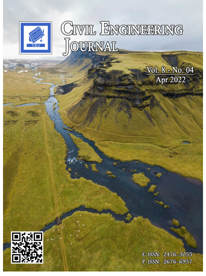
Available online at www.CivileJournal.org

# Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 8, No. 04, April, 2022



# Mechanical Properties of Compressed Earth Block Stabilized with Sugarcane Molasses and Metakaolin-Based Geopolymer

Ismaël Dabakuyo [1*], Raphael N. N. Mutuku [2], Richard O. Onchiri [2]

[1] *MSc, Department of Civil and Construction Engineering, Pan African University Institute for Basic Sciences, Technology and Innovation Hosted at Jomo Kenyatta University of Agriculture and Technology, Kenya.*

[2] *Department of Building and Civil Engineering, Technical University of Mombasa, Mombasa, Kenya.*

Received 07 January 2022; Revised 14 March 2022; Accepted 19 Marh 2022; Published 01 April 2022

**Abstract**

This research aims to investigate the mechanical performance of compressed earth blocks (CEBs) stabilized by a combination of metakaolin-based geopolymer (MKG) and sugarcane molasses (SM), to remedy the limitations present in CEBs stabilized with MKG alone. Two schemes of stabilization were used. In the first, the optimum MKG content for stabilizing CEB was partially substituted with various percentages of SM (10% MKG + 0% SM, 8% MKG + 2% SM, 6% MKG + 4% SM, 4% MKG + 6% SM, 2% MKG + 8% SM). The second stabilization scheme consisted of fixing 5% MKG and varying SM from 2% to 8% (5% MKG + 0% SM, 5% MKG + 2% SM, 5% MKG + 4% SM, 5% MKG + 6% SM, 5% MKG + 8% SM). The mechanical properties of the CEBs stabilized with SM and MKG were analyzed in terms of compressive strength, dry density, and water absorption. The test results showed that the combination of MKG and SM for stabilizing CEBs was not as effective as MKG alone in increasing the compressive strength of CEBs. However, this combination solved the high porosity of CEBs stabilized with just MKG by increasing their dry density and decreasing their water absorption capacity. In terms of compressive strength and water absorption, the optimum values were obtained respectively with 5% MKG + 4% SM (4.163 MPa at 28 days) and 6% MKG + 4% SM (8.73% at 28 days). Therefore, the suggested innovative stabilization approach is suitable for improving the overall mechanical properties of CEBs and addressing the shortcomings of CEBs stabilized only with MKG.

*Keywords:* Sugarcane Molasses; Metakaolin-Based Geopolymer; Compressed Earth Block; Compressive Strength; Water Absorption.

## 1. Introduction

From the dawn of mankind, people have used the earth as their paramount building material because of its affordability and maneuverability. Throughout history, the world has known different types of earthen construction. The traditional techniques of earthen construction included, among others, cob construction, adobe construction, poured earth construction, wattle and daub, and rammed earth construction [1]. Nowadays, earthen structures are being overshadowed by the emergence of cement. Despite this, there are still earthen constructions because not everybody can afford the modern houses made of cement since they are costly. As a direct consequence, there is a renewed interest in using the earth as a building material, particularly in undeveloped countries like African countries. Due to this context, modern earthen constructions, such as CEB, have arisen. The CEB is a masonry element made by compressing moist soil, in a mold. This process is a modern evolution of adobe, which employs sophisticated machinery to produce

* Corresponding author: dabakuyo.ismael@students.jkuat.ac.ke

http://dx.doi.org/10.28991/CEJ-2022-08-04-012

flawlessly calibrated pieces. The manufacture of CEBs follows specific product quality control standards. The clay in the soil is the principal binder for CEBs. Nevertheless, in their natural state, CEBs are prone to the whims of nature, particularly when it rains. Therefore, another type of binder is usually introduced to enhance its performance. This procedure is called stabilization. The most prevalent binders used for CEB stabilization are cement [2–4] and lime [5, 6]. However, due to their energy-intensive manufacturing processes, cement and lime production are some of the most significant contributors to global greenhouse gas emissions. Over 6% of global warming and anthropogenic greenhouse gas emissions are caused by the cement industry [7]. Regarding lime, in China (the world's largest energy consumer and generator of $CO_2$), lime production is the second most significant source of carbon emissions from industrial processes [8]. Therefore, there is a craze for more ecological perspectives than just cement and lime stabilization. The emergence of geopolymers as an alternative to cement arose from this viewpoint.

Geopolymers are alkali-activated materials obtained from an aluminosilicate source [9]. Contrary to cementitious materials, geopolymers need an alkali solution to harden. Sodium hydroxide (NaOH), sodium sulphate ($Na_2SO_4$), sodium silicate (waterglass), sodium carbonate ($Na_2CO_3$), potassium carbonate ($K_2CO_3$), potassium hydroxide (KOH), and potassium sulphate ($K_2SO_4$) are popular activators used in the geopolymerization process [10, 11]. On the other hand, the aluminosilicate sources used to synthesize geopolymers include industrial wastes such as rice husk ash, fly ash, blast furnace slag, and natural and synthetic materials like kaolin and metakaolin. Geopolymers have distinct benefits in hardening rate, strength and corrosion resistance, and durability [12]. Geopolymers are also thermally stable and resistant to high temperatures [13]. The most common aluminosilicate source for making geopolymers is metakaolin. Metakaolin is widely used for making geopolymer because it is a purer, more easily defined starting material for geopolymerization [14]. Furthermore, metakaolin is more environmentally friendly. For example, in equal quantities, the production of metakaolin produces 54% less $CO_2$ than the production of cement [15]. Nowadays, geopolymers are seen as an alternative to cement in stabilizing CEBs. Unlike Portland cement, which has calcium silicate hydrate (CSH) as its main binding element, the binding constituent of geopolymers comes from the formation of the geopolymer gel (Sodium Aluminosilicate Hydrate N-A-S-H). Recent studies have shown the effectiveness of MKG in soil and CEB stabilization.

