



Stabilization of compressed earth blocks (CEB) by pozzolana based phosphate geopolymer binder: Physico-mechanical and microstructural investigations



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ABSTRACT

This work proposes the poly(phospho-ferro-siloxo) binder resulting from the phosphoric acid activation of pozzolana (PZ) as a friendly stabilizing agent for compressed earth bricks (CEBs). Different proportions of pozzolana were incorporated into the clay soil (5, 10, 15 and 20 wt%). The CEBs were cured at 25 °C and at 70 °C. Powder X-ray diffraction (PXRD), Fourier transformed infrared spectroscopy (FTIR), water absorption as well as mechanical strength tests were used to characterize the 28 days aged CEBs. The compressive strength of CEBs varies from 9.2 to 20.6 MPa and 10.2 to 42.8 MPa at 25 °C and 70 °C, respectively. Water absorption ranges from 6 to 11% at 25 °C and 8 to 12% at 70 °C. These results indicated the possibility to use pozzolana based phosphate geopolymer binder as efficient stabilizer for the development of structural and functional CEBs. Pozzolana based phosphate geopolymer binder appears as energy-efficient and sustainable solution for the stabilization of CEB.

Introduction

In some developing countries such as Cameroon, the housing crisis is one of the most serious problem, affecting more than half of the population (UNISDR, 2018). Solving this problem brings real estate companies, cooperatives and other organizations to build low-cost housing for sale or rent. However, it has been noted that these offers do not satisfy all of the populations because the incomes of some households do not make it possible both to curb steadily rising consumer spending and at the same time to reduce the costs of renting or buying homes whose construction costs justify the unaffordable selling price. These prices, inaccessible to most of the population, are justified by the fact that the majority of building materials are imported, which makes it expensive to build a house in these countries. The vulgarization of local building materials is therefore very significant in countries such as Cameroon where basic inputs such as iron, building or decorative stones, wood frames, sand and stone quarries in all regions, as well

as earth for the manufacture of fired or unfired bricks, already exist on the spot.

However, fired bricks and compressed earth blocks (CEBs) are considered appropriate and low-cost materials for decent houses. But, the manufacture of fired bricks is energy intensive (Mimboe et al., 2020) and the manufacture of compressed clay blocks requires the use of a binder and waste material generate from industrial and agricultural activities ashes to improve their properties (Elinwa, 2007; Peys et al., 2017). Ordinary Portland cement (OPC) is the most widely used binder nowadays. The clinker used by local OPC industries almost all imported. This situation is justified by the unavailability of the raw material and the energy deficit as its manufacture is energy-intensive. It also releases an important quantity of CO₂ which has an environmental impact since it contributes to global warming (Davidovits, 2008; Nath et al., 2016; Tome et al., 2020).

The geopolymerization technology that has received considerable attention over the last decades is one of the many solutions advocated

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today to overcome the housing issue in developing countries. It involves the polymerization/polycondensation reaction between an aluminosilicate material such as calcined clays, fly and volcanic ashes, industrial and municipal wastes and an activating solution (alkaline or acid) at room or slightly elevated temperature ($T < 100\text{ }^{\circ}\text{C}$) (Djobo et al., 2014; Kamseu et al., 2009; Kumar and Kumar, 2011; Tome et al., 2021, Tome et al., 2018). The products obtained are capable of hardening within a reasonably short period of time (Tchakoute et al., 2013). The geopolymerization technology, despite its potential and its various advantages, remains poorly used until now. Previous work has shown that the geopolymer binder is an efficient alternative to OPC for the stabilization of compressed earth bricks (Abid et al., 2021; Beleuk à Mounkam et al., 2017; Kumar and Kumar, 2013; Md et al., 2014; Mimboe et al., 2020; Sore Omar et al., 2018; Teixeira et al., 2020). In addition to its ecological advantages, it is also beneficial for the physico-chemical and mechanical properties of the bricks obtained. The properties and cost of geopolymer products depend considerably on the feedstock. The use of several local materials remains to be explored in order to minimize the energy impact during the production of the bricks and achieved durable products. Pozzolans which are waste materials available in several countries near the volcanoes is a green solution because; its use as a precursor does not require energy activation such as calcination. Recently, Ghadir et al., 2021 (Ghadir et al., 2021), showed that pozzolana based alkaline activated is also an environmentally-friendly substitution for Portland cement in soil stabilization. However, previous works have shown that these materials have a better reactivity in acidic than in basic environment (Elimbi and Kouamo, 2016; Noël et al., 2020). The compressive strength of pozzolana based phosphate geopolymer binders is higher than pozzolana based alkaline geopolymer binders (Djobo et al., 2019; Tchakoute et al., 2013). Its use as stabilizer of CEB can produce structural and functional materials.

The purpose of this work is to investigate the stabilization of earth bricks using a the pozzolan-based phosphate geopolymer binder while examining the effect of geopolymer binder's amount (0, 10, 15 and 20 wt%) and curing temperature (room temperature and $70\text{ }^{\circ}\text{C}$) on the engineering and structural properties of CEB. The clay soil (CS) was characterized in order to evaluate the possibility of using it as a raw material in the production of CEB. The outcomes of this study would gear more research in the use of the sustainable and alternative binder for the stabilization of CEB in the construction applications in tropical areas.

Materials and methods

Preparation of raw materials and characterizations

The clay soil (CS) was collected in the quarry located at 500 m from the Dibamba ($\text{N}03^{\circ} 5'35.4''$ and $\text{E}009^{\circ} 53'31.2''$) Bridge while the pozzolana (PZ) was collected in Djoungo ($\text{N}^{\circ}9.629100021$ and $\text{E}^{\circ} 4.584020013$). Both raw materials were collected in Littoral-Cameroon. They were dried for three days in an oven at $105\text{ }^{\circ}\text{C}$, crushed using a ball mill and sieved to different grain sizes (500 and $80\text{ }\mu\text{m}$ for clay soil and pozzolan, respectively). The elemental composition of PZ and CS was determined using XRF analysis. The method of sedimentometry has been applied to determine the distribution of particles of CS according to the mass of samples in the medium. The particle sizes were done using dry sieving and sedimentation methods for fine particles according to ASTM D7928's standard. The plasticity analysis was determined through ASTM D4318's standard. The mineralogical composition of both feedstocks was determined with a Bruker D2 Phase powder X-ray diffractometer (Bruker, Germany), equipped with a flat sample holder, using $\text{CuK}\alpha$ radiation with $\lambda = 1.5418\text{ \AA}$ at 30 kV at a scan speed of $6^{\circ}/\text{min}$ ranging from 2θ angles of 5 to 70° . The functional groups of CS and PZ were determined through Fourier transform

infrared (FTIR) spectroscopy (Bruker Tensor 37, Bruker, Germany) as KBr pellets in the range of $400\text{--}4000\text{ cm}^{-1}$.

