

A comparative study of compressed lateritic earth bricks stabilized with natural pozzolan-based geopolymer binders synthesized in acidic and alkaline conditions

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ABSTRACT

Two geopolymer binder systems made under alkaline and acidic conditions have been evaluated for the stabilization of compressed lateritic earth bricks (CEBs) using natural pozzolan as aluminosilicate precursor. The preparation of alkaline and acidic activators involved the combination of sodium silicate and 10 mol/L sodium hydroxide solutions, as well as 10 mol/L phosphoric acid solutions, respectively. CEBs were prepared to comprise different proportions of natural pozzolan of 5, 10, 15, and 20 %. The physico-mechanical and mineralogical properties of compressed earth bricks were studied using the compressive strength, the dry and wet bulk density, the water absorption rate, Fourier transform infrared spectroscopy (FTIR), powder X-Ray Diffraction (PXRD) and optical microscopy (OM). The results showed that in the acid environment, the mechanical performance increased considerably with the pozzolan content and slightly with the curing time, whereas in the alkaline environment these performance decrease for the sample with 0 to 10 % of pozzolan and remain constant for the sample with 15 to 20 % of pozzolan after 14 days of curing. The utilization of acid-activated geopolymer binder in the production of laterite-based compressed earth bricks has been shown to be more effective compared to the utilization of an alkali-activated geopolymer binder. The high performance of acid-stabilized CEBs is related to the best reactivity of natural pozzolan in acid medium allowing the formation of Al-O-P bonds.

1. Introduction

The housing crisis affects more than half of the African population [1]. In Cameroon, earth has historically been used as a building material for many years. The development of Ordinary Portland Cement (OPC) has reduced the use of earth materials in the building and construction industry resulting in concrete structures being the most popular type of building nowadays. However, the production of OPC, which accounts for 40 to 45% of the materials used to build a concrete house, has an environmental impact [2,3]. Furthermore, the high price of these building materials on the Cameroonian market is now a serious concern. Recently, the Cameroonian government emphasized the need to build

one million housing units in the next 5–10 years to meet the demand of the growing urban population. Considering the significant environmental impact of OPC manufacturing, it is essential to develop alternative eco-friendly building materials.

The development of low cost and sustainable building materials is feasible in a country like Cameroon due to the abundance of natural resources such as aggregates, clay, laterite and natural pozzolan in all regions [4]. In view of this potential, the work was oriented towards the stabilization of compressed earth bricks (CEBs) with OPC. Although the mechanical properties obtained were satisfactory [5], the use of OPC has a negative environmental impact, degrades the thermal properties of CEBs and causes thermal comfort problems [6,7].

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Therefore, the necessity to discover alternative stabilizers to OPC, as well as the need to build structures in a sustainable, rational and environmentally friendly manner, motivated the researchers to develop acidic and alkali-activated binders through the geopolymerization process. Geopolymer technology has received considerable attention in recent decades, as one of the many solutions advocated today to meet the technical and environmental challenges of constructions. Geopolymerization involves the chemical reaction between an aluminosilicate and an activating solution at room or slightly elevated temperature [8]. However, despite the growing interest in this technique, its use in building and construction industry remains limited [9–11]. Earth bricks stabilized by acid/alkaline activation of an aluminosilicate present good performance [7]. Sore et al investigated the stabilization of compressed earth blocks (CEBs) by geopolymer binders based on local materials. The geopolymer was synthesized from a mixture of metakaolin and sodium hydroxide solution. Laterite formed the principal matrix of the bricks. The results showed that, stabilization of CEBs using geopolymer binder significantly improved their mechanical performance and gave them thermal properties that were very similar to those of non-stabilized blocks. Moreover, the highest compressive strength of 8.9 MPa was obtained with CEBs stabilized with 20 % of geopolymer [12]. In addition, Mimboe et al. also investigated the stabilization of mud bricks using calcined laterite activated with phosphoric acid. Compressed earth bricks with a dry compressive strength of up to 38 MPa were obtained. This work demonstrated the importance of adding these geopolymer binders on the properties of earth bricks. Despite the findings of previous studies, such as [13] and [8], which have demonstrated the potential of volcanic ash as a reliable and abundant source of aluminosilicate for geopolymer production in Cameroonian, the use of this material in the stabilization of compressed earth bricks (CEBs) remains limited.

This project aims to manufacture compressed earth bricks (CEBs) stabilized using natural pozzolan-based geopolymer binder synthesized in acidic and alkaline conditions. The physical, chemical and geotechnical properties of the raw materials were investigated. CEBs were prepared with various dosages of geopolymer binder (0, 5, 10, 15 and 20 %) at room temperature. The physico-mechanical and mineralogical properties of compressed earth bricks were studied using the compressive strength, the dry and wet bulk density, the water absorption rate, Fourier transform infrared spectroscopy (FTIR), powder X-Ray Diffraction (PXRD) and optical microscopy (OM).

2. Materials and methods

2.1. Raw materials

The lateritic soil (LS) was used as matrix of compressed bricks. LS was collected from Mangoule in the Littoral region of Cameroon (N°4°4'45" and E°9°40'10"30"). After collection, LS samples were stored in plastic bags and transported to the laboratory. One part was used for the determination of water content and the other part was dried in an oven at 105 °C for 24 h. The dried sample was ground in a ball mill and sieved through a 500 µm sieve.

Natural pozzolan (PZ) was used as a source of aluminosilicate. PZ was collected from a quarry located in Djoungo in the Littoral of Cameroon (N°9,629100021 and E°4,584020013). Once in the laboratory, PZ was dried in an oven at 105 °C for 48 h. Subsequently it was ground in a ball mill and sieved through an 80 µm sieve.

River sand (Sa), was sourced from the Sanaga Maritime River in Littoral-Cameroon and used as aggregate in the preparation of compressed earth bricks (CEBs). Sa was dried for 24 h and sieved through a 2 mm sieve and used to adjust the sand particle in LS.

In this study, the alkaline solution utilized consisted of a mixture of 10 mol/L NaOH with sodium silicate. The mass ratio of silicate to NaOH was kept as 2.4. For the acid solution, a 10 mol/L phosphoric acid solution was used.

2.2. Geotechnical characterization

2.2.1. Particle size analysis

For the determination of the weight proportions of the solid particles of laterite soil and natural pozzolan according to their size, the complete granulometric analysis was carried out via the sieving method according to the standards ASTM C and XP P13-901 [14,15].

2.2.2. Atterberg limits

To determine the different limits of the lateritic soil we followed the XP P13-901 standard [15]: the liquid limit (WL) (the passage from the liquid state to the plastic state) was determined according to the Casagrande disk method and the plasticity limit (WP) (the passage from the plastic state to the solid state) according to the roller method [15].

2.3. Stabilization process

The method used to manufacture the various samples of bricks was chosen based on the work carried out by Rolande Aurelie T.K. et al. [16]. LS, Sa and PZ were dry mixed for 5 min, then the activating solution was added and the mixing continued for 5 min. The mass ratio of H₃PO₄/pozzolan and NaOH/Pozzolan) was 0.8. For the samples with 0% pozzolan the ratio H₃PO₄/laterite and NaOH/ laterite was equal to 1. The obtained mortar was left to rest for 5 min for the geopolymerization process to start; then water was added until a malleable semi plastic mixture was obtained. Table 1 gives mixture proportions of the compressed earth bricks.