Sore et al. [16] investigated the feasibility of using MKG for stabilizing CEBs. By stabilizing CEBs with different amounts of MKG varying from 5% to 20% with a 5% rate of increase, they noted that the use of MKG as a stabilizer increases the compressive strength of the stabilized CEBs. However, the CEBs stabilized with MKG were highly porous with increasing MKG content. Furthermore, Zhang et al. [17] studied the feasibility of adopting a geopolymer made with metakaolin as a new soil stabilizer generation. The study consisted of stabilizing soil with a varied amount of MKG, ranging from 3% to 15%. As a result, they found that the soil stabilized with more than 11% MKG displayed an unconfined compressive strength (UCS) higher than that of the natural soil and the soil stabilized with 5% cement. With increasing MKG concentrations, the compressive strength of stabilized soils rose. Nonetheless, it appears that, as compared to stabilization with cement, a higher amount of MKG is needed to stabilize soils effectively.

Additionally, Dukuly et al. [18] have evaluated the use of MKG as a stabilizing agent for expansive soil by stabilizing expansive soil with 5%, 10%, and 15% MKG. They have found that the expansive soil's PI (Plasticity Index) is decreased immediately with the use of geopolymer as a stabilizer. MKG was also found to increase the UCS of the control soil, decrease its swell potential and shrinkage, and enhance its CBR (Californian Bearing Ratio).

In general, MKG has been found to enhance the mechanical properties of soils and CEBs and provide them with good cohesion. On the other hand, CEBs stabilized with MKG have some shortcomings like any building material. The CEBs stabilized with MKG are highly porous, which affects their stability in water [16]. In addition, it appears that a hefty dose of MKG is needed to stabilize the soil, which can be costly [17, 19, 20]. This study aims to address these issues that are encountered with CEBs stabilized with MKG.

Recently, the emerging trend in stabilizing CEBs is to promote the reuse of industrial waste products. This method helps tackle the high expense of conventional stabilizers. SM, a byproduct of the sugar refining process, is among the industrial wastes that have been shown to improve the mechanical characteristics of CEBs. Mandala et al. [21] investigated the mechanical properties of earth blocks stabilized with SM by varying the percentage of SM from 4% to 12% with a 4% increase rate. This study revealed that SM increases the compressive strength of the stabilized earth blocks. Therefore, Mandala et al. [21] recommended it for earth block stabilization.

In addition to being good at improving the mechanical properties of CEBs, SM also improves the process of geopolymerization. In their study on the durability of geopolymer concrete, Karthik et al. [22] concluded that the inclusion of bio-additive (SM) in geopolymer concrete reduces porosity and facilitates ambient temperature curing. Therefore, by combining MKG with SM during the stabilization process of CEBs, it can be possible to address the high porosity of those stabilized with MKG alone.

Although current studies have shown the effectiveness of SM in making geopolymer concrete at ambient temperature and for stabilizing earth blocks, there is a limitation of information about studies providing experimental evidence for the combination of MKG and SM for stabilizing CEBs. This current research effort is a novel approach for stabilizing CEBs by combining MKG with SM to address the shortcomings of CEBs stabilized with only MKG and improve the overall mechanical properties of such blocks.

## 2. Materials and Methods

### 2.1. Materials

***Laterite Soil***

Soil is the main component in making CEBs. In this study, laterite soil was used for that purpose. The laterite soil used for this investigation came from the farm of Jomo Kenyatta University of Agriculture and Technology. The sieve analysis results, displayed in Table 1, reveal the particle size distribution of the laterite soil. The laterite soil was classified as "Silty Sandy GRAVEL" since it was composed of 75% gravel, 18% sand, and 7% silt.

**Table 1. Sieve analysis results**

| Sieve Size (mm) | Weight of Sieve and Soil (g) | Weight of Sieve only (g) | Weight of Soil Retained on sieve (g) | Cumulative Weight Retained (g) | Soil Retained on Sieve (%) | Soil Passing Sieve (%) |
|---|---|---|---|---|---|---|
| 50.8 | 542.94 | 542.94 | 0.00 | 0.00 | 0.00 | 100.00 |
| 38.1 | 514.84 | 514.84 | 0.00 | 0.00 | 0.00 | 100.00 |
| 25.4 | 576.83 | 525.06 | 51.77 | 51.77 | 3.311 | 96.69 |
| 19.1 | 643.64 | 574.04 | 69.60 | 121.37 | 7.763 | 92.24 |
| 9.52 | 834.33 | 518.26 | 316.07 | 437.44 | 27.978 | 72.02 |
| 4.76 | 859.05 | 472.68 | 386.37 | 823.81 | 52.690 | 47.31 |
| 2.00 | 815.95 | 460.68 | 355.27 | 1179.08 | 75.413 | 24.59 |
| 0.84 | 590.42 | 412.00 | 178.42 | 1357.50 | 86.825 | 13.18 |
| 0.42 | 484.20 | 403.46 | 80.74 | 1438.24 | 91.989 | 8.01 |
| 0.25 | 428.38 | 381.88 | 46.50 | 1484.74 | 94.963 | 5.04 |
| 0.105 | 405.41 | 358.18 | 47.23 | 1531.97 | 97.984 | 2.02 |
| 0.074 | 386.60 | 360.60 | 26.00 | 1557.97 | 99.647 | 0.35 |
| Pan | 356.25 | 350.72 | 5.53 | 1563.50 | 100.00 | 0.00 |

***Geopolymer Binder***

The geopolymer used to stabilize CEBs was MKG. It was made of metakaolin, used as an aluminosilicate source, and sodium hydroxide (NaOH) as the activation solution. The metakaolin used in this study was created by transforming local kaolin through a sequence of modifications. Firstly, the kaolin was crushed and ground into powder. Following that, it was sieved through a 75 µm sieve. Finally, the metakaolin was created by calcining the kaolin powder at 650 °C for 1 hour and 30 minutes. Figure 1 illustrates the process of manufacturing metakaolin. The activation solution was made of caustic soda of 99% purity. The caustic soda flakes were dissolved in distilled water so that the final concentration of the NaOH solution was 12M.