Stabilization of clay soil

The geopolymer bricks were obtained by mixing clay soil (CS), pozzolana (PZ) and sand (sieved at 2 mm) with a phosphoric acid solution (10 M). The phosphoric acid solution/ pozzolan mass ratio was kept constant at 0.8. This choice of activating solution ratio was done according to the work of Aude Minboe et al (Grace et al., 2020). The sand/powder (clay soil + pozzolana) ratio in weight was 1.0. In order to obtain a good workability, tap water was added to the whole mixture. In samples without pozzolana (CEB_0), the ratio $\text{H}_3\text{PO}_4/\text{Clay soil}$ was 1.0. The proportions of the mixtures for the five (05) formulations are showed in Table 1. The formulation of the brick consists of four steps, namely: (i) Manual mixing of the clay soil powder, pozzolan and sand; (ii) Mixing of the phosphoric acid solution and product of (i) and stirring for 5 min; (iii) Addition of little amount of tap water to the mixture (iii) and stirring for 5 min and (iv) Compression of the product of (iii) in a cubic ($4 \times 4 \times 4\text{ cm}^3$) and prismatic moulds ($4 \times 4 \times 16\text{ cm}^3$) at a pressure of 8 MPa by a MANNETI hydraulic press. The samples obtained were sealed in plastic bags and stored at $25\text{ }^{\circ}\text{C}$. After 7 days of curing, other samples were thermally activated at $70\text{ }^{\circ}\text{C}$ for 48 h. These samples were labeled as described in Table 1.

Characterizations of compressed earth bricks (CEB)

The analyses below were performed on 28-day old samples. The three-point flexural and compressive strengths of the stabilized CEBs were evaluated on wet and dry specimens using a compression test machine from Impact test, UK with a maximum load capacity of 250 kN. The physical properties such as water absorption, apparent density and porosity were performed on $4 \times 4 \times 4\text{ cm}^3$ samples. The wet strengths were determined from samples previously immersed in water at $25 \pm 3\text{ }^{\circ}\text{C}$ for 24 h. For the water absorption test, the samples dried in an oven at $105\text{ }^{\circ}\text{C}$ were first weighed and then immersed in water at room temperature ($25 \pm 3\text{ }^{\circ}\text{C}$) for 24 hrs. After removal of water, the mass of the wet samples was weighed and compared to the mass of the dry samples according to ASTM C642 – 06 (ASTM, 2013). The bulk density was calculated as the ratio of the dry mass of the sample to its total volume.

The mineralogical and structural properties of powdered CEBs were monitored throughout powder XRD and FTIR analyses, respectively as described above.

Results and discussion

Characterization of raw materials

The clay soil and pozzolana were subjected to various characterizations before the manufacture of the bricks. The results of the chemical composition of both materials, particle size by sedimentology and Atterberg limits carried out on the CS are recorded in Table 2. The main oxides in both materials are SiO_2 , Al_2O_3 and Fe_2O_3 which are 47.4, 25.9 and 9.2% for CS and 47.9, 15.8 and 12.9% for PZ. The CS appears as plastic silty clay material regarding the particle size distribution and Atterberg limits values. X-ray diffraction analysis (Fig. 1) showed that CS is composed of minerals such as: Quartz (SiO_2 , ICDD#46-1045); Magnetite (Fe_2O_3 , ICDD#00-0551); clay minerals such as Kaolinite ($\text{Si}_2\text{O}_5\text{Al}_2(\text{OH})_4$, ICDD#14-0164); Montmorillonite ($(\text{Na}, \text{Ca})_{0.3}(\text{Al}, \text{Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_2 \cdot n\text{H}_2\text{O}$ ICDD#13-0135) and Muscovite ($\text{KAl}_2\text{Si}_3\text{AlO}_{10}(\text{OH})_2$, ICDD#06-0263). The pozzolana is predominantly made of crystalline phases that include: Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$, ICDD#41-1486); Diopside ($\text{CaMgSi}_2\text{O}_6$, ICDD#01-0071); Feldspar Na_2 ($\text{Al}_2\text{Si}_3\text{O}_{10}$, ICDD#01-0083), Forsterite (Mg_2SiO_4 ,

Table 1
Mixing proportions of the geopolymer brick formulations.

Formulations	CEB ₀	CEB ₅	CEB ₁₀	CEB ₁₅	CEB ₂₀
CS (Wt.%)	47.5	41.0	37.5	33.3	29.0
PZ (Wt.%)	0	4.6	9.4	14.3	19.4
Sand (Wt.%)	47.5	45.6	46.9	47.6	48.4
H ₃ PO ₄ (Wt. %)	5	8.8	6.2	4.8	3.2
H ₂ O (g)	29	28	22	14	6
H ₃ PO ₄ /PZ ratio	0	0.8	0.8	0.8	0.8

Table 2
Chemical composition, particle size by sedimentology and Atterberg limits of raw materials.