After mixing, the mortar was molded in 4 × 4 × 4 cm molds and compacted with a manual press at 8 MPa. The obtained brick specimens were demolded, coded and covered by a plastic for 7 days in order to initiate the geopolymerization process. After these 7 days, the plastic was removed and the specimens were cured at ambient temperature. The compressive strength test was conducted on the specimens after 7, 14 and 28 days of curing. The physical characterization was carried out after 14 and 28 days of curing and the mineralogical characterizations after 28 days of curing.

The samples are coded to facilitate identification on the different proportions of their mixtures. The coding system used is composed of capital letters that designate the first letter of each activating solution (A for acidic solution and B for alkaline solution) and numbers representing the pozzolan proportion. For example, CEB_A^B designates a compressed earth brick formulated with an alkaline solution and having × % pozzolan.

2.4. Characterizations of compressed earth bricks

The water absorption coefficient (Cb) deduced from this test is proportional to the mass gain with the immersed surface. The bulk density is a test that is done according to NF P 98–250 and allows determining the dry and wet density of materials. The water absorption test was carried out according to the Cameroonian Standard for CEB [17]. The blocks were immersed in a water for 24 h at the ambient temperature of the laboratory and the increase in weight was measured.

2.5. Analytical techniques

The geochemical composition of the LS and PZ samples was determined by flame emission spectrometry using the device WDXRF, S4 Pioneer. The functional groups of LS and PZ were determined by Fourier transform infrared spectroscopy (FTIR) (Bruker Tensor 37, Bruker, Germany) in KBr pellets of reflection modality in the range 400–4000 cm⁻¹. The mineralogical composition of PZ and LS was determined with a Bruker D2 Phase powder X-ray diffractometer (Bruker, Germany), equipped with a flat sample holder, using CuKα radiation with λ = 1.5418 Å at 30 kV at a scan speed of 6°/min ranging from 2θ angles of 5 to 70°. The mineralogical and microstructural properties were carried

Table 1

Mixtures of compressed earth bricks.

Formulation	CEB ₀ ^A	CEB ₅ ^A	CEB ₁₀ ^A	CEB ₁₅ ^A	CEB ₂₀ ^A	CEB ₀ ^B	CEB ₅ ^B	CEB ₁₀ ^B	CEB ₁₅ ^B	CEB ₂₀ ^B
LS (%)	90	85	80	75	70	90	85	80	75	70
PZ (%)	0	5	10	15	20	0	5	10	15	20
Sand (%)	10	10	10	10	10	10	10	10	10	10
Ratio Liquid/PZ	1	0,8	0,8	0,8	0,8	1	0,8	0,8	0,8	0,8
Water (g)	30	28	22	18	16	24	22	21	16	13

out on the 28 days old CEBs powders are determined by FTIR, XRD and optical microscopy (OM) analyses described above. The optical microscope (OM) was equipped with a stereomicroscope (Ceramics Instruments Model 101 T-MT), a binocular head and a Tablet 7 with integrated camera.

3. Results and discussion

3.1. Characterization of raw materials

The raw materials characterized are laterite soil (LS), natural pozzolan (PZ) and sand (Sa).

The Table 2 presents the results of the particle size analysis of LS, PZ, Sa and the Table 3 shows the results of the liquidity limit and plasticity limit of LS.

The different samples show varied proportions of gravel, sand, silt and clay. LS was made of 28 % of gravel, 20.1 % of sand, 18 % of silt and 33 % of clay. According to the recommendations for the use of laterite in construction, which specifies a percentage of 70 and 30 for clay-silt and sand-gravel, respectively, which is not the case of the soil used in this study [18]. A particle size correction by adding sand will be carried out in order to improve the properties of the materials by increasing the content in aggregate [19,20]. The natural PZ consists of 78.7 % gravel, 20.1 % sand and 1.2 % fines.

The high percentage of fine particles obtained of LS justifies the high water content of the material (31 %) and its plasticity index (27.6) (Table 3).

The sand plays an important role in reducing the volume variations and the cost price of the bricks [21]. The raw sand (Sa) used for this work consists of 39.8 % coarse sand, 60.02 % fine sand and 0.8 % fines.

Table 4 gives results of the chemical compositions of PZ and LS that has been characterized by using XRF. According to the Table 4, silicon dioxide (SiO₂), aluminum (Al₂O₃) and iron oxide (Fe₂O₃) are the main oxides present in the two samples. However, for LS, Fe₂O₃ is the major oxide. Results from XRF also shows the total Al₂O₃ + SiO₂ + Fe₂O₃ content of PZ and LS to be above 70 %.

Loss of Ignition (LOI) is a simple method for estimating the content of organic matter and the water content from crystallization in the materials [22]. The LOI value of LS and PZ are 13.4 and 0.9 respectively.

Fig. 1(a-b) gives XRD patterns of PZ and LS. The diffractogram shows that PZ is predominantly made of crystalline phases that include Anorthite (CaAl₂Si₂O₈, 2 θ = 21.95°, 27.86°); Diopside (CaMgSi₂O₆, 2 θ =

Table 2

Result of particle size analysis and sand equivalent of raw materials.

Particle size					
Samples	Aspect	% of gravel ($\phi > 2$ mm)	% of sand ($2 > \phi > 0.02$ mm)	% of silt (0.02 > ϕ > 0.002 mm)	% of clay ($\phi < 0.002$ mm)
LS	Gravel lateritic	28.9	20.1	18	33
PZ	Clean sand	78.7	20.1	1.2	
Sa	Clean sand	39.8	60.2	0.8	

Table 3

Result of the liquidity limit and plasticity of LS.

Atterberg limits				
	Liquidity limit	Limit of plasticity	Plasticity index	Water content
LS	57.5	29.9	27.6	31

26.62°); Feldspar (Na₂Al₂Si₃O₁₀, 2 θ = 36.52°), Forsterite (Mg₂SiO₄, 2 θ = 23.9° 29.76°); Calcite (CaCO₃, 2 θ = 56.53°) and Magnetite with 2 θ = 35.67 and 62.22° [23,24]. The presence of a dome between 20 and 35° (2 θ) indicates the presence of an amorphous phase in PZ. The amorphous phase is the most reactive phase of raw materials used for geopolymer synthesis [8]. Laterite soil powder (Fig. 1b) exhibited the predominant peaks of: Kaolinite (with 2 θ = 14.8°, 25.1°, 42°, 45°, and 68°), Hallosite (with 2 θ = 18°, 28°, 36.2°, 43°), Muscovite (with 2 θ = 18°, 28°, 36.2°, and 55°), Quartz (with 2 θ = 23°, 28°, 43°, 53.2°, 60°, 68°), Anatase (with 2 θ = 33.4°), magnetite (with 2 θ = 43° and 63°), Maghemite (36.2° and 68°) and Boehmite (42° and 65°).

Fig. 2(a-b) shows the FTIR spectra of LS and PZ. PZ spectrum (Fig. 2a) exhibits the bond characteristic of the asymmetric stretching vibrations of Si-O-T (T = Si or Al) with peaks at 966 cm⁻¹ [25,26]. The peaks appearing at 631 and 728 cm⁻¹ correspond to Si-O bending vibration [27] while the peak at 569 cm⁻¹ represents the vibration of Si-O-Fe(Al) bond. This absorption band confirms the partial replacement in the octahedral site of aluminum cations (Al³⁺) by iron cations (Fe²⁺ and Fe³⁺) [28].

In the LS spectrum (Fig. 2b), the bands appearing at 3699, 3624 and 794 cm⁻¹ are attributed to OH vibrations of kaolinite [29]. Bands at 3433 and 1633 cm⁻¹ are indicative of water molecules. The bands corresponding to the Si-O vibration of quartz are found at 753, 467 and 428 cm⁻¹. Bands appearing at 912 cm⁻¹ are attributed to the Al(IV)-O-H et Al(VI)-O-Si bending vibration of the bonds indicating the kaolinite group [29,30]. The bands at 693 and 534 cm⁻¹ are the Fe-O bonds of maghemite or magnetite detected by PXRD [31].

