

Research Article

# Effects of Production Factors on the Physicochemical and Mechanical Properties of Compressed Earth Bricks Stabilized by Geopolymerization

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## Abstract

Geopolymerization presents an environmentally friendly and sustainable alternative to conventional construction materials, particularly in the production of compressed stabilized earth bricks (CSEB). This study investigates the influence of two key production factors which are the volcanic ash/laterite mass ratio ( $X_1$ ) and the amount of phosphoric acid ( $H_3PO_4$ ) activating solution ( $X_2$ ), on the physicochemical and mechanical properties of CSEB. The raw materials, laterite and volcanic ash collected from the Adamaoua region in Cameroon, exhibit low porosity, high specific surface area, and are rich in silica and alumina oxides. The central composite design (CCD) was employed to model and optimize the CSEB production process, with compressive strength as the response variable. Results indicate that the compressive strength is predominantly governed by the mass ratio of volcanic ash to laterite, whose main effect is 49 times greater than that of the  $H_3PO_4$  amount. However, due to the significant interaction effect between the volcanic ash/laterite mass ratio and the amount of  $H_3PO_4$ , and the important quadratic effect of the volcanic ash/laterite mass ratio, the variation in compressive strength is nonlinear. Optimal conditions were determined to be a volcanic ash/laterite mass ratio of 0.16 and an  $H_3PO_4$  amount of 8.69 mL, yielding a compressive strength of 33MPa. The evaluation of the hydration behavior of CSEB under optimal conditions revealed minimal water absorption under capillary rise and full immersion. In the wet state, the compressive strength decreased by approximately 10% (full immersion) and 8% (partial immersion) compared to the dry state. Overall, geopolymerization significantly enhances both the compressive strength and water resistance of CSEB.

## Keywords

Compressed Stabilized Earth Bricks, Geopolymerization, Laterite, Volcanic Ash, Production Factors, Central Composite Design, Compressive Strength

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## 1. Introduction

Earth Bricks are highly valued construction materials due to their energy efficiency, low environmental impact, and the wide availability of their constituent materials. However, their low mechanical properties and low resistance hydration limit their use in certain types of construction. In order to improve these properties, methods such as stabilization with Portland cement, lime, compaction, the use of natural fibers, or thermal treatment have already been implemented [1-4]. However, these methods, have the disadvantage of being either very expensive, sometime low effectiveness, or often requiring costly equipment. In the search for alternative methods that are less expensive and more environmentally friendly, geopolymerization has recently attracted more attention due to the good mechanical properties and durability it imparts to the geopolymer produced at the end of the reaction [5-7].

Geopolymerization is a chemical process that transforms, under the action of a basic or acidic activating solution, an amorphous, aluminosilicate-rich powdery material into a consolidated material called geopolymer [8, 9]. The production of compressed earth bricks by geopolymerization involves using laterite as the matrix, volcanic ash as the aluminosilicate material, and phosphoric acid as the activating solution. The properties of the resulting brick are strongly related to the origin of the materials used, the amount of volcanic ash, the quantity and concentration of acid, the mass ratio between the components, and the working temperature [5, 10]. Work carried out on production of geopolymer-stabilized earth bricks often focuses on examining the variation of one of the production factors mentioned above on the properties of the resulting bricks [2, 11]. Although these studies show that the factors that most influence the properties of the bricks are the mass of volcanic ash, the mass of laterite, and the amount of acid, they remain limited because they do not take into account the interactions between the production factors and do not allow to work under optimal conditions.

Therefore, the present study aims to use a central composite design to produce compressed earth bricks stabilized by geopolymerization in order to elucidate the interactions between the volcanic ash/laterite mass ratio ( $X_1$ ) and the amount of phosphoric acid ( $X_2$ ), and to determine the optimal production conditions for CSEB. The compressive strength and hydration behavior of the produced compressed and stabilized earth bricks will be examined during this study.

## 2. Material and Methods

### 2.1. Material

This study uses laterite, volcanic ash, phosphoric acid, and a hydraulic press. The laterite was collected from a quarry located at 11 km from the Ngaoundere town (9°16'38.2" N, 13°29'44.6" E, 257 meters above sea level; Adamaoua Region

of Cameroon). The laterite was air-dried and sieved to 5 mm to obtain a material with a granular class of 0/5 mm (according to ARS 674 standard).