Chemical composition										
Oxides	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	Na ₂ O	K ₂ O	MgO	P ₂ O ₅	TiO ₂	LOI
CS (%)	47.4	25.9	2.36	9.27	2.5	1.87	1.7	0.8	1.78	5.6
PZ (%)	47.9	15.8	8.6	12.9	3.7	2.8	6.4	–	–	0.9
Particle size										
CS	Appearance	% of gravel ($\phi > 2$ mm)		% of sand ($2 > \phi > 0.02$ mm)		% of silt (0.02 greater than $0\phi > .002$ mm)		% of clay ($\phi < 0.002$ mm)		
	Silty clay	13.3		21.6		32.7		32.8		
Atterberg limits										
CS	Liquidity limit	Plasticity limit		Plasticity index		Cameroonian Standards for plasticity index of CEB (NC 102–114, 2002–2006)				
	70.4	53.9		16.5		2.0–30.0				

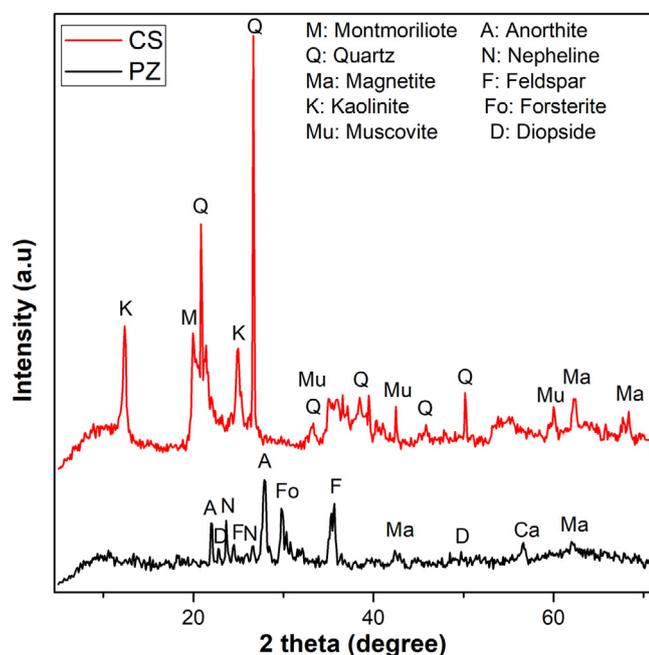


Fig. 1. XRD patterns of clay soil (CS) and pozzolana (PZ).

ICDD#85–1357); Calcite (CaCO₃, ICDD# 00-005) and Magnetite with $2\theta = 35.67$ and 62.22° .

Fig. 2 depicts the FTIR spectrum of CS and PZ. The FTIR spectra of CS shows the absorption bands at ~ 3650 cm⁻¹ and 1632 cm⁻¹ characteristic of the hydroxylated O–H bonds (Gritco et al., 2005). The presence of bands at ~ 995 cm⁻¹ reflects the presence of Si–O–Si or Si–O–Al bonds characteristic of the aluminosilicate phases (Criado et al., 2008; Kriskova et al., 2015). The bands located at ~ 912 cm⁻¹ correspond to Al–OH bonds (Tchakoute et al., 2015). The absorption band at ~ 770 cm⁻¹ of high intensity is attributed to the Si–O–Al^{IV} group. The vibration bands around ~ 670 and

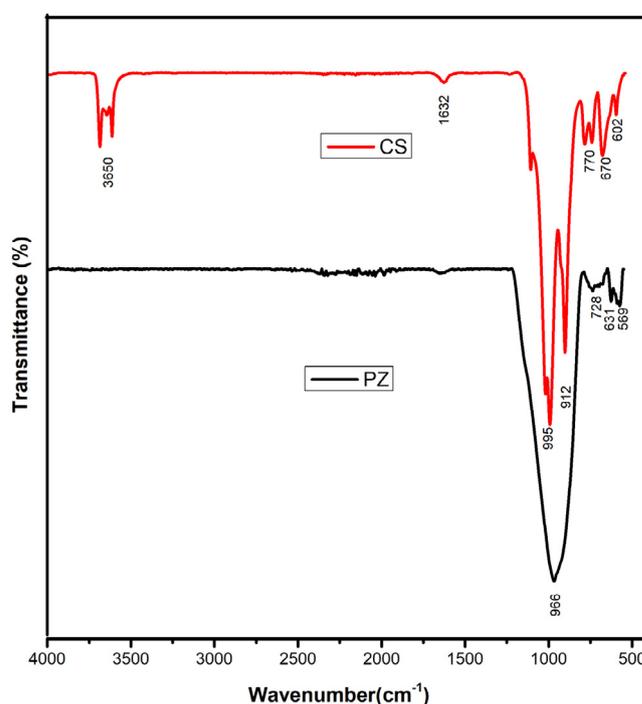


Fig. 2. FTIR spectra of clay soil (CS) and pozzolana (PZ).

602 cm⁻¹ correspond respectively to the deformations of the Si–O and Si–O–Al^{VI} bonds (Nyankson et al., 2018). The spectra of PZ exhibits the bond characteristic of the asymmetric stretching vibrations of Si–O–T (T = Si or Al) with peaks at ~ 966 cm⁻¹ (Criado et al., 2008; Kriskova et al., 2015). The peaks appearing at ~ 631 and 728 cm⁻¹ correspond to Si–O bending vibration (Saikia et al., 2008) and the peak at ~ 569 cm⁻¹ for represents the vibration of Si–O–Fe bond (Tchakouté et al., 2015). The bulk density of clay soil, pozzolana and sand are 1.75, 1.45 and 1.40 g/cm³, respectively.

Physical properties of stabilized CEBs

Fig. 3 shows the appearance of samples used for bulk density, porosity; water absorption and flexural and compressive strengths analyses (a) and the samples immersed in water after 24 h.