3.2. Characterization of compressed earth bricks

3.2.1. Stability of compressed earth bricks

Fig. 3 presents the pictures of the brick specimens used in the various tests conducted. It can be noted that there is a visual differentiation between the bricks stabilized with the alkaline binder and those stabilized with the acid binder. The bricks stabilized with the acid binder exhibit clear water after immersion, which can be attributed to their improved stability in water compared to those stabilized with the alkaline binder. The latter group of bricks resulted in a slightly yellow-colored water after immersion, which may be due to the release of fine laterite particles, as reported by F. Ntimugura, S.O. Sore et al, 2017 [7].

3.2.2. Compressive strength

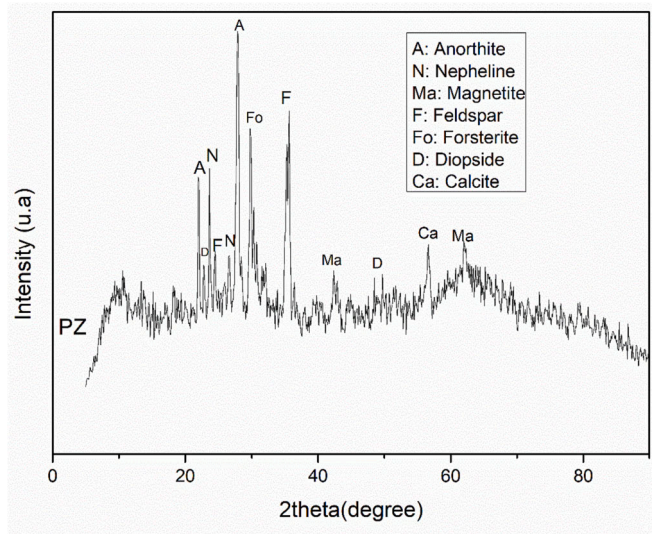
Figs. 4 and 5 show the results of the compressive strength of CEBs consolidated with acid and alkaline binders exposed at room temperature. The compressive strength test was performed after 7, 14 and 28 days.

In acid condition (Fig. 4), the increase of the binder content improves the mechanical performance of CEBs. The results showed that

Table 4

Geochemical composition of the raw materials.

Major oxides (%)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	K ₂ O	MgO	P ₂ O ₅	CaO	ZrO ₂	S	V ₂ O ₅	LOI
PZ	47.9	15.8	8.6	12.9	3.7	2.8	6.4	–	–	0.9	0.04	0.9
LS	22.42	24.51	40.69	1.25	0.25	0.13	0.09	0.04	0.09	0.06	0.05	13.40

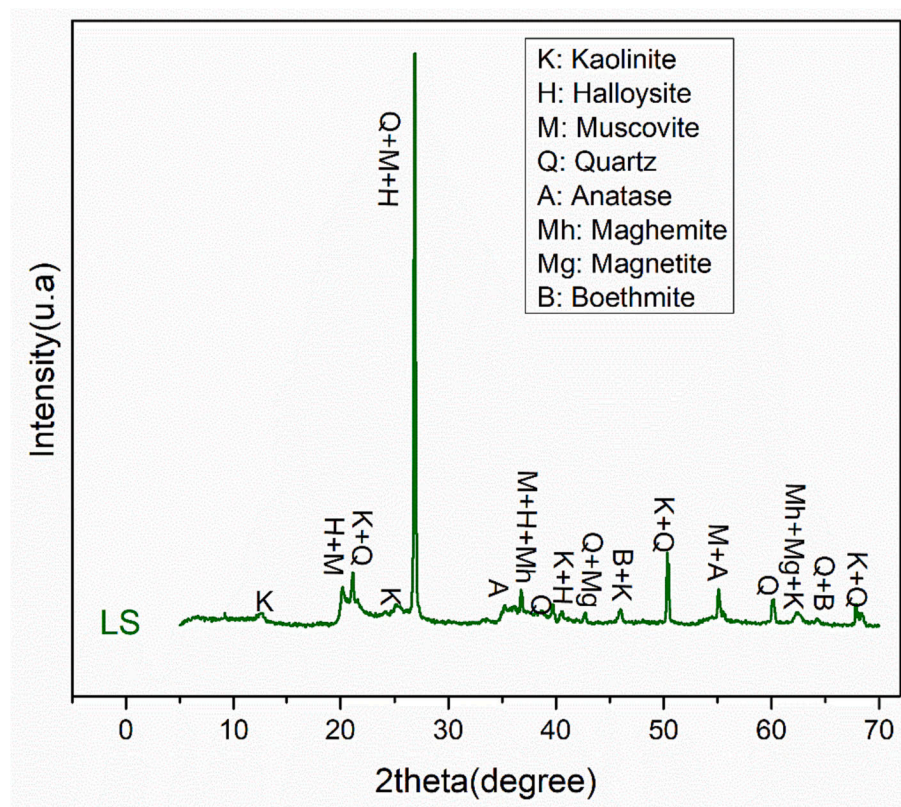
**Fig. 1a.** Powder X-Ray diffractogram of natural pozzolana (PZ).

compressive strength of CEBs increase with the addition of natural pozzolan. The values range varies from 6.24 to 16.8 MPa at 7 days of curing, 7.5 to 17.7 MPa at 14 days and from 7.5 to 17.76 MPa at 28 days, respectively for the samples with 5 and 20 % of the natural pozzolan.

Increase in compressive strength was also observed with increase in curing time. The samples containing 0 to 5 % pozzolan keep their mechanical strength at 28 days curing and those containing 10, 15 and 20 % pozzolan had a slight increase in compressive strength. This can be justified by the formation of hydrated aluminum phosphate (Al-O-P) in the material resulting from the reaction between the phosphoric acid solution and the aluminosilicates. The proportion of Al-O-P increases with the addition of pozzolan and with time. That hydrate strengthened the concrete structure and increasing the resistance. That conclusion is in accordance with the findings by A. Grace, M. Tatiane et al, 2020 and T.K.R. Aurelie et al, 2021 [12,19].

In alkaline condition (Fig. 5) the results showed that, the increase of pozzolan improves the compressive strength. The values obtained varied from 7.5 to 8.4 MPa at 7 days, from 8.4 to 9.36 MPa at 14 days and from 7.5 to 9.36 MPa at 28 days, respectively for the samples with 5 and 20 % of the natural pozzolan. The strengths obtained remain constant after 14 days of curing for the specimens containing 15 and 20 % pozzolan, but for the strengths of the specimens containing 0 to 10 % pozzolan, it decreases. This drop in strength can be justified by the fact that some aluminosilicates are insoluble in an alkaline medium and therefore the dissolved could not form a large amount of binder to consolidate the fines so as to improve the properties of the materials exposed to room temperature and over a relatively long period of time [7].