The volcanic ash used in this study were collected from the locality of Tizon (7°15' 22.00" N, 13°34'84" E, altitud 6 m, Adamaoua Region of Cameroon). Prior to be used, the collected volcanic ash was oven-dried at 105 C for 48 hours, ground using a ball mill and then sieved thanks to the use of a 200  $\mu$ m sieve.

The activating solution used is a 8M phosphoric acid solution obtained by dilution of an analytical solution of phosphoric acid.

The press used is a hydraulic press type 769YP-24B. This press was used in the compression step during the production of earth bricks and for compressive strength tests. The pressures ranging from 0 to 60MPa.

### 2.2. Methods

#### 2.2.1. Characterization of Laterite and Volcanic Ash

Laterite particle size analysis was carried out by sieving and gravitational sedimentation according to NF P18-560 and NF P94-057. Volcanic ash was analyzed by laser diffraction (Masterseizer 3000). Densities, waters contents and porosities of the two materials were determined in accordance with standards NF P18-554, NF P94-410-1 and NF P94-410-3 respectively. Specific surface area was determined by the methylene blue method, and chemical composition by X-ray fluorescence spectrometry.

#### 2.2.2. Production of Geopolymerization-stabilized Compressed Earth Bricks

To a mass  $m$  of laterite is added a mass  $m_l$  of volcanic ash and the whole is dry-homogenized. A volume of phosphoric acid is then added to the mixture and the whole is homogenized again. The wet sample is therefore placed in a mold and then compressed using the hydraulic press to a predefined pressure. The earth bricks are finally removed from the mold and placed in a wet curing for 7 days and then in a dry curing at room temperature until its weight stabilizes.

#### 2.2.3. Implementation of the Central Composite Design on the Production of Compressed and Stabilized Earth Bricks by Geopolymerization

The production of earth bricks by the methodology of experimental design to get started with the choice of the experimental design, which here is the central composite design because it not only enables us to work beyond the experimental field and explain the interaction effect between factors, but also allow to determine the optimal production conditions.

The choice of factors and the definition of their levels of

variation was made on the base of the bibliography and preliminary works. The response studied is the compressive strength expressed in Mega Pascal (MPa). Table 1 presents the factors and their levels of variation.

**Table 1.** Factors and levels of variation.

| Factors        | Levels of variation |      |      |      |            |
|----------------|---------------------|------|------|------|------------|
|                | - $\alpha$          | -1   | 0    | +1   | + $\alpha$ |
| X <sub>1</sub> | 0.05                | 0.08 | 0.17 | 0.25 | 0.28       |
| X <sub>2</sub> | 1.96                | 3.00 | 5.50 | 8.00 | 9.03       |

X<sub>1</sub>: Volcanic ash /laterite mass ratio

X<sub>2</sub>: Amount of H<sub>3</sub>PO<sub>4</sub>

The value of the alpha coefficient is calculated by the following formula:

$$\alpha = \left( \frac{N_f \left( \sqrt{N} - \sqrt{N_f} \right)^2}{4} \right)^{\frac{1}{4}} \quad (1)$$

The total number of experiments performed is given by the relation:

$$N = N_f + N_\alpha + N_{f0} \quad (2)$$

$N_f$ : Number of tests of the factorial design

$$N_f = 2^k = 4 \quad (k = 2) \quad (3)$$

$N_\alpha$ : Number of tests of the star plane

$$N_\alpha = 2k = 4 \quad (4)$$

$N_0$ : Number of attempts at the center  $N_0 = 5$

Total number of experiments to be carried out  $N = 13$

In order to verify whether the model generated by the Statgraphic 19-X64 software is applicable to explain the effect of the factors studied on geopolymerization, validation indices namely the coefficient of determination ( $R^2$ ), the absolute analysis of the maximum deviation (AAMD), the Bias factor (Bf) and the Accuracy factors ( $Af_1$  and  $Af_2$ ) were calculated. The equation of the mathematical model is a quadratic equation of type:

$$Y_{CS} = a_0 + a_1 X_1 + a_2 X_2 + a_{11} X_1^2 + a_{22} X_2^2 + a_{12} X_1 X_2 \quad (5)$$

$Y_{CS}$ : Response (compressive strength);  $a_0$ : Constant term;  $a_1$  and  $a_2$ : Linear coefficients;  $a_{11}$  and  $a_{22}$ : Quadratic coefficients;  $a_{12}$ : Interaction coefficients.

