lumpy wet mixtures that would impact the compaction of geopolymer-stabilized earthen materials. However, despite the increased clay component of our clay soil compared to Preethi et al. [13], our geopolymer-stabilized clay bricks show interesting mechanical properties. This is likely because the clay percentage increases the accessible reactive silica and alumina [13].

Figure 2b further presents the evolution of the coefficient of structural efficiency of CEB stabilised with geopolymer. This coefficient is the ratio of the compressive strength and bulk density of CEB. It significantly improved from 400 to 5300 J/kg, almost twice that of CEB stabilised with cement (3400 J/kg). This suggests that this CEB can carry more load building construction. CEB_15G reaches better coefficient of structural efficiency than CEB stabilised with lime and lime-rice husk binder [11], ranging respectively in 2530 - 3050 J/kg and 2902 - 4462 J/kg.

Abrasion resistance

Figure 3a shows the coefficient of abrasion resistance with values ranging from 1.5 - 76.7 cm^2/g for CEBs stabilised between 0 - 15% geopolymer. The 15% geopolymer CEBs have the highest coefficients suggesting improved abrasion resistance with increasing geopolymer substitution, compared to CEB_8C (23.44 cm^2/g). That suggests the suitability of the CEBs for dry climates. The coefficient of abrasion resistance was also correlated with dry compressive strength to assess the mechanical performances of CEB via a non-destructive test. Figure 3b suggests that the compressive strength, RC (MPa), of CEB, stabilised with geopolymer, could be estimated from the coefficient of abrasion, Cb (cm^2/g), via a power law of type $Rc = 0.59Cb^{0.59}$. The previous studies had reported similar correlation for CEBs stabilised with lime-rich binders, such as $Rc = 1.6Cb^{0.35}$ [14] and $Rc = 0.71Cb^{0.64}$ [15].

Capillary water absorption

Figure 4a shows the water uptake by capillary action of the different CEBs, as a function of the square root of time. The slopes of the different linear correlations between the water absorption by capillarity and the square root of time allow the determination of the sorptivity between 1 h and 24 h. The CEB_15G has the highest sorptivity, with a 0.078 $g/cm^2.min^{0.5}$, followed by CEB_10G (0.068 $g/cm^2.min^{0.5}$) and CEB_8C (0.035 $g/cm^2.min^{0.5}$). The high values of sorptivity obtained with CEB_15%G would be related to a higher pore radius than for CEB_10G and CEB_8C. This coefficient

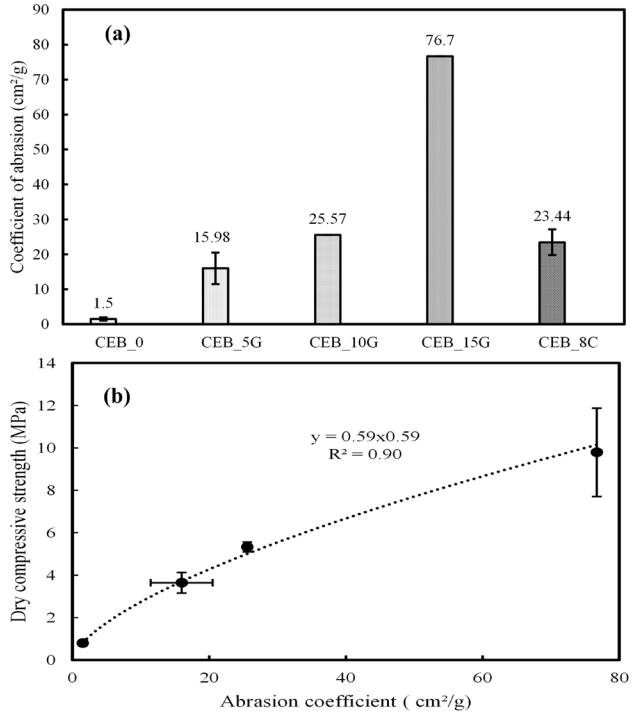


Figure 3: Resistance to abrasion: **(a)** coefficient of abrasion and **(b)** correlation with the dry compressive strength.

makes it possible to evaluate the absorption rate in the capillary pores. These pores generally have a size that varies from 0.1 µm to 10 µm [16]. This capillary absorption would induce high capillary pressure in the pores, which would significantly negatively influence the development of wet strength and shrinkage behaviour, among others [17].