**Figure 1. Metakaolin manufacturing process**

### *Sugarcane Molasses*

The SM used in this study was purchased from a Kenyan wholesaler in Kiambu County, specifically in Juja. Figure 2 depicts SM used in this study.

**Figure 2. Sugarcane molasses**

## 2.2. Methods

### *Blocks Production*

The production of blocks included a series of steps. The first step consisted of the preparation of the soil. The soil used for block production was sieved through a 5 mm sieve. After that, the laterite soil was mixed with varying amounts of metakaolin in the second step. Table 2 illustrates the various mixing scenarios in making blocks. Next, the third step involved the preparation of the sodium hydroxide solution (activation solution) of 12M by diluting caustic soda in distilled water. Then, the alkaline solution was added to the dry mixture of laterite soil and metakaolin with an alkaline solution/metakaolin ratio of 0.8. The entire mixture was then carefully mixed. In the fourth step, SM was added in various amounts, as shown in Table 2. In the fifth step, water was added. The amount of water needed was the optimum water content obtained during the compaction test on different percentages of MKG and SM. For homogeneity, the whole sample was mixed after the addition of SM and again after the addition of water. Afterwards, the sixth step involved the production of the blocks using the manual press machine. Before making the blocks, the press machine was lubricated with drain oil. The homogeneous mixture was then compressed into the mold to make the blocks. Finally, the seventh step consisted of the curing of the CEBs. Following production, the blocks were covered with polystyrene for 24 hours and allowed to air-dry until testing. Figure 3 depicts the production of the compressed earth blocks.

**Table 2. Schemes for stabilizing CEBs**

| Production of blocks by replacing the optimum MKG content (10%MKG) with SM | | | | |
|---|---|---|---|---|
| Binder | | Laterite soil | Water | Designation |
| MKG | SM | | | |
| 10% | 0% | Constant | OMC | 10%MKG+0%SM |
| 8% | 2% | Constant | OMC | 8%MKG+2%SM |
| 6% | 4% | Constant | OMC | 6%MKG+4%SM |
| 4% | 6% | Constant | OMC | 4%MKG+6%SM |
| 2% | 8% | Constant | OMC | 2%MKG+8%SM |
| **Production of blocks by fixing 5% MKG and varying SM from 0 to 8%** | | | | |
| **Binder** | | **Laterite soil** | **Water** | **Designation** |
| **MKG** | **SM** | | | |
| 5% | 0% | Constant | OMC | 5%MKG+0%SM |
| 5% | 2% | Constant | OMC | 5%MKG+2%SM |
| 5% | 4% | Constant | OMC | 5%MKG+4%SM |
| 5% | 6% | Constant | OMC | 5%MKG+6%SM |
| 5% | 8% | Constant | OMC | 5%MKG+8%SM |


**Figure 3. Blocks production process**

### *Chemical Characterization of Basic Materials*

The basic materials' chemical compositions were established to quantify the distinct chemical elements as a percentage of the mass of their oxides. The chemical compositions of the materials were determined using the X-ray fluorescence (XRF) approach in this investigation. A primary X-ray source was used to excite the samples, and then the excited samples released a fluorescence X-ray. Finally, the XRF analyzer detected the fluorescence X-ray, which determines the chemistry of the samples.

### *Mechanical Properties of CEBs*

The mechanical properties of the CEBs stabilized by combining MKG with SM were investigated in terms of compressive strength, dry density, and water absorption. The blocks were tested at 7, 14, and 28 days old. The compressive strength test was carried out following the requirements of the British Standard (BS EN 772-1, 2011). It was conducted using the Universal Testing Machine (UTM). The compressive strength was calculated using the following formula:

$$\sigma = \frac{F}{S} \quad (1)$$

where σ was the maximum stress; F was the maximum load; and S was the loaded area. Figure 4 depicts the compressive strength test of blocks.

(a) Block sandwiched between the trays of the UTM for compression test

(b) Block after compression test

**Figure 4. Compressive strength test procedure**

Regarding the dry density of the CEBs determination, it has been conducted according to the requirements of the Nigerian Industrial Standard (NIS 87, 2004). The dry density of blocks was computed as follows:

$$\gamma_d = \frac{W_d}{V} \quad (2)$$

where $W_d$ was the weight of the dry sample (kg); V was the volume of the blocks ($m^3$); and $\gamma_d$ was the dry density of the blocks ($kg/m^3$). Figure 5 shows the procedure for the determination of the dry density.

(a) Drying in oven

(b) Dry weight

**Figure 5. Determination of the dry density of CEBs**

The water absorption of the CEBs was determined per the British Standard 1377 (1967). Figure 6 illustrates the procedure of the water absorption test. The following formula was used to calculate the water absorption:

$$M_c = \frac{(W_a - W_b)}{W_b} \times 100 \quad (3)$$

where $W_a$ is Mass of the block after absorption, $W_b$ is Mass of the block before absorption, and $M_c$ is Percentage moisture absorption on dry basis (%).

(a) Drying in oven

(b) Dry weight

(c) Immersion in water for 24 hours

(d) Weight after immersion in water

**Figure 6. Water absorption test procedure**

# 3. Results and Discussion

## 3.1. Chemical Characteristics of Basic Materials

### *Laterite Soil*

The XRF analysis carried out on the laterite soil showed that its major components are $SiO_2$ (56.77%), $Fe_2O_3$ (19.69%), and $Al_2O_3$ (17.26%). For soil to be classified as lateritic soil, the silica-sesquioxide ratio ($SiO_2$/ ($Fe_2O_3$ + $Al_2O_3$)) should lie between 1.33 and 2 [23]. The silica-sesquioxide ratio of the soil used in this study was 1.54. This result confirmed that the soil used in making CEBs was lateritic soil. Table 3 illustrates the chemical composition of the laterite soil.