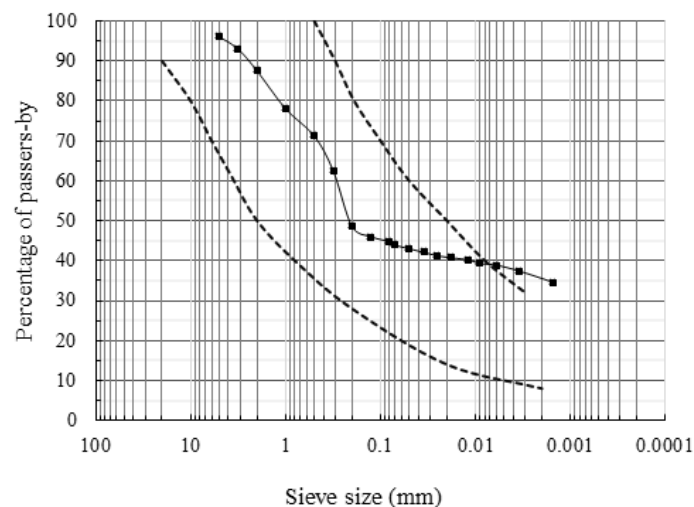
## 2.2.4. Physico-chemical and Mechanical Characterization of Compressed and Stabilized Earth Bricks Under Optimal Conditions

The compressive strength of the CSEB was evaluated using a hydraulic press according to the XP13-901 standard. Linear shrinkage during production was evaluated after demolding, wet curing and dry curing. Hydration behavior was assessed by total immersion and partial immersion (capillary) methods (ASTM C 373-88).

## 3. Results and Discussion

### 3.1. Particle Size Distribution of Laterite

Figure 1. shows the particle size distribution of laterite.



**Figure 1.** Particle size distribution of laterite (—■—) and upper and lower limit of the granular spindle (-----).

It appears from this figure that nearly 90% of the laterite particle size curve is inscribed in the granular spindle recommended for materials that can be used in the manufacture of compressed earth bricks. However, nearly 10% of the curve exceeds the upper limit of the granular zone. This overflow is attributed to the small particles corresponding to the clay fraction of the laterite. This presence of clay is an asset for the geopolymerization phenomenon because it is well known that clay materials are sources of aluminosilicates [12, 13]. This particle size distribution shows a variability in the proportions of the different classes of laterite particles, which are respectively 57.40% for sands (coarse and fine), 15.00% for silts and

27.60% for clays. This result is a strong indication of the heterogeneous distribution of laterite particles. This heterogeneous character of laterite could be favorable for the densification operation of earth bricks during their production, leading to the achievement of the important mechanical properties of compressed and stabilized earth bricks [2, 14, 15].

### 3.2 Particle Size Distribution of Volcanic Ash

Figure 2 present the particle size distribution of volcanic ash.

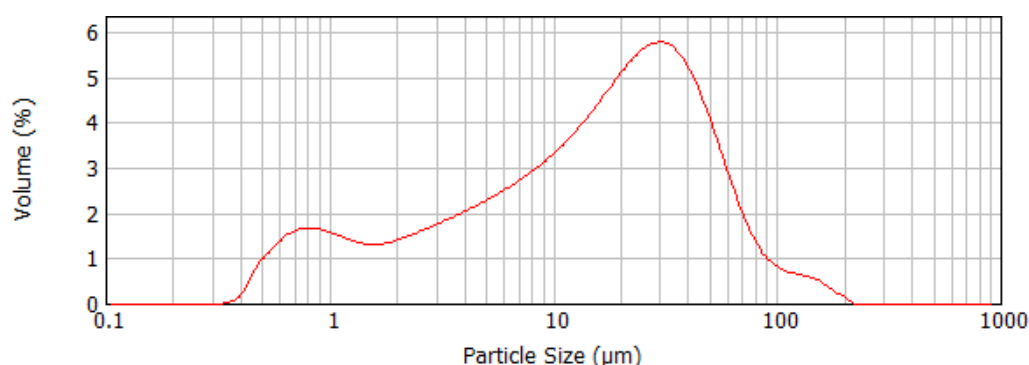


Figure 2. Particle size distribution of volcanic ash.

It can be observed that the particle size distribution curve of volcanic ash particles has a unimodal appearance with a shoulder. The evaluation of the maximum diameter corresponding to 10% ( $d_{10}$ ), 50% ( $d_{50}$ ) and 90% ( $d_{90}$ ) of the cumulative volume of the particles yielded the following values, respectively: 1.16  $\mu\text{m}$ , 18.99  $\mu\text{m}$  and 85.49  $\mu\text{m}$ . This result shows that volcanic ash particles are small in size, so their specific surface area would probably be high, which would play a key role in their reactivity during geopolymerization [15-17].