Water absorption and porosity

The variation of water absorption and porosity of stabilized CEBs at 25 °C and 70 °C is shown in Figs. 4 and 4, respectively. It is apparent that the water absorption values range from 11.64% (CEB₀) to 5.98.0 % (CEB₂₀) and from 11.82% (CEB₀) to 7.63% (CEB₂₀) at 25 and 70 °C, respectively (Fig. 4). These values are mostly affected by the stabilizer content. Similarly, this trend is observed with the variation of porosity which is generally deduced from water absorption behavior. Then, the specimens without incorporation of stabilizer (CEB₀) show a porosity of 37.65 and 37.81% for 25 and 70 °C, respectively (Fig. 5). These values decrease progressively with the incorporation of geopolymer stabilizers and reach to 30.93 and 32.94% for the specimens with 20 wt% of stabilizers (CEB₂₀) at 25 and 70 °C, respectively. These values obtained can be justified with the proliferation of the geopolymer binder and the capacity of pozzolana particles to fill the open and capillary pores. The presence of pozzolana particles reduces significantly the pores created by the air bubbles in the geopolymer matrices. Then, the geopolymer networks become denser with stabilizers. Compared to the samples cured at 70 °C, it is observed that those cured at 25 °C (room temperature) show a slight reduction of the water absorption and porosity values. This can be due to the fast evaporation of water molecules at this temperature which causes residual dehydration and created the micro-cracks responsible of this variation. This fact also reveals that the geopolymer networks obtained at 70 °C is more porous than those obtained at 25 °C. This porosity is due to dehydration of geopolymer network at high temperature which generates cavities. It can also be justified by the fact that at 70 °C, pozzolana has a good reactivity and produces more binder than those obtained at 25 °C (Djobo, 2016). These absorption values, which do not exceed 14%, are in accordance with the standard for building materials (Pancharathi et al., 2019). It is commonly known that porosity has a close relationship with mechanical strengths and that an increase in porosity could be negatively affected mechanical strength values. These binders form strong bonds with non-reactive particles.

Bulk density

The density values of CEBs stabilized at 25 and 70 °C are shown in Fig. 6. These values vary from 1.55 g/cm³ (CEB₀) to 1.5 g/cm³ (CEB₂₀) at 25 °C and from 1.52 g/cm³ (CEB₀) to 1.47 g/cm³ (CEB₂₀) at 70 °C. It is observed that the densities of geopolymer bricks increase slightly with the incorporation of geopolymer stabilizer. This is justified by the difference in density of its precursors (1.9 and 1.7 g/cm³ for PZ and CS, respectively). Although the pozzolana undergoes a transformation after an acid attack, these results show that this restructuring takes place without loss of material. The density is also influenced by the curing temperature. It decreases with the rise of temperature. This is justified by the residual dehydration mentioned in the previous paragraph.

Wet and dry compressive strengths

Fig. 7 shows the results of dry and wet compressive strengths of stabilized CEBs cured at 25 and 70 °C. Generally, it appears that the strength of geopolymer specimens is mostly affected by the incorporation of stabilizers. At 25 °C, the dry compressive strength (Fig. 6a) increases progressively with the addition of the stabilizer from 9.7 to 20.6 MPa for 0 wt% to 20 wt% of stabilizers added. At 70 °C, the strength increases from 10.2 MPa (0 wt%) and reaches the highest value of 42.8 Mpa at 15 wt% of stabilizer incorporated. Further addition at 20 wt% decreases these values to 36.9 MPa (Fig. 6a). Indeed, the value of the compressive strength of stabilized CEBs is influenced by the cohesion between the products generated by the stabilizer and the unreacted particles. This cohesion generates compact bricks, thus producing materials with important mechanical properties. These results reveal that the phosphate geopolymer gels produced by the pozzolana really ensure the stabilization of CEBs based clay soil. The increase in temperature to 70 °C, which according to the literature is the threshold temperature for geopolymerization based pozzolana (Djobo, 2016), catalyzes the polymerization/polycondensation reaction and allows a considerable mechanical gain. The compressive strength values of the CEBs without pozzolana at 25 °C (9.7 MPa) and 70 °C (10.2 MPa) show that there is intra-stabilization of CS in an acidic environment. This phenomenon according to the literature (Han et al., 2018; Noël et al., 2020; Wagh and Jeong, 2003) is due to the formation of Poly(phospho-ferro-siloxo) networks resulting from the reaction between phosphoric acid, amorphous



Fig. 3. Appearance of samples used for physical properties (a) and samples after 24 h in water (b).

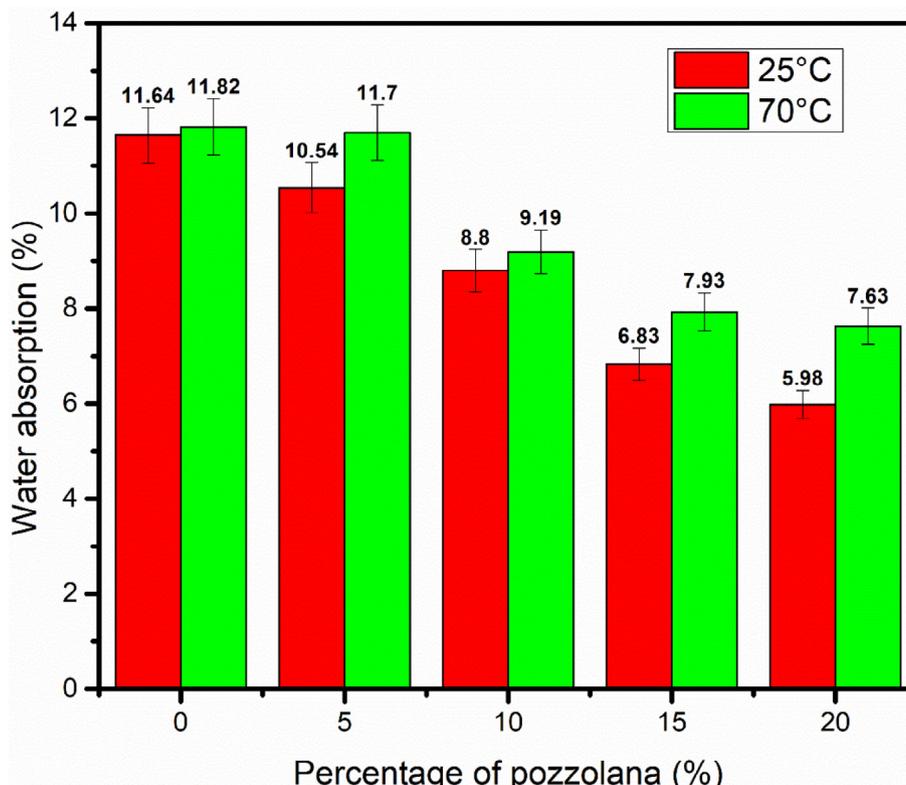


Fig. 4. Percentages of water absorption of stabilized CEBs at different temperatures.