**Table 3. Laterite soil's chemical composition**

| Element Name | Percentage (%) |
|---|---|
| $Al_2O_3$ | 17.26 |
| $SiO_2$ | 56.77 |
| Cl | 0.04 |
| $K_2O$ | 1.22 |
| CaO | 0.78 |
| Mn | 2.29 |
| $Fe_2O_3$ | 19.69 |

### *Metakaolin*

The XRF analysis performed on the metakaolin showed that it was mainly composed of $SiO_2$ (73.30%), $Al_2O_3$ (14.88%), and $Fe_2O_3$ (5.52%). Additionally, $SiO_2$ + $Al_2O_3$ + $Fe_2O_3$ (93.70%) is greater than 70%. Therefore, this metakaolin was classified as class N pozzolan according to the requirements of the standard ASTM C-618. Table 4 illustrates the chemical composition of the metakaolin used in this study.

**Table 4. Metakaolin's chemical composition**

| Element Name | Percentage (%) |
|---|---|
| $Al_2O_3$ | 14.88 |
| $SiO_2$ | 73.30 |
| $P_2O_5$ | 0.11 |
| Cl | 0.01 |
| $K_2O$ | 4.70 |
| CaO | 0.51 |
| $Fe_2O_3$ | 5.52 |

### *Sugarcane Molasses*

The chemical characteristics of the SM used in this study is summarized in Table 5.

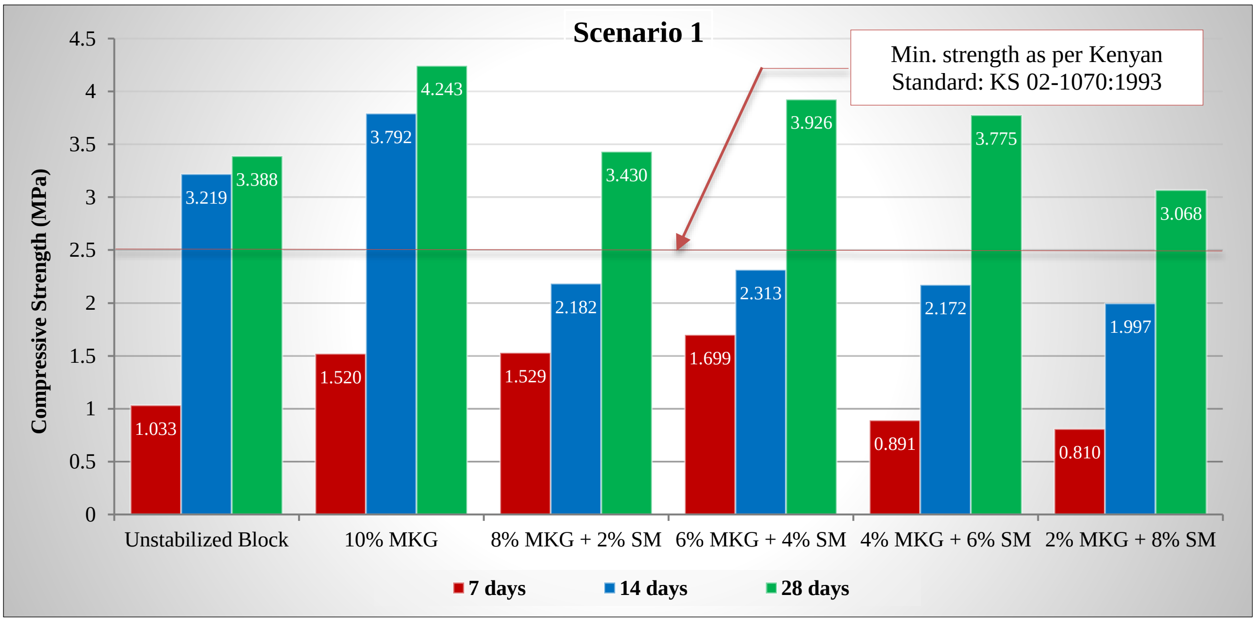
**Table 5. Chemical characteristics of sugarcane molasses**

| Element Name | Percentage (%) |
|---|---|
| Magnesium | 11.0 |
| Potassium | 5.8 |
| Calcium | 3.4 |
| Manganese | 12.8 |
| Copper | 11.6 |
| Iron | 70.0 |
| Glucose | 12.2 |
| Fructose | 12.8 |
| Crude Protein | 5.6 |
| Sucrose | 18.2 |
| Magnesium Oxide | 1.88 |
| Calcium Oxide | 0.75 |
| Potassium Oxide | 36.0 |
| Sodium Oxide | 6.3 |

## 3.2. Mechanical Properties of CEBs Stabilized by Combining MKG with SM

### *Compressive Strength*

Compressive strength is one of the most important parameters considered in assessing the mechanical properties of CEBs. The minimum compressive strength recommended by the Kenyan standard (KS 02-1070:1993) for earth blocks is 2.5 MPa. The results of the compressive strength test are illustrated in Figure 7. It should be noted that the compressive strength of all the CEBs increased as the curing period increased. The higher value of the compressive strength of the un-stabilized CEBs was 3.388 MPa and was achieved at 28 days.