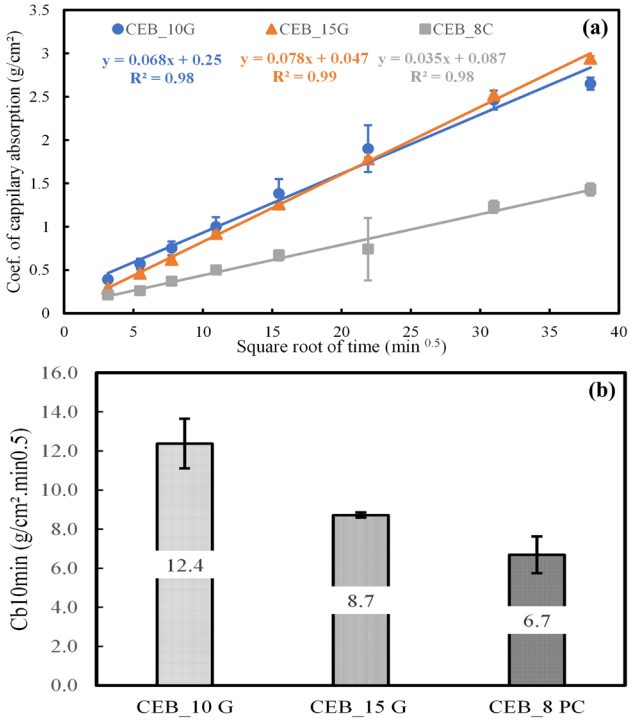


Figure 4: Capillary water absorption: **(a)** sorptivity between 1 to 24 h and **(b)** Cb10 min after 10 min of immersion of CEBs.

Figure 4b shows the capillary absorption coefficient after 10 minutes (Cb_{10min}). The Cb_{10min} of CEB_10G to CEB_15G is respectively 12.4 and 8.7 g/cm².min$^{0.5}$. The CEB_8C showed the lowest value of Cb_{10min} of 6.7 g/cm².min$^{0.5}$. That can be explained by the low porosity accessible by water of CEB_8C (Figure 1). Therefore, all CEBs in this study have Cb_{10min} values below 20 g/cm².min$^{0.5}$ can be classified as very low capillary absorption CEBs [10].

Total water absorption

Figure 5 shows the evolution of water absorption after saturation by total immersion for 24 h (Ab_{24h}) of the CEBs. Some CEBs reached saturation before 2 h (Ab_{2h}) of immersion. The Ab_{2h} varied from 10.9 to 18% for CEB_10G to CEB_15G; with the lowest value of 9.9% observed for CEB_8C. The Ab_{24h} of all CEBs varies from 14 to 18.4%, with the highest value reached with CEB_15G. The Ab_{2h} represents the water content at which the wet compressive test was carried out. The ratio Ab_{2h}/Ab_{24h} indicates the water absorption rate, so the lower the ratio, the better the resistance to water absorption. This ratio is 0.7 for CEB_10G and CEB_8C and 0.98 for CEB_15G. The Ab_{24h} of all the CEBs in this study remains below the lower limit of 20 % for application in wet environments [18].

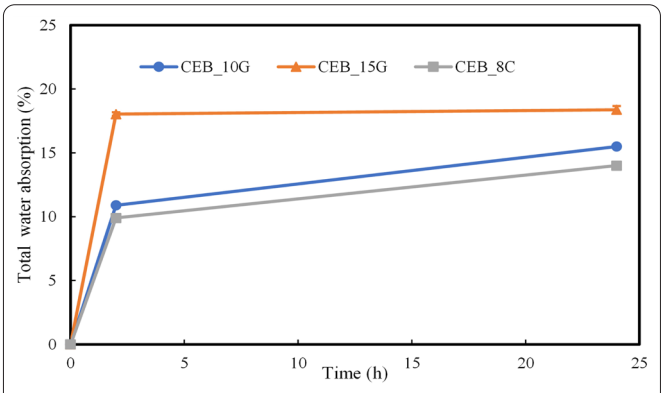


Figure 5: Total water absorption rate of CEBs.

Conclusion

The physico-mechanical properties and durability of CEBs stabilised with 0 - 15% geopolymer were investigated. Based on the results of this study, the following conclusions could be drawn: Firstly, the increase in geopolymer binder substitution content decreases the bulk density of the CEBs, reaching the value of 1847 kg/m³ with CEB_15G, with water-accessible porosity of 27.4%. Secondly, the stabilisation of CEB with MK geopolymer improved the compressive strength, reaching the values of 9.78 MPa and 4.84 MPa, respectively, in dry and wet conditions, comparable to the CEBs stabilised with cement. This improved their structural efficiency up to 5300 J/kg, almost twice that of CEB stabilised with cement. That suggests that stabilisation of CEB with geopolymer allows the load-bearing wall of buildings. Thirdly, the abrasion resistance was also improved by stabilisation with geopolymer, reaching the coefficient of 76.7 cm²/g with CEB_15G, almost 3 times that of CEB_8C. This coefficient was also successfully correlated with the compressive strength, allowing for estimating the strength through a non-destructive abrasion test. Regarding water absorption, the high sorptivity obtained for CEBs stabilised with 15% geopolymer, compared to the CEB stabilised with 10% geopolymer and 8% C, suggesting a higher capillary pore radius. The small pore radius for the CEB_8C, combined with their low porosity (26%), explains the low coefficient of capillary absorption (6.7 g/cm².min$^{0.5}$) after 10 min. For all the CEBs, the total water absorption after 24 h is below the 20% limit recommended for the wet application of CEBs. Finally, the results of this study showed the excellent performances of MK-based geopolymer stabilised CEBs. Therefore, it would be appropriate to investigate other indicators of durability and performance at high-temperature.

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Conflict of Interest

None.

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