### 3.3. Physicochemical Characteristics of Laterite and Volcanic Ash

The absolute and apparent densities, apparent porosity, water content and specific surface area of laterite and volcanic ash have been determined and the results obtained are presented in Table 1.

It appears from this table that the absolute and apparent densities of laterite and volcanic ash are broadly similar. However, the absolute density is twice as high as the apparent density. This result was predictable because absolute density, unlike bulk density, does not take into account voids due to the material itself and those between the particles of the material. These density results reflect the heterogeneity of laterite and volcanic ash particles as shown by the particle size distribution curves [2, 18].

Examination of the water content of the different base materials shows that the water contents of laterite and volcanic ash are statistically similar, i.e., 7.33% and 8.00% respectively for laterite and volcanic ash. These differences in water content are due to the origin of these different basic materials. Indeed, the water content of volcanic ash and laterite would come from the nature of these materials. However, the drying phenomenon is attributed to the departure of free water contained in a material [19, 20], this result show that earth bricks will take some time to stabilize their mass during wet curing and dry curing.

Table 1. Physicochemical characteristics of laterite and volcanic ash.

|   | Laterite | Volcanic ash |
|---|----------|--------------|
| Absolut density ( $\text{g}/\text{cm}^3$ )  | 2.05     | 2.01         |
| Apparent density ( $\text{g}/\text{cm}^3$ ) | 1.18     | 0.98         |
| Water content (%)                           | 7.33     | 8.00         |
| Apparent porosity (%)                       | 4.18     | 7.52         |
| Specific area ( $\text{m}^2/\text{g}$ )     | 79.37    | 121.39       |

The values of the apparent porosity of laterite and volcanic ash are low (less than 8%). This result is a strong indication of the fact that there are very few voids in these materials and can be explained by the fact that these materials have a heterogeneous morphology which is an advantage during the densification. Indeed, during the densification phenomenon, small particles interlock in the voids created by the arrangement of large particles, improving their cohesion and leading to the obtaining of bricks with high mechanical and hydration stability [21, 22, 7].

The specific area is the surface area developed by a unit of mass of a material. This is an important parameter that influences the properties of a material, especially in surface reactions. Indeed, the reactivity of a material is strongly correlated with the fineness of its particles because the larger a specific surface area a material has, the more it interacts with other particles [15, 4]. The values of the specific areas evaluated are 79.37 and 121.39m<sup>2</sup>/g respectively for laterite and volcanic ash. These results were predictable in view of the particle size analysis of these materials, which showed that the large majority of volcanic ash has small particles compared to laterite. Thus, the smaller the particle size and the higher the specific surface area, the more likely the material is to react in the presence of the phosphoric acid activating solution. It is therefore certain that volcanic ash will react strongly with laterite particles by forming strong chemical bonds [10, 7].

### 3.4. Chemical Composition of Laterite and Volcanic Ash

The results of the chemical analyses, expressed in terms of the mass percentages of oxide present in the various materials studied, have been determined and the results obtained are presented in Table 2.

It appears from this table that silica, alumina and iron oxides (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, and Fe<sub>2</sub>O<sub>3</sub>) are the main oxides present in laterite and volcanic ash, the other oxides are considered to be minority and in trace. The high contents of silica and alumina oxides and the low values of their loss on ignition show that the laterite and volcanic ash studied are non-swelling materials and therefore suitable for the production of earth bricks [15, 7]. The SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> mass ratios are 1.50 and 2.71 respectively for laterite and volcanic ash. These reports confirm that volcanic ash could be suitable binder for geopolymerization as it is well known that for the production of earth bricks, the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> ratio must be greater than 2. This would promote the formation of geopolymer earth bricks with a 3-dimensional structure consisting of network repeating units of silicophosphate (Si-O-P), aluminophosphate (Al-O-P) and silico-aluminophosphate (Si-O-P-O-Al). However, the high iron oxide in basic materials could lead the formation of ferro-silico-aluminophosphate (Fe-O-P-Si-O-Al-O-P) in the network.