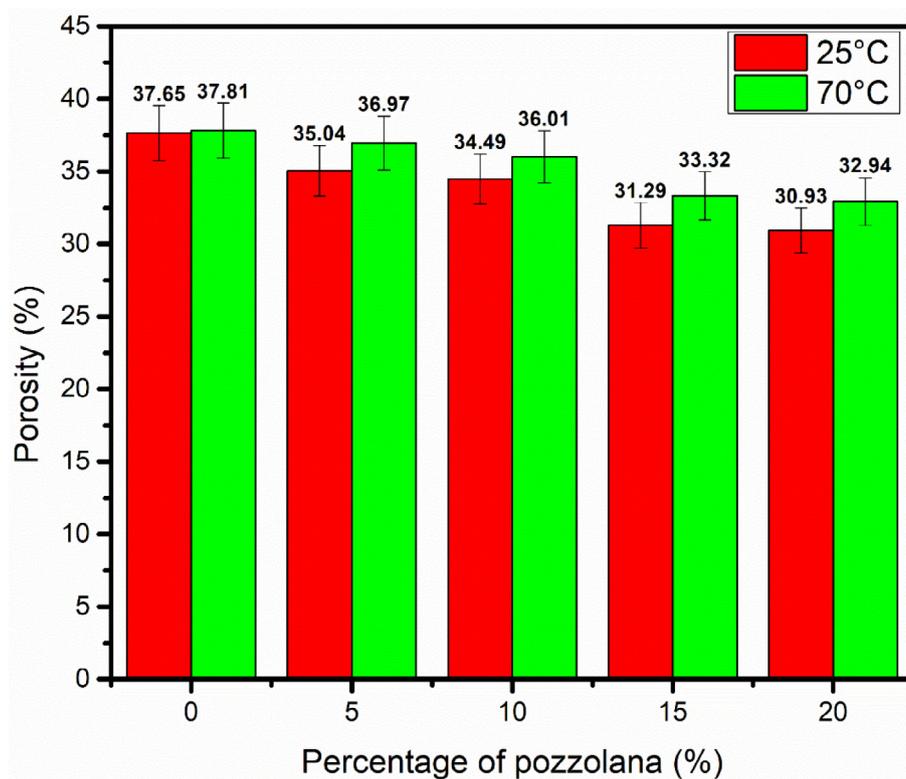


Fig. 5. Percentages porosity of stabilized CEBs at different temperatures.

aluminosilicate phases and iron oxide. The slight difference in compressive strength at 25 and 70 °C shows that temperature is a kinetic factor for the dissolution of iron oxide in an acidic medium. The

decrease of compressive strength at 20 wt% of stabilizer shows that 15% wt% of stabilizer is sufficient for the efficient stabilization of the clay soil used.

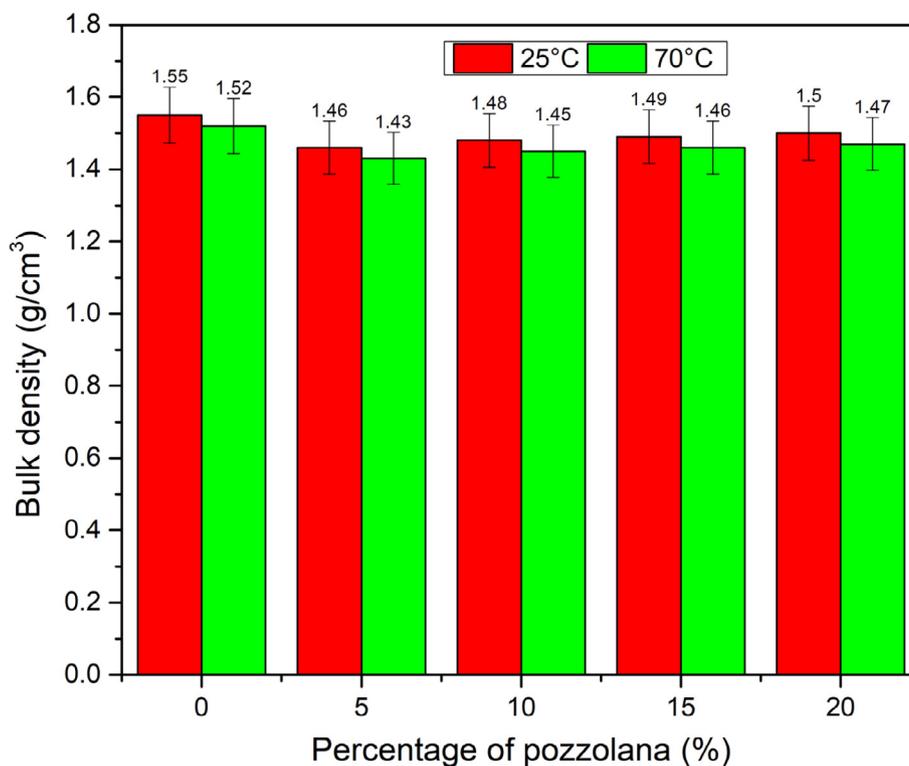


Fig. 6. Bulk density of stabilized CEBs at different temperatures.

The evolution of the values of wet compressive strength matches with the one of dry compressive strength. However, there is a substantial drop in resistance of $\sim 43.7\%$ at $25\text{ }^{\circ}\text{C}$ and $\sim 43.8\%$ at $70\text{ }^{\circ}\text{C}$. This drop is consistent with previous work that investigated the effect of water on the physico-mechanical properties of phosphate geopolymer binders (Bewa et al., 2018; Grace et al., 2020). In these works based on metakaolin and calcined laterite as precursors, the optimum compressive strength loss in wet conditions was more than 60% of dry strength for all samples. The fewer lower values here predict that the phosphate geopolymer binder from pozzolana is more water-resistant than those from metakaolin and calcined laterite. Indeed water is an aggressive agent for materials; it moistens the various bonds formed and makes them fragile. With regard to its mechanical properties, the addition of 15 wt% pozzolana at $70\text{ }^{\circ}\text{C}$ appears to be the ideal conditions to stabilize the compressed earth bricks by the phosphate geopolymer binder. The strength value of the bricks obtained with this composition is higher than those of CEBs stabilized by OPC ($<10\text{ MPa}$) (Sore Omar et al., 2018) and other geopolymer binders ($<39\text{ MPa}$) (Ghadir and Ranjbar, 2018; Grace et al., 2020). In the view of these compressive strength and water absorption values, the CEB₁₅ and CEB₂₀ at $70\text{ }^{\circ}\text{C}$ can be used as building bricks in areas with severe weathering (ASTM C62) and the other bricks as load-bearing masonry units (ASTM C90) (Kuranchie and Shukla, 2014).