In general, it can be observed that materials stabilized with acid activated geopolymer showed highest compressive strength. All the observations suggest that under these synthesis conditions, the acidic-stabilized CEBs would resist exposure to open air better than those

**Fig. 1b.** Powder X-Ray diffractogram of laterite soil (LS).

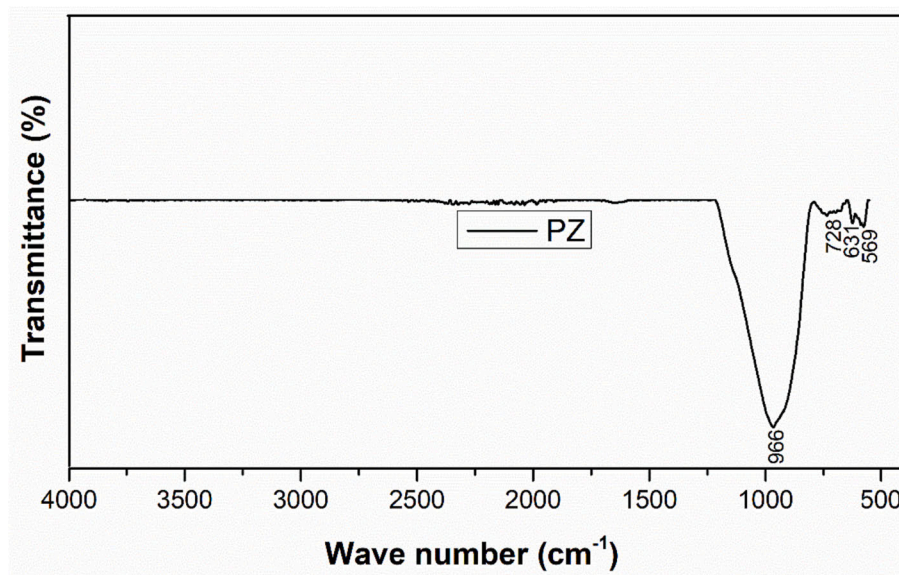


Fig. 2a. FTIR spectra of natural pozzolan (PZ).

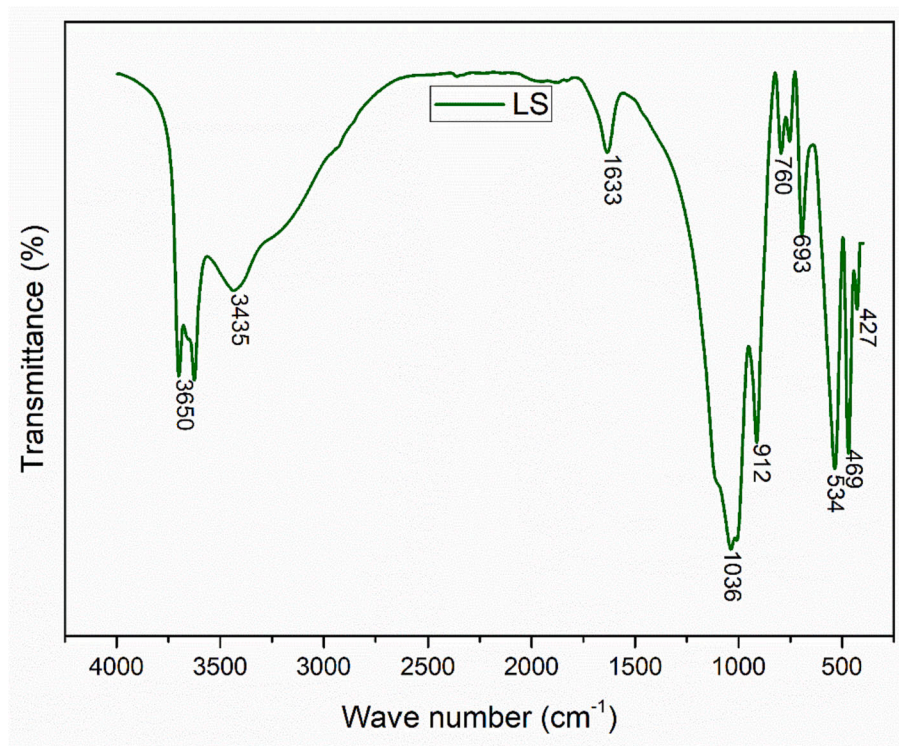


Fig. 2b. FTIR spectrum of laterite soil (LS).

stabilized using alkali activated binder. Moreover, the polymerization/polycondensation reaction of the natural pozzolan in an acid medium is closely linked to the curing time. This difference may be because bonds formed by acid activation would be more stable than those formed by alkaline activation at room temperature. In fact, in open air, a carbonation reaction occurs between the free Na^+ and the CO_2 from atmosphere in the alkali stabilized CEBs which creates efflorescence within the material and endanger the strength of this alkali-stabilized CEBs [32].

3.2.3. Water absorption

Figs. 6 and 7 show the variation of the absorption rate of the studied samples according to the addition of pozzolan and the curing time. The test was performed at 14 days and 28 days.

Fig. 6 shows that in acid condition, the values of the water absorption decrease with the addition of binder and the curing time. They vary from 18.04 to 6.95 % at 7 days, from 17.68 to 6.60 % at 14 days and from 15.76 to 5.85 % at 28 days of curing respectively for the sample containing 5 and 20% of natural pozzolan. The CEB without pozzolan at 7 days disintegrated after 24 h of curing in water.

In alkaline condition, the Fig. 7 shows that CEBs with 0, 5 and 10 %

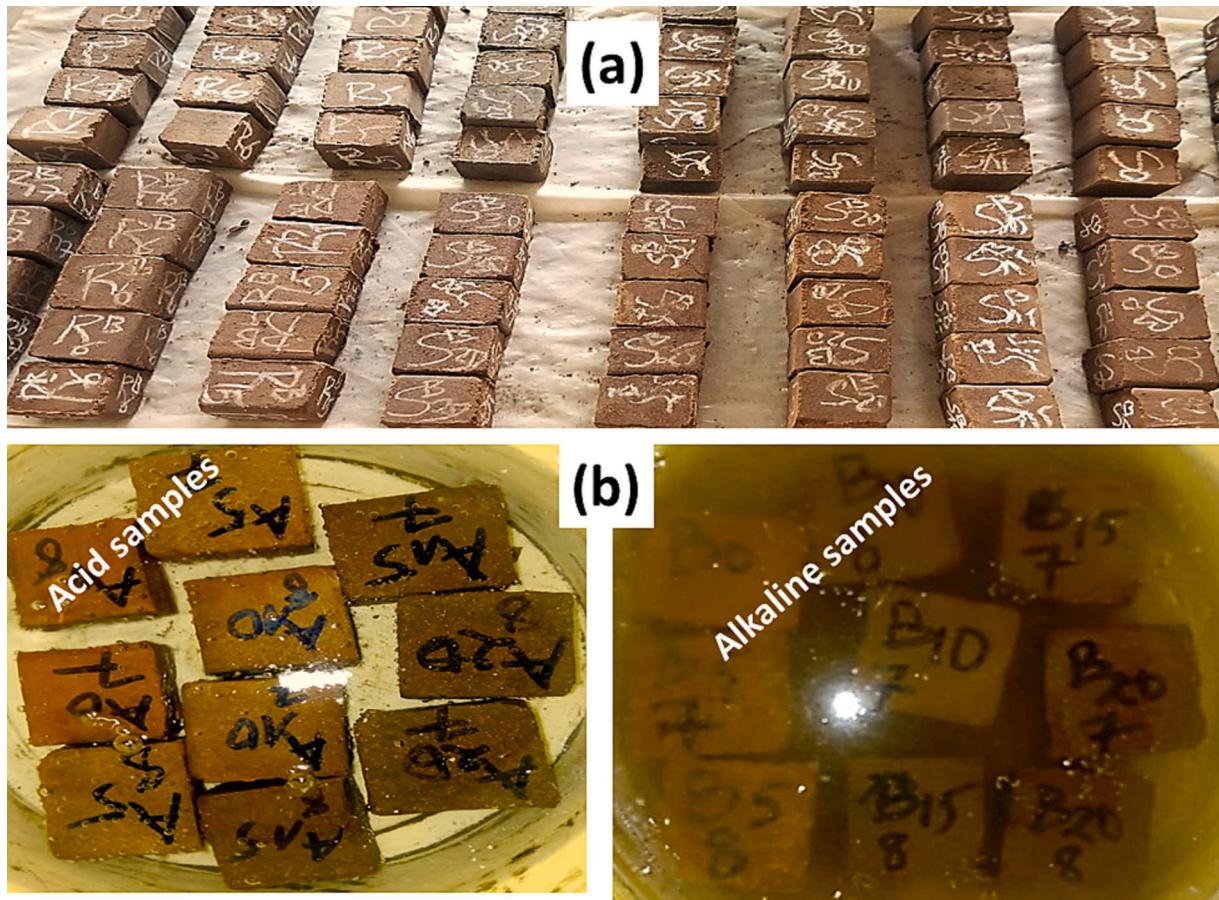


Fig. 3. Appearance of samples used for physical, mechanical properties (a) and samples in water (b).