**Table 2.** Chemical composition.

| Oxides (%)                                       | Laterite | Volcanic ash |
|--|----------|--------------|
| SiO <sub>2</sub>                                 | 31.26    | 46.18        |
| Al <sub>2</sub> O <sub>3</sub>                   | 20.89    | 17.03        |
| Fe <sub>2</sub> O <sub>3</sub>                   | 36.83    | 12.56        |
| TiO <sub>2</sub>                                 | 3.32     | 2.81         |
| MnO <sub>2</sub>                                 | 0.04     | 0.19         |
| MgO  | 0.29     | 6.40         |
| CaO  | 0.03     | 6.94         |
| Na <sub>2</sub> O                                | < 0.004  | 3.42         |
| K <sub>2</sub> O                                 | 0.22     | 1.25         |
| SrO  | /        | 0.13         |
| SO <sub>3</sub>                                  | 0.04     | /            |
| Cr <sub>2</sub> O <sub>3</sub>                   | /        | /            |
| BaO  | /        | 0.08         |
| P <sub>2</sub> O <sub>5</sub>                    | 0.06     | 0.61         |
| ZrO <sub>2</sub>                                 | 0.13     | /            |
| LOI  | 6.87     | 0.63         |
| Total  | 99.98    | 99.92        |
| SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub> | 1.50     | 2.71         |

### 3.5. Implementation of the Composite Center Design in the Production of Compressed and Stabilized Earth Bricks by Geopolymerization

#### 3.5.1. Production Matrix

Table 3 presents the CSEB production experience matrix.

**Table 3.** Experimental matrix of production the CSEB.

| N° <sub>exp</sub> | Experimental Conditions |                     | CS <sub>Exp</sub> (Mpa) |
|-------------------|-------------------------|---------------------|-------------------------|
|                   | X <sub>1</sub> (%)      | X <sub>2</sub> (ml) |                         |
| 1                 | 0.08                    | 3.00                | 14.00                   |
| 2                 | 0.25                    | 3.00                | 10.00                   |
| 3                 | 0.08                    | 8.00                | 22.00                   |
| 4                 | 0.25                    | 8.00                | 22.00                   |
| 5                 | 0.05                    | 5.50                | 10.00                   |
| 6                 | 0.28                    | 5.50                | 2.00                    |
| 7                 | 0.17                    | 2.00                | 22.00                   |

| N <sup>o</sup> <sub>exp</sub> | Experimental Conditions |                     | CS <sub>Exp</sub> (Mpa) |
|-------------------------------|-------------------------|---------------------|-------------------------|
|                               | X <sub>1</sub> (%)      | X <sub>2</sub> (ml) |                         |
| 8                             | 0.17                    | 9.00                | 33.00                   |
| 9                             | 0.17                    | 5.50                | 20.00                   |
| 10                            | 0.17                    | 5.50                | 21.00                   |
| 11                            | 0.17                    | 5.50                | 19.00                   |
| 12                            | 0.17                    | 5.50                | 21.00                   |
| 13                            | 0.17                    | 5.50                | 20.00                   |

CS<sub>Exp</sub>: Experimental compressive strength.

It appears from this table that the compressive strengths of compressed and stabilized earth bricks vary according to the proportions of the different factors involved. These compressive strengths are between 2 and 33MPa. These values are all fitting the validation conditions meaning that the study model is valid. Table 4 presents the values of the validation indices.

**Table 4.** Validation of model.

|                 | Values | Validation conditions         |
|-----------------|--------|-------------------------------|
| R <sup>2</sup>  | 0.98   | > 90%                         |
| AAMD            | 0.01   | 0 ≤ AAMD ≤ 0.3                |
| Bf              | 1.01   | 0.75 ≤ Bf ≤ 1.25              |
| Af <sub>1</sub> | 1.01   | 0.75 ≤ Af <sub>1</sub> ≤ 1.25 |
| Af <sub>2</sub> | 1.05   | 0.75 ≤ Af <sub>2</sub> ≤ 1.25 |

### 3.5.2. Equation Model and Coefficients

The equation of the compressive strength model of compressed and stabilized earth bricks by geopolymerization is given by the following relationship:

$$Y_{CS} = 9.86 + 273 X_1 - 5.53 X_2 - 974 X_1^2 + 0.5940 X_2^2 + 4.71 X_1 X_2 \quad (6)$$

The coefficients of the compressive strength model in absolute value have been grouped in Table 5 for better analysis.