Flexural strength

Fig. 8 displays the flexural strength values of the stabilized CEBs. It can be observed that the flexural strength of the geopolymer binder is mostly affected by the temperature of curing. At $25\text{ }^{\circ}\text{C}$, the strength is almost constant ($\sim 0.5\text{ MPa}$) despite the incorporation of stabilizers up to 10 wt%. At 15 wt% of stabilizer incorporated, these values increased slightly and reach 1.0 MPa. Further addition at 20 wt% permits to obtain 1.3 MPa. These observations show that the binders provided by 5–10 wt% of pozzolana are insignificant to ensure the good homogeneity between binders and non-reactive particles. Also, this behavior could be due to the weakness of chemical bonds developed

during the geopolymerization of this binder. It is well known that flexural strength is directly related to the binding forces between the different particles of the system. Then, despite the incorporation of stabilizer particles, they were not sufficient to develop enough bonding that considerably enhances the strength. However, the thermal curing (at $70\text{ }^{\circ}\text{C}$) permits to increase from 3.8 to 4.6 MPa between 15 and 20 wt% of stabilizer added. This can be explained by the good reactivity of the pozzolana particles in these conditions.

In the view of above results, the CEBs stabilized with geopolymer and cured at $70\text{ }^{\circ}\text{C}$ have relatively higher values of the water absorption, porosity and compressive and flexural strength than the one cured at $25\text{ }^{\circ}\text{C}$. In fact, at high temperature, the physicochemical reactions such as the leaching of excess water are produced within the materials which lead to the formation of cavities and can modify certain properties of the materials. Muñiz-villarreal, et al., 2011 showed that, the macrospores and microspores distributions of geopolymer network decrease and increase with the rise of temperature, respectively and the compressive strength increases with the rise of temperature (Muñiz-villarreal et al., 2011). These microspores are the reservoirs of which take up enough water. However due to their low size, these microspores will not affect the strength evolution of products. The compressive and flexural strengths evolution depend mainly on the improvement of geopolymer network and the rise of temperature is a kinetic parameter for geopolymerization reaction (Djubo, 2016).

Microstructural properties

Xrd

Fig. 9 shows the powder X-ray patterns of CEBs cured at 25 and $70\text{ }^{\circ}\text{C}$. Comparing the diffractograms of samples of CEBs without stabilizer with that of CS (Fig. 1), we observe a small shift of $\sim 26^{\circ}$ (CS) to $\sim 28^{\circ}$ (CEBs) from the most intense peak. This situation shows that there is a restructuring of CS after activation in an acidic environment. This is obvious because the aluminum, silica and iron oxide phases

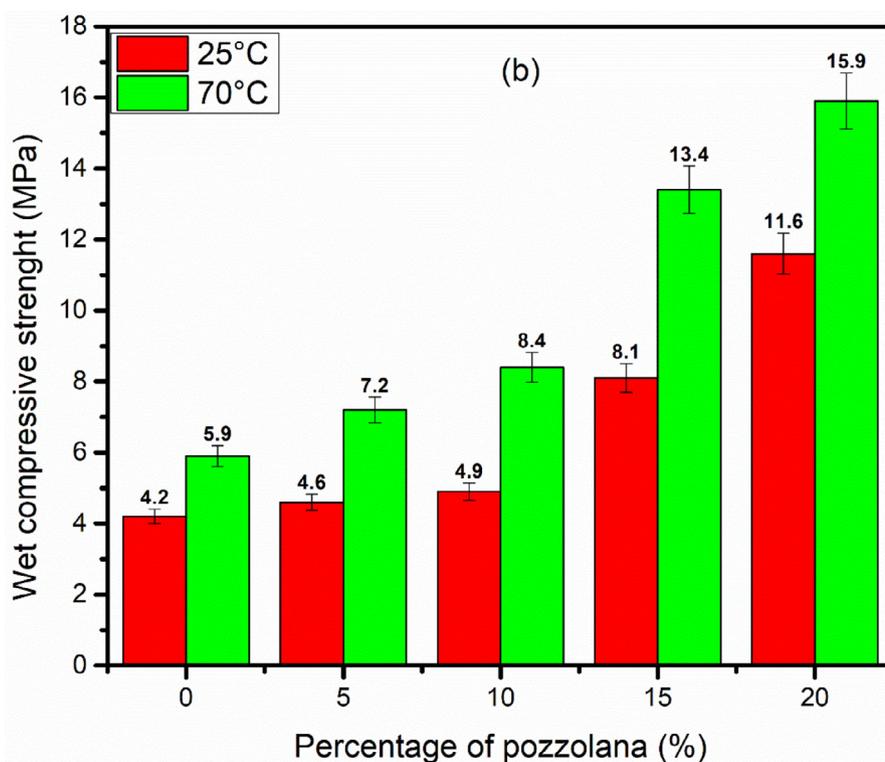
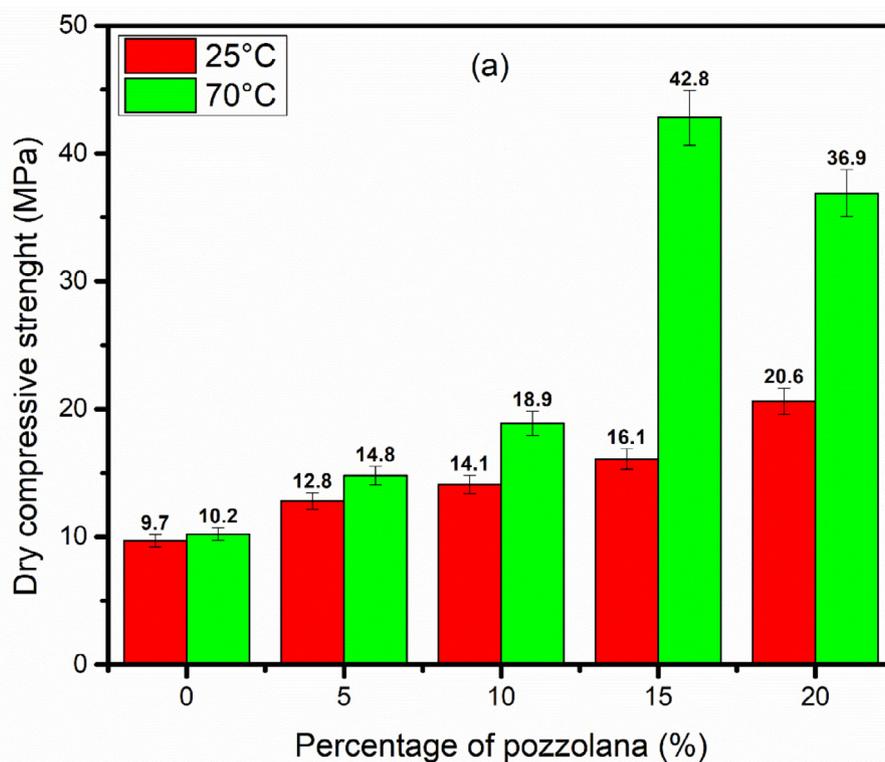