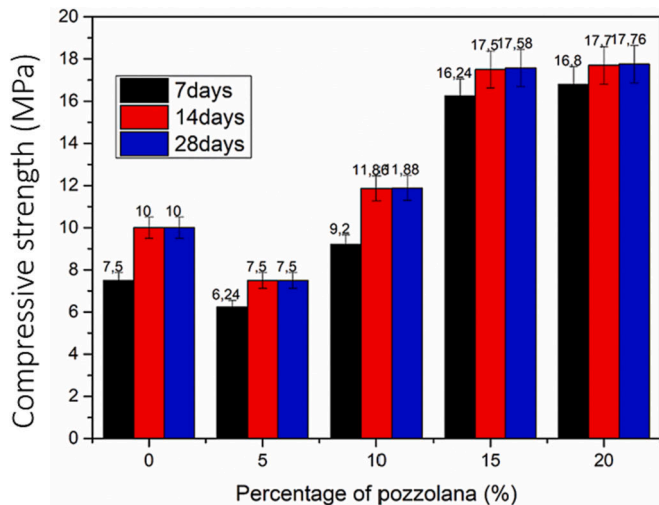


Fig. 4. Compressive strength of acid stabilized CEBs cured at room temperature.

of natural pozzolan were very vulnerable to water and disintegrated completely. This made it impossible to quantify their water absorption. However, the absorption values for the CEBs with 15 and 20 % of pozzolan vary from 14.44 to 14 % and from 12 to 11.19, respectively at 7 and 28 days of curing.

The previous observations show that, the water absorption percentage evolves inversely with the addition of pozzolan. As the percentage of pozzolan added increases, the quantity of activating solution

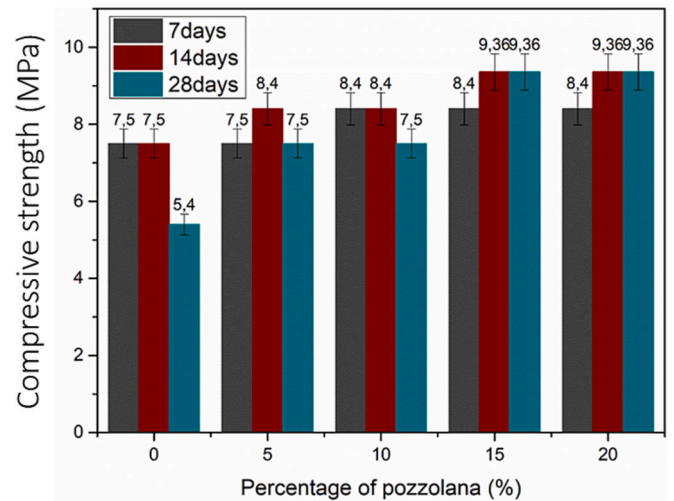


Fig. 5. Compressive strength of alkaline stabilized CEBs cured at room temperature.

added also increases. Therefore, large amount of activator solution will allow the dissolution of greater amount of aluminosilicate present in the raw materials and therefore, during the polycondensation phase there will be better agglomeration in the material, making it denser and less porous than materials with a low percentage of pozzolan [8]. The latter phenomenon is more significant in the acidic environment.

In general, CEB stabilized in an acidic environment has a relatively low water absorption percentage compared to those stabilized in an

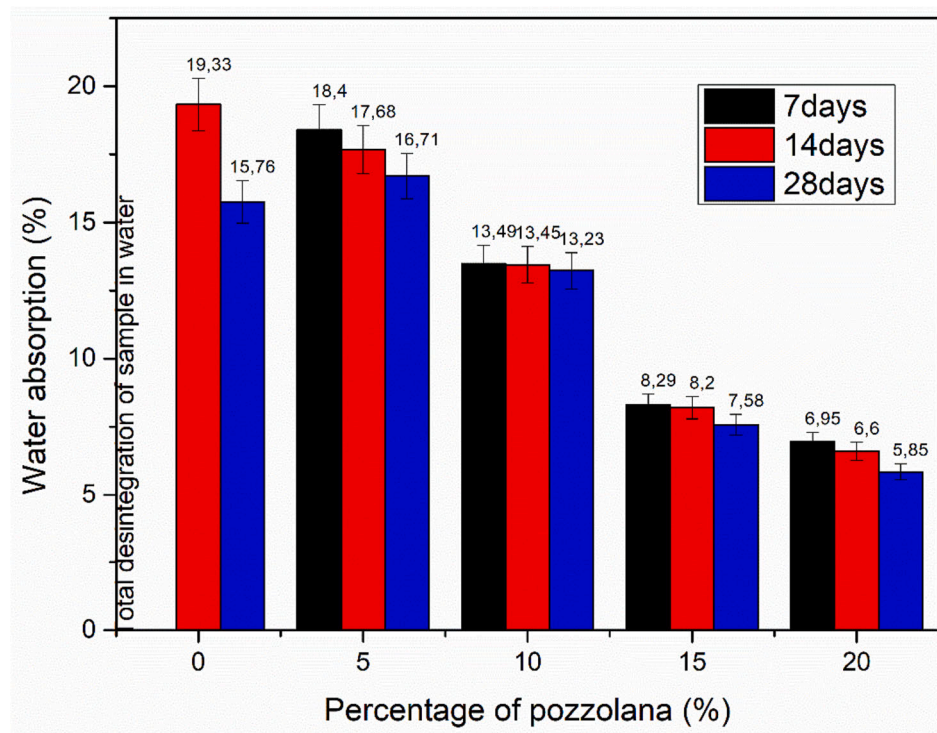


Fig. 6. Water absorption of acidic-stabilized CEBs cured at room temperature.