**Table 5.** Model coefficients in absolute value.

| Coefficients values           |      |
|-------------------------------|------|
| X <sub>1</sub>                | 273  |
| X <sub>2</sub>                | 5.53 |
| X <sub>1</sub> X <sub>2</sub> | 4.71 |
| X <sub>1</sub> <sup>2</sup>   | 974  |
| X <sub>2</sub> <sup>2</sup>   | 0.59 |
| Constant                      | 9.86 |

X<sub>1</sub>: Volcanic ash/laterite mass ratio; X<sub>2</sub>: Phosphoric acid.

It appears from this table that the main effect of the volcanic ash/laterite mass ratio (X<sub>1</sub>) is by far the dominant factor because it is 49 times greater than the main effect of the amount of H<sub>3</sub>PO<sub>4</sub> (X<sub>2</sub>). The interaction effect of the volcanic ash/laterite mass ratio and the amount of H<sub>3</sub>PO<sub>4</sub> is negligible compared to the effect volcanic ash/laterite mass ratio but significant compared to the effect of the amount of H<sub>3</sub>PO<sub>4</sub> because they are almost of the same order of magnitude. However, the quadratic effect of the volcanic ash/laterite mass ratio is very important compared to that of the amount of H<sub>3</sub>PO<sub>4</sub>. In short, it can be concluded that the factor that governs compressive strength is the volcanic ash/laterite mass ratio. This result is explained by the fact that volcanic ash is the main source of aluminosilicates needed for geopolymerization.

Indeed, during geopolymerization, phosphoric acid reacts with aluminosilicates by attacking the bonds between alumina, silica and oxygen atoms. H<sub>3</sub>PO<sub>4</sub> protonates the basic sites of the structure, facilitating bond breaking and releasing aluminate and silicate ions. These ions then rearrange to form new bonds called phosphate bridges, leading to the formation of a three-dimensional polymeric structure that improves the mechanical properties of the bricks [15, 10]. However, this variation in compressive strength is not linear because it follows the influence of the amount of H<sub>3</sub>PO<sub>4</sub> due to the interaction effect of the volcanic ash/laterite mass ratio and the amount of H<sub>3</sub>PO<sub>4</sub> which is significant and the important quadratic effect of this mass ratio.

### 3.5.3. Response Surface and Isoresponse Curve of the Production of CSEB

The isoresponse surface of compressive strength is shown in figure 3.

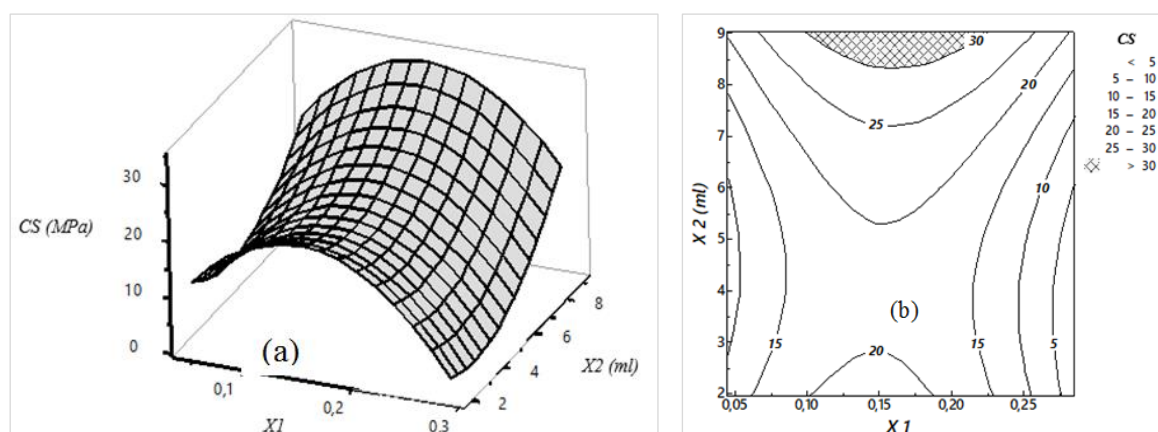


Figure 3. Response surface (a) and isoresponse curve (b) of CSEB.

Overall, it appears from this figure that the increase in the volcanic ash/laterite mass ratio improves the compressive strength which passes through a threshold beyond which this resistance drops. This improvement is explained by the fact that  $\text{H}_3\text{PO}_4$  activates the aluminosilicates of volcanic ash, which creates cohesive three-dimensional polymeric structures with laterite particles. This decrease in compressive strength after a certain threshold time can be explained by the fact that an excess of volcanic ash will lead to saturation of aluminosilicates leading to a disruption of the balance of geopolymerization reactions, resulting in the formation of a less cohesive structure or the appearance of microcracks [7, 5]. Moreover, the excess of volcanic ash modifies the porosity of the bricks, thus affecting their density and mechanical strength.