Fig. 7. Dry (a) and wet (b) compressive strength of stabilized CEBs cured at 25 and 70 °C.

dissolve in phosphoric acid to form amorphous phases i.e. geopolymer network (Bewa et al., 2019; Noël et al., 2020). Regarding the compressive strength values of CEB₀, these binders are not sufficient for intrastabilization of CS based CEBs. The appearance of peaks of aluminum, silica and iron oxide phases from raw materials with almost the same

intensities in CEBs reveals that these minerals dissolve weakly in acidic media. We also observe the appearance of a new peak in the sample containing 20 wt% of stabilizer cured at 70 °C attributable to aluminum phosphate hydrate. According to the literature (Bewa et al., 2019; Tchakouté et al., 2017) the formation of this mineral results

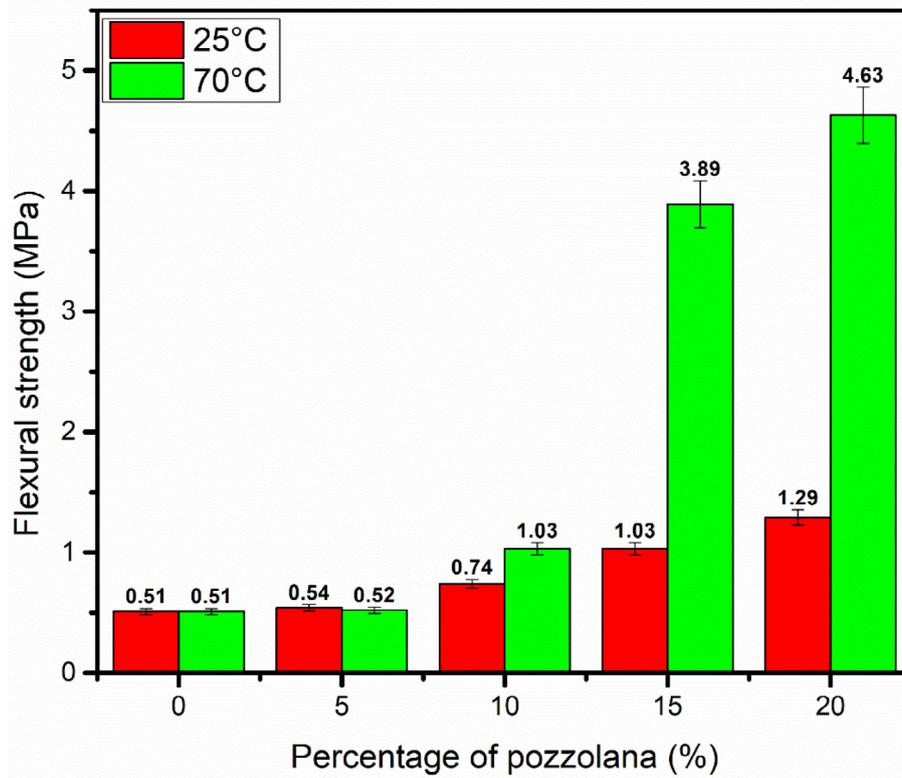


Fig. 8. Flexural strength of stabilized CEBs at different temperatures.

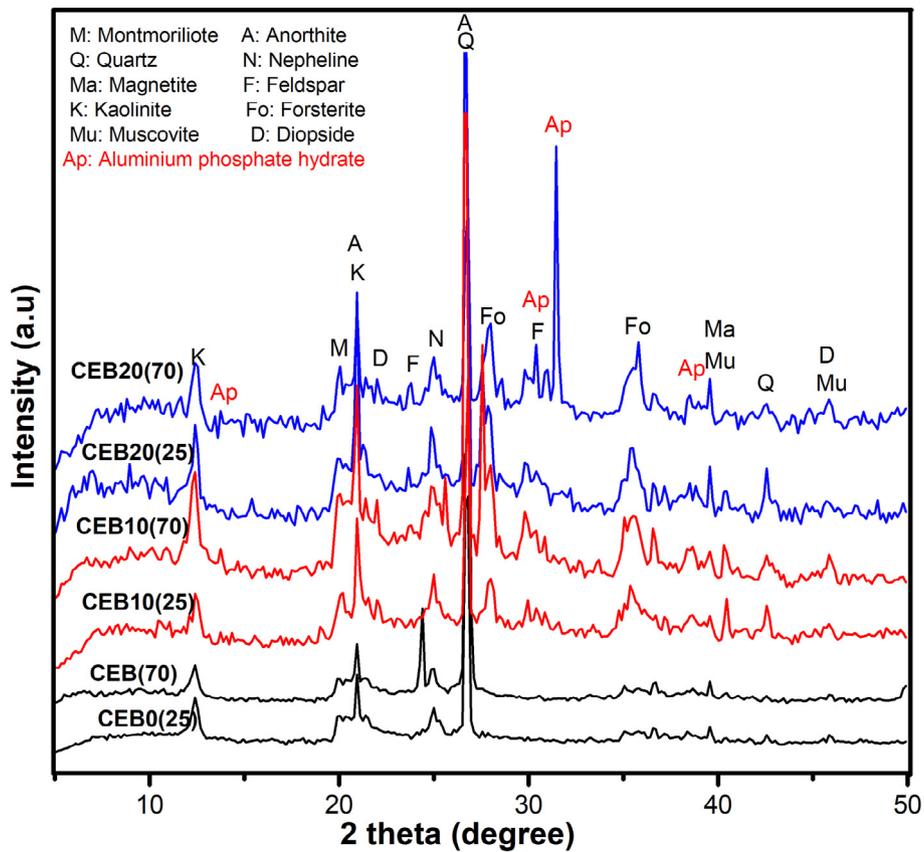


Fig. 9. X-ray patterns of CEBs cured at room temperature and 70 °C.