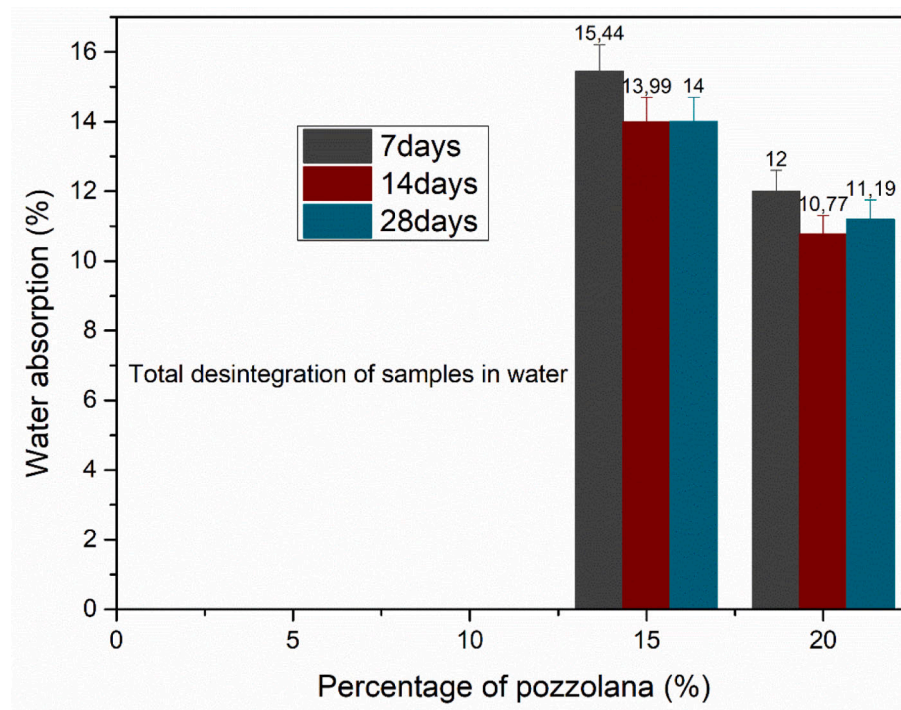


Fig. 7. Water absorption of alkali-stabilized CEBs cured at room temperature.

alkaline environment; and their water absorption rate decreases with the curing time.

3.2.4. Bulk density

Figs. 8 and 9 show the bulk density of the acidic and alkaline samples at 14 and 28 days of curing as a function of the percentage of pozzolan.

Fig. 8 shows that, at 28 days of curing, the wet density in acidic

medium increases from 1.71 to 2.02 g/cm³; the dry bulk density rises from 1.65 to 1.92 g/cm³. At 14 days, the wet density increases from 1.65 to 1.82 g/cm³ the dry density rises from 1.58 to 1.89 g/cm³ for the samples containing 5 and 20 % pozzolan addition, respectively.

In alkaline medium (Fig. 9), after 28 days of curing the wet bulk density varies from 1.62 to 1.65 g/cm³; the dry bulk density ranges from 1.57 to 1.61 g/cm³ and, at 14 days, the wet density ranges from 1.60 to

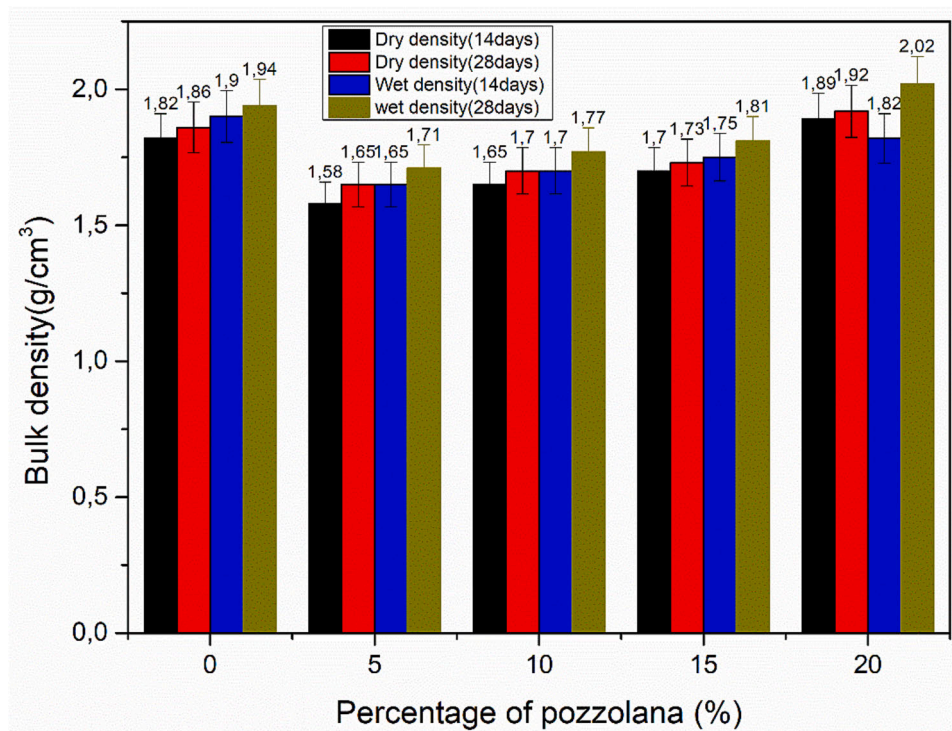


Fig. 8. Bulk density of acid stabilized CEBs cured at room temperature.

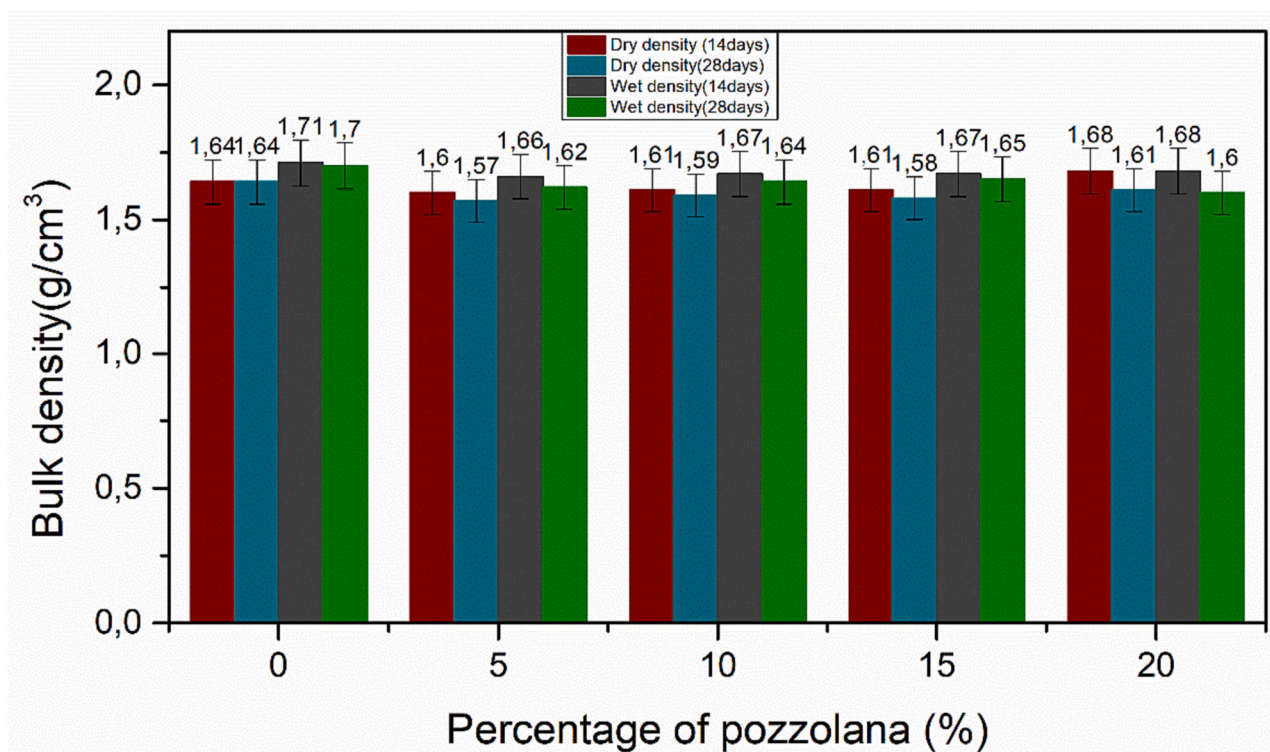


Fig. 9. Bulk density of alkali stabilized CEBs cured at room temperature.