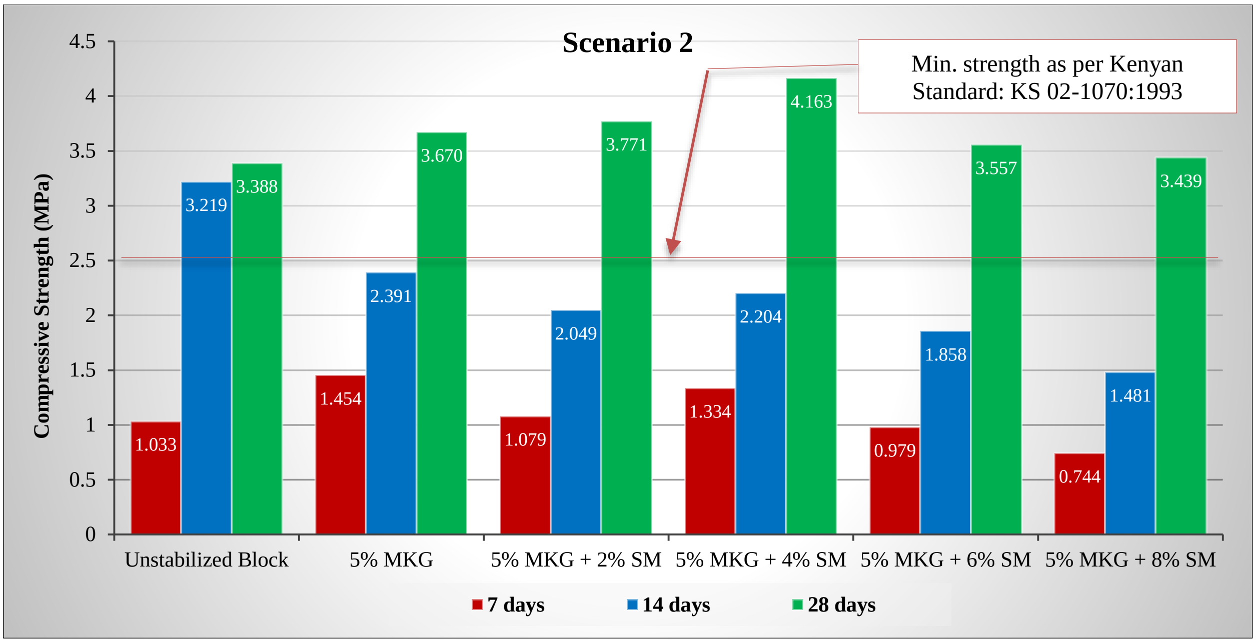



**Figure 7. Compressive strength of SCEBs**

In scenario 1 of stabilization, the CEBs stabilized with 10% MKG showed a compressive strength increase rate of 25.24% at 28 days. This increase in the compressive strength of the CEBs stabilized with MKG is consistent with the findings of Tchouateu et al. [24] in their experimental investigation of the physicomechanical, structural, and microstructural properties of CEBs stabilized by pozzolana-based phosphate geopolymer. The increase in the compressive strength of the CEBs stabilized with 10% MKG is credited to the formation of geopolymer gels that bind the soil particles together, making the sample more resistant [16]. The partial replacement of this optimum MKG content with SM displayed a smaller compressive strength. Thus, the compressive strength of CEBs stabilized with 10% MKG decreased from 4.243 MPa to 3.430 MPa for CEBs stabilized with 8% MKG + 2% SM at 28 days. As the rate of replacement of the MKG with SM increased, the compressive strength of the blocks increased but remained less than that of CEBs stabilized with 10% MKG. Above an optimum replacement of 4% of MKG by SM, the compressive strength of the CEBs dropped.

On the other hand, in scenario 2 of stabilization, it should be noted that the CEBs stabilized with 5% MKG displayed a compressive strength increase rate of 8.32% at 28 days. This trend is also in accordance with the study of Tchouateu et al. [24]. It can be attributed to the formation of geopolymer gels that bind the soil particles together, making the sample more resistant [16]. Then, it should be highlighted that the addition of SM to 5% MKG for stabilizing CEBs enhanced their compressive strength more than the use of 5% MKG alone. As the percentage of SM increased, the compressive strength of the CEBs increased too. The highest compressive strength value of 4.163 MPa was obtained with 5% MKG + 4% SM at 28 days. Above 4% of SM, the compressive strength of the stabilized compressed earth blocks (SCEBs) dropped.

From all the two stabilization scenarios, in terms of compressive strength, the optimum MKG and SM content for stabilizing CEBs was 5% MKG + 4% SM (4.163 MPa at 28 days). In general, it should be deduced from the results of the two scenarios of stabilization that SM is not as effective as MKG in increasing the compressive strength of CEBs. However, the combination of MKG and SM for stabilizing CEBs is useful in improving the compressive strength of CEBs. This result matches the finding of Mandala et al. [21] in which the use of SM for stabilizing earth blocks have enhanced their compressive strength. The increase of the compressive strength of the CEBs stabilized by combining MKG with SM is due to the combined action of the development of the geopolymer gel and the adhesive properties of SM. Indeed, the adhesive properties of SM, derived from the hydrogen bonds found in its sucrose, also enhance the electrochemical attraction within soil particles and bind them together [25]. As a result, the SCEBs produced are more compact and resistant. Nevertheless, the combination of more than 4% SM with MKG for stabilizing CEBs has been found to reduce the compressive strength of the SCEBs. This result is because the high amount of SM combined with MKG for stabilizing CEBs has coated the soil-geopolymer matrix, which inhibits the electrochemical attraction between soil particles and the geopolymer. The bond formed by the adhesive properties of SM then acts alone, but it is insufficiently strong to withstand higher loads applied to the CEBs. It should also be highlighted that at 28 days, all the CEBs had a compressive strength higher than the minimum value recommended for CEBs (2.5 MPa) by the Kenyan standard. Therefore, these SCEBs can be recommended for construction purposes.

### *Dry Density*

The results of the dry density of the CEBs are depicted in Figure 8. It should be noted that the CEBs stabilized with both MKG and SM were denser than those that were un-stabilized, and the ones stabilized only with MKG. The evolution of the dry density of each type of SCEB as a function of the curing period did not show a specific trend. This is because 100% mixing homogeneity is practically impossible to achieve during CEB production. However, it should be noted that the dry density of the CEBs decreased with the increase in MKG content. This outcome is in accordance with the findings of Sore et al. [16]. The decrease in the dry density of the CEBs stabilized with MKG is related to the development of porosity, which results from an increase in weight loss as the amount of geopolymer used for stabilizing the CEBs increases [16].