On the other hand, the increase of amount  $\text{H}_3\text{PO}_4$  in the mixture of the basic constituents gradually improves the compressive strength. This improvement is explained by the fact that the acid promotes cohesion between laterite and volcanic ash particles and thus improves the desired compressive strength. The interaction between the volcanic ash/laterite mass ratio and the amount of  $\text{H}_3\text{PO}_4$ , improves the compressive strength in its low values up to a certain extent and then unfavors it. There would therefore be a threshold of proportionality between the volcanic ash/laterite mass ratio of and the amount of  $\text{H}_3\text{PO}_4$  leading to the achievement of maximum compressive strength [7, 3]. The nonlinearity of the compressive strength is shown in figure 3(b) of iso-response. In this figure, the optimal resistance zone is shown in grey. It can be observed that the bricks in this zone have theoretical compressive strengths of more than 30MPa. In this area, the optimum point of production of compressed and stabilized earth bricks has therefore been deduced.

It appears from this optimal zone that the CSEB for a volcanic ash/laterite mass ratio of 0.16 and an amount of  $\text{H}_3\text{PO}_4$  of 8.69 ml the CSEB have a theoretical compressive strength of 33.92MPa, that obtained experimentally is 32MPa.

### 3.6. Physicochemical and Mechanical Characteristics of the CSEB Obtained Under Optimal Conditions

#### 3.6.1. Linear Shrinkage

The linear shrinkage of the CSEB during the wet and dry curing was evaluated, the following figure presents the results obtained. It can be seen from this figure that the linear shrinkage during the wet curing is much lower than that during the dry curing. i.e 0.52% and 1.11% respectively for the shrinkage during the wet curing and the dry curing of the CSEB. This observation is justified by the fact that, during the wet curing, the CSEB are covered with plastic film to create a humid environment. The relative humidity of the ambient air inside the plastic film enclosure tends to rise and can reach 100%.

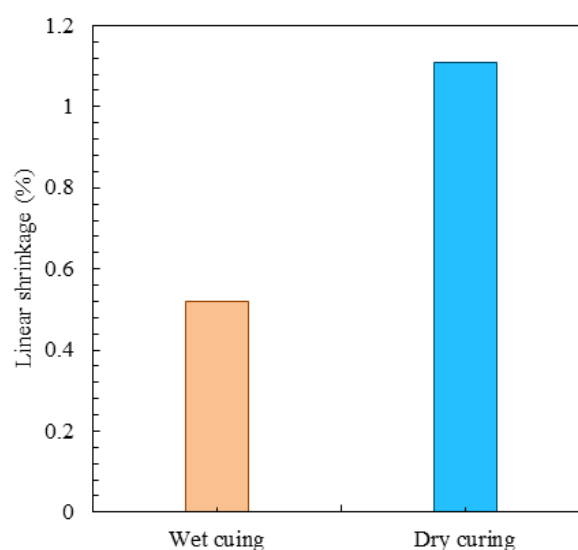


Figure 4. Linear shrinkage of CSEB during the different curing.

The evaporation of the free water contained in the CSEB

ends up creating an equilibrium with the ambient atmosphere. At steady state, the linear shrinkage is maximum. The high shrinkage during dry curing is a strong indication of the fact that during dry curing, the ambient atmosphere being relatively dry, the free water contained in the CSEB will be able to evaporate until it is exhausted in the material. During the various curing bonds are created between the laterite and volcanic ash particle indicating that the geopolymerization process is still ongoing. The particles move closer together to form a three-dimensional geopolymer structure of the Si-O-P, Al-O-P and Si-O-P-O-Al types thus, making the brick stable and more compact [23, 24].

### 3.6.2. Hydration Behavior

Figure 5 shows the evolution of water uptake by capillary action (a) and total immersion (b) of the CSEB.