1.68 g/cm³, the dry bulk density evolves from 1.66 to 1.68 g/cm³ respectively for the samples with 5 and 20 % pozzolan addition. It can be seen that the bulk density of those samples varies very little with the increase in geopolymer binder and decreases with the curing time.

In general, the increase in pozzolan content and curing time influences the bulk density and it is noticed that the bulk density values

are higher for acidic samples compared to those obtained in alkaline condition. This can be justified by the fact that, pozzolan is more reactive in acidic medium than in alkaline solution. The added phosphoric acid solution causes a greater dissolution of aluminosilicate phases than the alkaline solution [33]. Therefore, during the polycondensation in acidic medium, the binder formed creates strong bonds with the fines

present in the material, making it more denser [19].

3.2.5. PXRD

Fig. 10 exhibits the diffractograms of CEB stabilized by acid activation of different proportions of natural pozzolan (0, 5 and 15 %) and cured at room temperature for 28 days. In general, all these diffractograms show the presence of the previously identified crystallized minerals of lateritic soil and natural pozzolan. For the sample with 0 % pozzolan (CEB_0^A) the reflection located at 20° and 40° (2θ) corresponding to quartz-kaolinite and quartz-magnetite increase compared to the raw material (LS) peaks. This would be due to the dissolution of reactive phases such as kaolinite and magnetite contained in this soil that allowed intra-stabilization in this material. This intra-stabilization allowed this material to be stable in water. With 5% addition of stabilizer (CEB_5^A) the intensity of the peaks drops. This is in adequacy with the evolution of the compressive strength previously studied (section 3.2.1). When the proportion of pozzolan is increased to 15 % (CEB_{15}^A), the intensity of the peaks increases as well as the width of the dome characteristic of amorphous phases located between 20° and 30° (2θ). Moreover, there is the formation of a new peak characteristic of the hydrated aluminum phosphate which results from the reaction between the aluminates from the aluminosilicate source and the phosphate of the phosphoric acid solution ($Al_2O_3 + 6H_3PO_4 \rightarrow 2AlH_2P_3O_{10} + 7H_2O$) [12,19]. it can be concluded that in the case of the stabilization of compressed earth bricks (CEBs) using natural pozzolan activated by a phosphoric acid solution, the amorphous phases as well as some iron-containing crystalline phases play a role in the geopolymerization reaction [34].

For the CEB stabilized by alkaline activation of the natural pozzolan cured at 28 days and at room temperature (Fig. 11). All these diffractograms show the presence of the previously identified crystallized minerals on the lateritic earth and the natural pozzolan. This would be justified by the fact that these minerals dissolve very little or almost not in the presence of the sodium silicate solution [20]. Moreover, we observe the formation of a dome between 20° and 30° (2θ) characteristic of the amorphous phases whose width increases with the addition of the alkaline binder [8,35]. This suggests that only the amorphous phases actively participate in the geopolymerization processes by alkaline activation. The appearance of the new peaks around 30° (2θ) is due to the formation of sodium carbonate resulting from fluorescence following a reaction between free Na^+ and CO_2 from atmosphere (CO_2

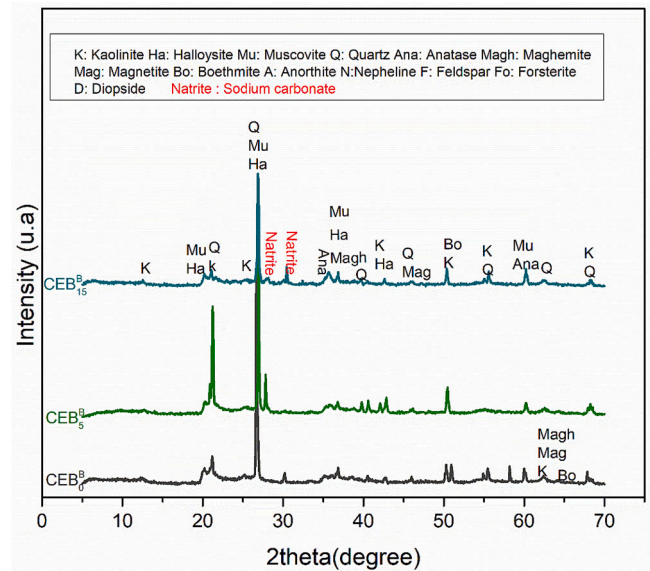
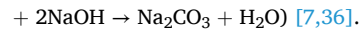


Fig. 11. PXRD of 28 days old alkaline stabilized CEBs cured at room temperature.



3.2.6. FTIR

Figs. 12 and 13 display the infrared spectra of acid and alkali-activated compressed bricks stabilized with different proportions of natural pozzolan (0, 5 and 15 %) cured at room temperature for 28 days. The spectra show four spectral regions. The first group is noted between 3699 and 3450 cm^{-1} , the second between 2929 and 2350 cm^{-1} , the third between 1633 and 1040 cm^{-1} , and the fourth starting from 915 cm^{-1} .

For acid and alkaline stabilized CEBs, the absorption bands around 3701 , 3425 , 3699 and 3439 cm^{-1} are attributed to O-H stretching and bending bands belonging to geopolymer network. The absorption bands around 1642 and 1638 cm^{-1} for acid samples and around 1636 cm^{-1} for alkaline samples are attributed to the vibration of O-H of water molecules present in geopolymers network [37]. The bond characteristic of the asymmetric stretching vibrations of Si-O-T (T = Si or Al) with peaks

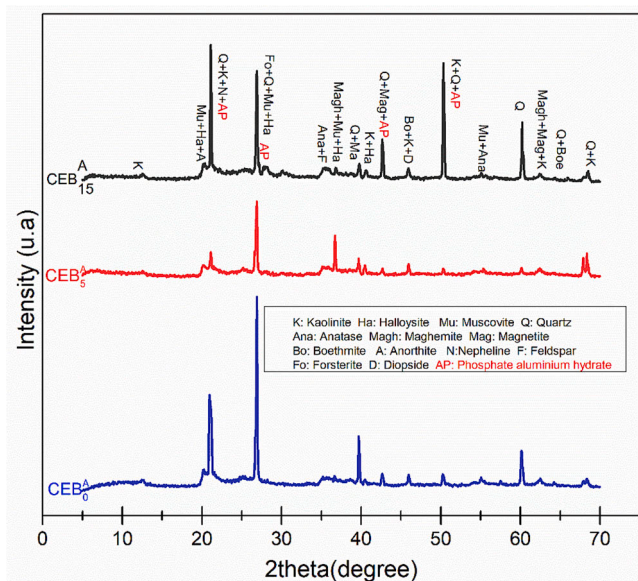


Fig. 10. PXRD of 28 days old acid stabilized CEBs cured at room temperature.

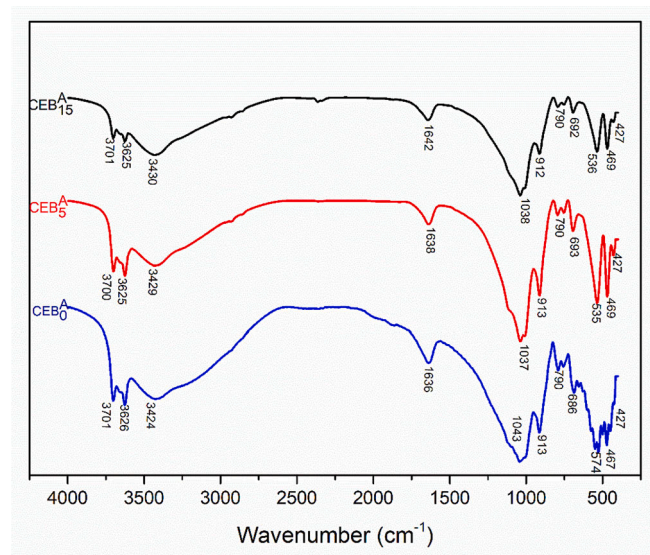


Fig. 12. FTIR spectra of 28 days old acid stabilized CEBs cured at room temperature.