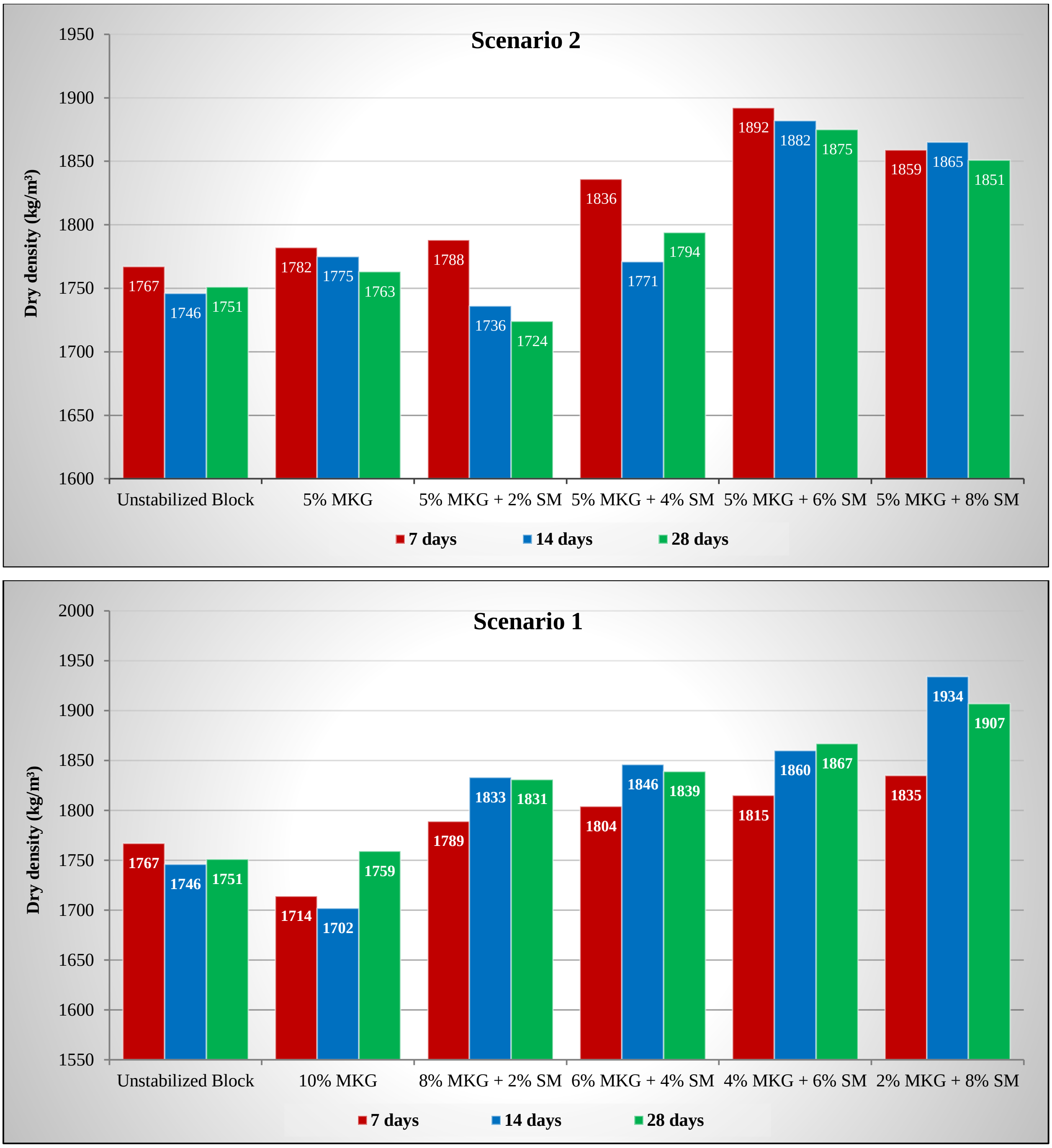



**Figure 8. Dry density of SCEBs**

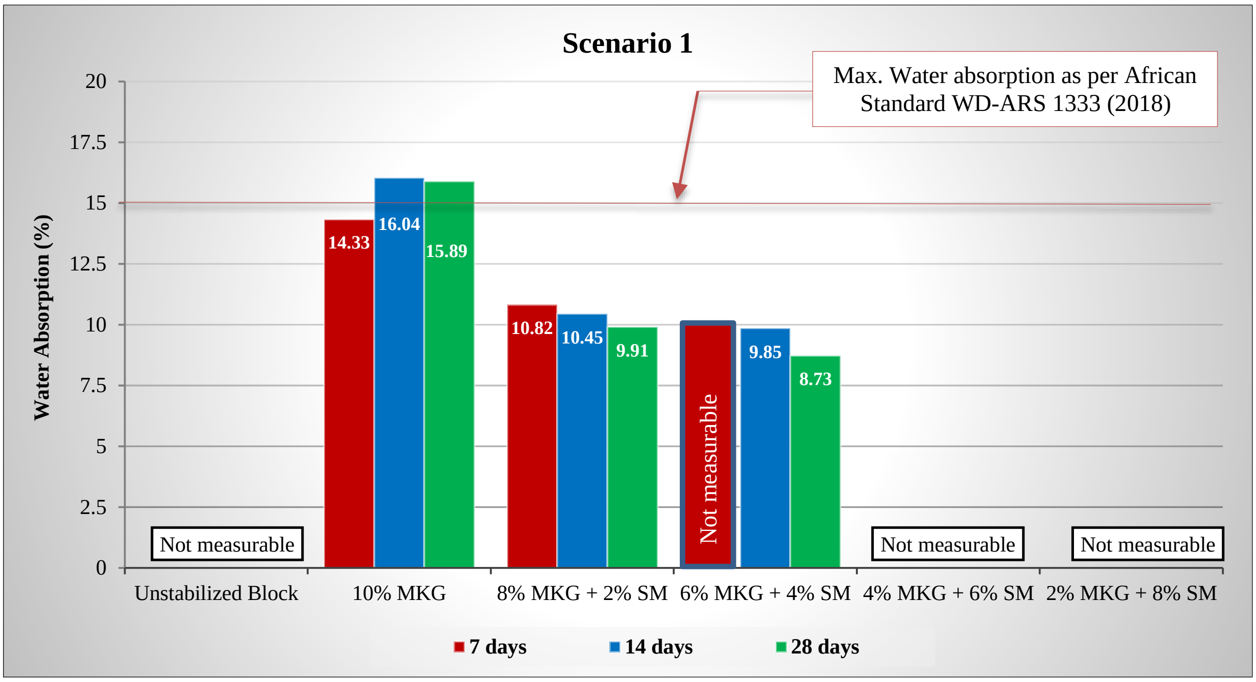
Nevertheless, in scenario 1 of stabilization, it should be highlighted that the dry density of the blocks increased as the percentage of SM used as a partial replacement of MKG increased. At different ages, the CEBs stabilized with SM as a partial replacement of MKG had a higher dry density than those stabilized with only 10% MKG (the optimum MKG content for stabilizing CEBs). The CEBs stabilized with 2% MKG + 8% SM displayed the highest dry density.