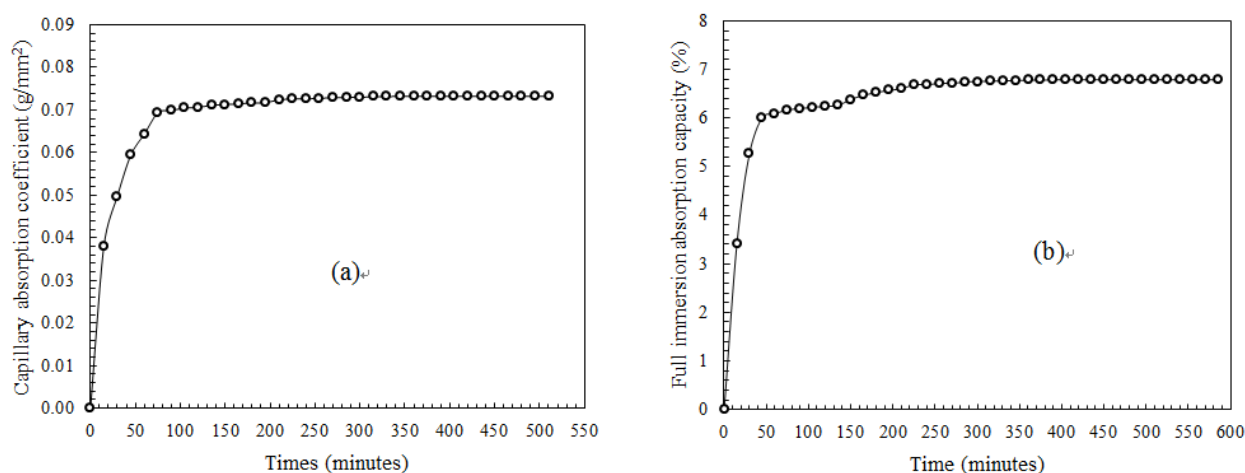


Figure 5. Water absorption by capillary (a) and water absorption by total immersion (b).

Overall, it appears from the Figure 5(b) that the water absorption capacity by total immersion is less than 7%, which is in accordance with the CRAterre recommendation, which stipulate that the absorption by total immersion of a stabilized brick must be less than or equal to 15%. The wet compressive strength is 28.8MPa, i.e. there is a 10% reduction in the dry strength of our material. This decrease in strength is explained by the fact that when water is in contact with the material, it weakens the structure of the material [28, 29].

## 4. Conclusion

The central composite design was used to model and optimize the production of compressed stabilized earth bricks (CSEB) by geopolymerization. The analysis of the physico-chemical properties of raw materials confirmed that the particle size distribution of laterite falls within the recommended grading spindle for materials suitable for compressed stabi-

lized earth bricks. Both laterite and volcanic ash exhibit heterogeneous particle morphologies and are mainly composed of silica, alumina, and iron oxides, compounds favorable to geopolymerization. The use of a central composite design revealed that the compressive strength of the CSEB is governed by the main effect of the volcanic ash/laterite mass ratio, as it is 49 times greater than the main effect of the amount of H<sub>3</sub>PO<sub>4</sub>. However, due to the significant interaction effect between the volcanic ash/laterite mass ratio and the amount of H<sub>3</sub>PO<sub>4</sub>, and the important quadratic effect of the volcanic ash/laterite mass ratio, the variation in compressive strength is not linear. Optimal production conditions, defined by a volcanic ash/laterite mass ratio of 0.16 and 8.69 mL of phosphoric acid, led to a maximum compressive strength of 32MPa. Hydration behavior analysis showed that the bricks absorb water due to porosity, but absorption by capillarity and total immersion remains limited. Mechanical tests under wet conditions demonstrated a compressive strength reduction of

approximately 10% compared to the dry state, yet the strength remains within acceptable limits. Overall, geopolymerization enhances both the mechanical performance and water resistance of the produced CSEBs.

## Abbreviations

|                   |   |
|-------------------|---|
| CSEB              | Compressed and Stabilized Earth Brick   |
| MPa               | Mega Pascal                             |
| CS                | Compressive Strength                    |
| CS <sub>Exp</sub> | Experimental Compressive Strength       |
| CRAterre          | Earthen Research and Application Center |

## Author Contributions

**Tekoumbo Tedontsa Larissa Canuala:** Methodology, Writing -original draft, Data curation, Investigation

**Taybe Ngaba:** Resources, Formal Analysis, Methodology

**Adatz Jean Claude Jean Claude De Tout:** Investigation, Resources

**Fognaba Honor é** Data curation, Formal Analysis

**Bike Mbah Jean Baptiste:** Conceptualization, Methodology, Writing -original draft, Supervision, Validation, Data curation

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## Data Availability Statement

The data is available from the corresponding author upon reasonable request.

## Conflicts of Interest

The authors declare no conflicts of interest.

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