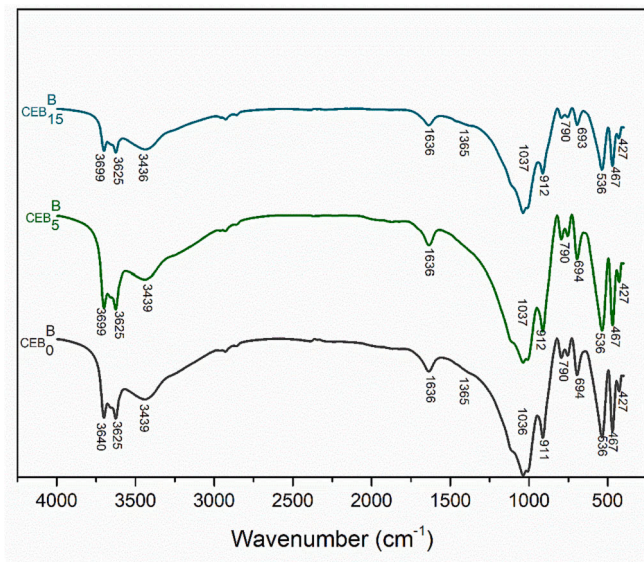


Fig. 13. FTIR spectra of 28 days old alkaline stabilized CEBs cured at room temperature.

around $1038\text{--}1043\text{ cm}^{-1}$ for acid samples and around 1036 cm^{-1} for alkaline samples decrease with the incorporated of geopolymer binder. The decrease of the bands during the geopolymerization process is justified by the new chemical environment that is created when the acid or alkaline binders are incorporated into the lateritic soil due to the formation of the new Si-O-T bonds (T = Al, Fe or Si) [20,25,26,38]. On the infrared spectrum of alkali-activated, the vibration mode at 1365 cm^{-1} of C-O bonds is attributable to carbonate group resulting from a reaction between the free Na^+ and CO_2 from atmosphere confirming the XRD results [7].

The fundamental difference between the two cases of stabilization is that when it comes to acid stabilization the bands that make up the third spectral regions shifted towards high wavenumbers 1038 , 1037 and 1043 cm^{-1} this translate the possible insertion of PO_4 from the phosphoric acid solution into geopolymer network [832].

3.2.7. Optical microscopy

Fig. 14 exhibits the OM images of CEBs stabilized by acid activation (CEB_0^A , CEB_5^A and CEB_{15}^A) and by alkaline activation (CEB_0^B , CEB_5^B and CEB_{15}^B) obtained with 0, 5 and 15 % pozzolan cured at room temperature for 28

days. From these figures, it can be seen that the images obtained by acid activation appear very homogeneous with few accessible voids especially for the sample contained 5 and 15 % of PZ. In the case of the alkaline samples, the images present more voids. The formation of these open voids alongside the images of these alkaline CEBs affected the strength development recorded on these samples. In general, brick matrices become more compact with the increase of pozzolan content, although those obtained in the case of acid stabilization are much more compact than those obtained in alkaline stabilization are. Indeed, the carbonation reaction that occurs between free Na^+ and CO_2 from atmosphere as demonstrated by the results of XRD and FTIR (Figs. 11 and 13) results in poor and lesser compact matrix affecting the physico-mechanical properties [32,39]. These observations corroborate with the results of the physico- mechanical tests explained earlier (Section 3.2.1 and 3.2.2).

4. Conclusion

This work evaluated the difference between the CEB-based laterite stabilized by acid-geopolymer binder and by alkali-geopolymer, binder based natural pozzolan. The following conclusions were drawn from this study:

- In ambient conditions, the natural pozzolan reacts better in acidic activation than in alkaline activation. The acidic samples presented high performance than the alkaline samples.
- Compressive strength and bulk density of the acid and alkaline samples increase with an increase in natural pozzolan.
- Compressive strength and bulk density also increase with increase in curing time, but in alkaline conditions, after 14 days there was a slight decrease of that two parameters for the samples containing 0 to 10 % of natural pozzolan.
- In general, sample matrices become more compact with the increase of pozzolan. However, those obtained in the case of acid stabilization are much more compact than those obtained in the case of alkaline stabilization.

For future work, we intend to study the effect of curing temperature on the properties of these compressed bricks.

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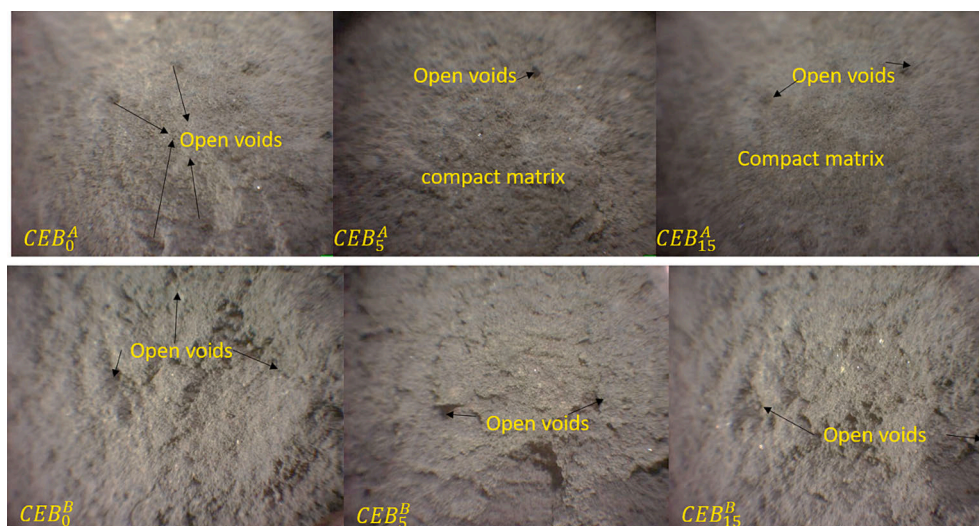


Fig. 14. Optical micrograph images of CEB stabilized.

CRediT authorship contribution statement

Rolande Aurelie Tchouateu Kamwa: Conceptualization, Methodology, Validation, Investigation, Writing – review & editing, Writing – original draft, Visualization. **Leonel Tchadjie Noumbissie:** Conceptualization, Methodology, Investigation, Writing – review & editing, Writing – original draft, Resources. **Sylvain Tome:** Conceptualization, Methodology, Investigation, Validation, Visualization, Writing – review & editing, Writing – original draft, Resources. **Eggekeng Idriss:** Conceptualization, Methodology, Investigation, Writing – original draft. **Juvenal Giogetti Deutou Nemaleu:** Methodology, Writing – review & editing, Supervision, Resources. **Birgit Tommes:** Validation, Writing – review & editing, Writing – original draft, Visualization. **Dennis Woschko:** Validation, Writing – review & editing, Writing – original draft, Visualization. **Christoph Janiak:** Supervision, Resources. **Marie-Annie Etoh:** Methodology, Validation, Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources.

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

No data was used for the research described in the article.

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