The same trend was also observed in scenario 2 of stabilization. The density of the SCEBs increased as the percentage of SM added to 5% MKG, for stabilizing CEBs, increased. The CEBs stabilized with 5% MKG + 6% SM displayed the optimum value. The combination of more than 6% SM with 5% MKG for stabilizing CEBs dropped the dry density of the SCEBs. However, it remained higher than that of CEBs stabilized with 5% MKG alone.

It is also interesting to note that the dry density of all the SCEBs was consistent with the study of Riza et al. [26], which located the suitable range for the dry density of earthen blocks within 1500 kg/m³ and 2000 kg/m³. Generally, the increase in the dry density of the CEBs stabilized by combining MKG and SM compared to that of CEBs stabilized with just MKG, may be explained by the adhesive properties of SM, which enhance the electrochemical attraction and bind aggregated soil particles together [25]. Therefore, it should be deduced that the combination of MKG with SM effectively addresses the high porosity of CEBs stabilized with MKG alone and makes them more compact and denser.

***Water Absorption***

The water absorption test results are shown in Figure 9. For earthen blocks to be adopted for construction, their water absorption should be less than or equal to 15% [27]. These results showed that the un-stabilized CEBs were not stable in water, and therefore, their water absorption was not measurable.



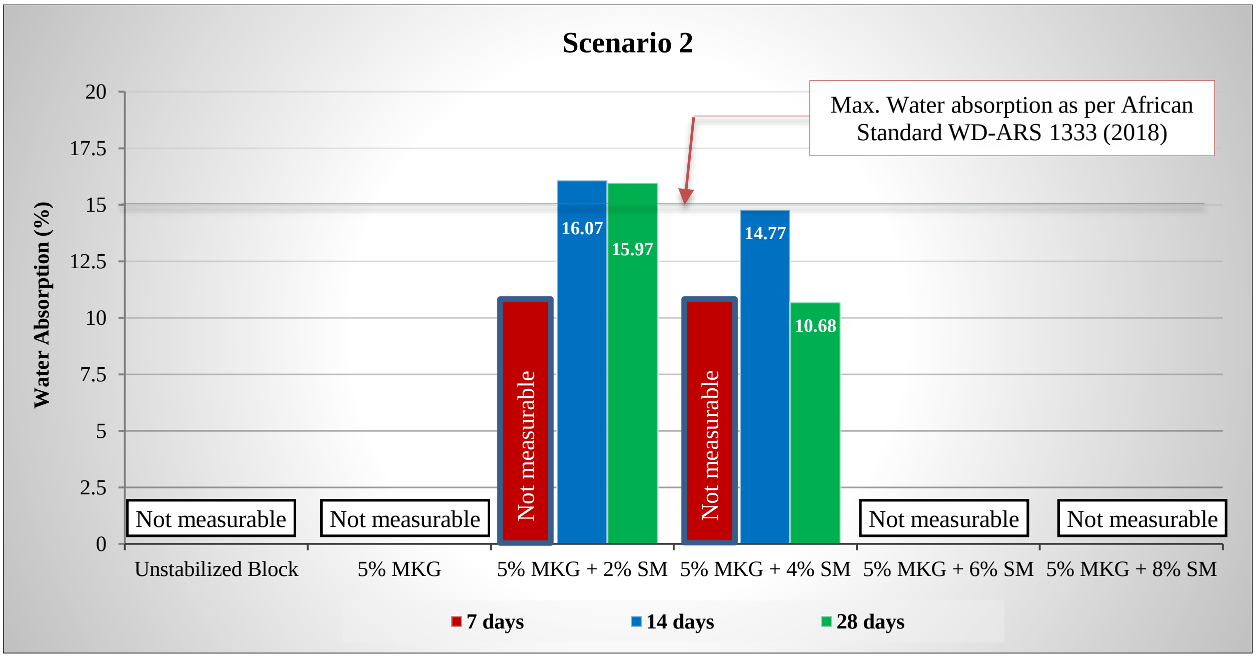




**Figure 9. Water absorption of SCEBs**

In scenario 1 of stabilization, it should be noted that the CEBs stabilized with 10% MKG displayed greater water absorption than the limit value recommended (15%). This outcome, related to the porosity of the CEBs stabilized with MKG, was in accordance with the study of Emeso et al. [28]. The partial replacement of this optimum MKG content with SM improved the stability of SCEBs in water. As SM increased by up to 4% and the curing period increased, the water absorption decreased. The water absorption values of the blocks stabilized with 8% MKG + 2% SM, and 6% MKG + 4% SM were all below the limit value of 15%. Nevertheless, the water absorption of the SCEBs with 6% MKG + 4% SM was not measurable at 7 days because the blocks crumbled in water. Then, as the curing periods increased, these blocks became more stable in water. Beyond the 4% replacement of MKG by SM, the water absorption of the SCEBs was not measurable. Thus, all the blocks stabilized with 4% MKG + 6% SM and 2% MKG + 8% SM crumbled in water. Table 6 displays the water absorption values of CEBs stabilized according to scenario 1.