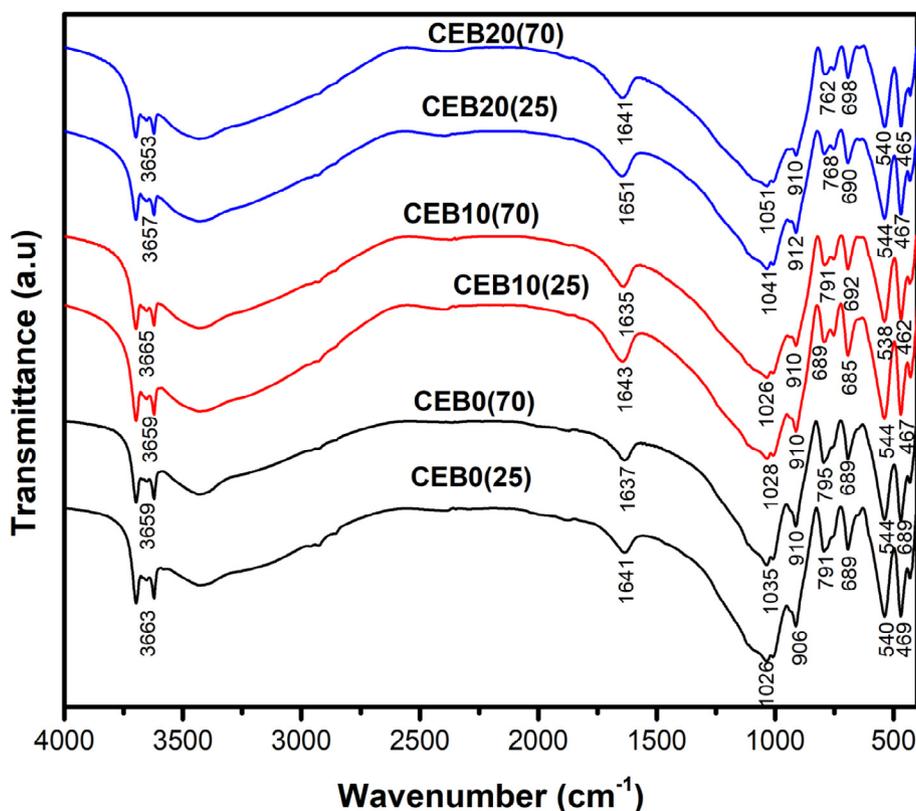


Fig. 10. FTIR spectra of CEBs cured at room temperature and 70 °C.

from the precipitation of aluminate ions (AlO_4^-) from the dissolution of aluminosilicate phases and phosphate ions (PO_4^{3-}) from phosphoric acid.

FTIR

Fig. 10 depicts the FTIR spectra of CEBs cured at 25 °C and 70 °C. Comparing these spectra with those of raw materials, it highlights that all the bands of CS spectrum (Fig. 2) are present on CEBs spectra. This fact approves the aforementioned low dissolution of different minerals detected in CS. The phenomenon of restructuration of aluminosilicate phases in both materials after activation in acid medium is sustained with the shift of Si-O-T (T = Si or Al) from 995 cm^{-1} (CS) and 966 cm^{-1} (PZ) to $\sim 1026\text{ cm}^{-1}$. This shift is significant with the incorporation of PZ and the rise of temperature. The increase of band intensity initially in raw materials at $\sim 560\text{ cm}^{-1}$ is attributed to the formation of Al-O-P bond of AlPO_4 chains confirming the formation of the aluminum phosphate hydrate (Bewa et al., 2019) detected in above section (Fig. 10).

Conclusion

The main objective of this work was to stabilize Compressed Earth Bricks (CEB) by pozzolana based phosphate geopolymer binder. The following characterizations techniques: X-ray diffraction (XRD), Fourier Transformed Infrared Spectroscopy (FTIR), water absorption and compressive strength tests were used in order to understand the effect of the incorporation of 0–20 wt% of pozzolana on the properties of the products. The results of physico-mechanical, and structural analyses displayed that.

1. The water absorption of geopolymer matrices obtained was in the range: 5.98–11.6% at 25 °C and 7.63–11.82% at 70 °C.

2. The compressive strength values increase with the addition of the stabilizer from 9.7 to 20.6 MPa and 10.2 to 42.8 MPa at 25 °C and 70 °C, respectively.
3. Similarly, the flexural strength values increase with the incorporation of the stabilizer from 0.51 to 1.29 MPa and 0.5 to 4.63 MPa at 25 °C and 70 °C, respectively.

These results thus showed that ground pozzolana can be used in the same way as calcined laterites and clays for efficient geopolymerization stabilization of compressed earth blocks. The pozzolana based phosphate geopolymer binder appears as sustainable material for the stabilization of CEB. CEB with 15% of PZ is the greatest composition in this study, nevertheless further studies with intermediate percentages range between 12 and 18% of PZ are required in order to validate this composition. In the view of the compressive strength and water absorption values achieved, the CEB₁₅ and CEB₂₀ at 70 °C can be used as building bricks in area with severe weathering and the other bricks as load bearing masonry units. However the study of the durability is required in order to approve their use.

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.

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Availability of data and materials

All data generated or analyzed during this study are included in this article.

Compliance with ethical standards

Consent to participate
Not Applicable.
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