**Table 6. Water absorption of CEBs stabilized with SM as a partial replacement of MKG (scenario 1)**

| Age (days) | Percentage of binder (%) | Water Absorption (%) | Observation | |
|---|---|---|---|---|
| 7 | 10% MKG + 0% SM | 14.33 | Good condition |  |
| | 8% MKG + 2% SM | 10.82 | Good condition |  |
| | 6% MKG + 4% SM | Not Measurable | Cracks in two parts |  |
| | 4% MKG + 6% SM | Not Measurable | Blocks crumbled before24h |  |
| | 2% MKG + 8% SM | Not Measurable | Blocks crumbled before24h |  |
| 14 | 10% MKG + 0% SM | 16.04 | Good condition |  |
| | 8% MKG + 2% SM | 10.45 | Good Condition |  |
| | 6% MKG + 4% SM | 9.85 | Good Condition |  |
| | 4% MKG + 6% SM | Not Measurable | Blocks crumbled before24h |  |
| | 2% MKG + 8% SM | Not Measurable | Blocks crumbled before24h |  |
| 28 | 10% MKG + 0% SM | 15.89 | Good condition |  |
| | 8% MKG + 2% SM | 9.91 | Good Condition |  |
| | 6% MKG + 4% SM | 8.73 | Good Condition |  |
| | 4% MKG + 6% SM | Not Measurable | Blocks crumbled before 24h |  |
| | 2% MKG + 8% SM | Not Measurable | Blocks crumbled before 24h |  |

Additionally, in scenario 2 of stabilization, it should be pointed out that the CEBs stabilized with 5% MKG were not stable in water. They crumbled during the water absorption test. This result is also consistent with the study of Emeso et al. [28]. Nevertheless, when the same amount of geopolymer was combined with 2% SM, the stability in water of the SCEBs obtained was enhanced. The blocks crumbled in water at 7 days, but as the curing period increased, the CEBs resisted in water. However, the water absorption of CEBs stabilized with 5% MKG + 2% SM was beyond the recommended water absorption limit value for earthen blocks (15%). The water absorption of the SCEBs dropped as the amount of SM increased by up to 4%. The SCEBs with 5% MKG + 4% SM had a water absorption value that was less than 15%. Above, 4% of SM, all the blocks stabilized with 5% MKG + 6% SM, and 5% MKG + 8% SM crumbled in water. Table 7 shows the water absorption values of CEBs stabilized according to scenario 2.

**Table 7. Water absorption of CEBs stabilized by fixing 5% MKG and varying the percentage of SM from 2% to 8% (Scenario 2)**

| Age (days) | Percentage of binder (%) | Water Absorption (%) | Observation | |
|---|---|---|---|---|
| 7 | 5% MKG + 0% SM | Not Measurable | Blocks crumbled before 24h |  |
| | 5% MKG + 2% SM | Not Measurable | Cracks in two parts |  |
| | 5% MKG + 4% SM | Not Measurable | Blocks crumbled before 24h |  |
| | 5% MKG + 6% SM | Not Measurable | Blocks crumbled before 24h |  |
| | 5% MKG + 8% SM | Not Measurable | Blocks crumbled before 24h |  |
| 14 | 5% MKG + 0% SM | Not Measurable | Blocks crumbled before 24h |  |
| | 5% MKG + 2% SM | 16.07 | Good Condition |  |
| | 5% MKG + 4% SM | 14.77 | Good Condition |  |
| | 5% MKG + 6% SM | Not Measurable | Blocks crumbled before 24h |  |
| | 5% MKG + 8% SM | Not Measurable | Blocks crumbled before 24h |  |
| 28 | 5% MKG + 0% SM | Not Measurable | Blocks crumbled before 24h |  |
| | 5% MKG + 2% SM | 15.97 | Good Condition |  |
| | 5% MKG + 4% SM | 10.68 | Good Condition |  |
| | 5% MKG + 6% SM | Not Measurable | Blocks crumbled before 24h |  |
| | 5% MKG + 8% SM | Not Measurable | Blocks crumbled before 24h |  |

In general, it should be noted that the combination of MKG and SM for stabilizing CEBs improved their stability in water more than the use of just MKG as a stabilizer. The CEBs stabilized with MKG and SM were stable in water, but as the amount of SM increased, the SCEBs needed a more extended curing period to display good behavior in water. This may be credited to the sucrose present in SM. Indeed, sucrose can be coupled with ions found in geopolymer matrices like Ca, Al, and Fe to produce insoluble metal-organic complexes that coat the particles and slow down the geopolymerization process [29]. The optimum binder content in terms of water absorption was 6% MKG + 4% SM. When the amount of SM increased beyond 4%, the SCEBs crumbled in water. This result may be explained by the fact that the high amount of SM used has coated the soil-geopolymer matrix, which inhibits the electrochemical attraction between soil particles and the geopolymer. Therefore, when the CEBs stabilized with a high amount of SM are immersed in water, the hydroxyl groups of SM absorb and hold water before diluting [30].

In conclusion, it should be noted that the use of SM with MKG for stabilizing CEBs effectively addresses the porosity of CEBs stabilized with just MKG. As a result, the CEBs stabilized by combining MKG and SM are more stable in water and can be recommended for making external walls in humid areas subjected to frequent rainfall.

## 4. Conclusion

From the findings of the experiments conducted above, it should be deduced that SM is not as effective as MKG in increasing the compressive strength of CEBs. However, the combination of MKG and SM for stabilizing CEBs is helpful in improving their compressive strength. The optimum MKG and SM content, at which the highest compressive strength is achieved, is 5% MKG + 4% SM (4.163 MPa at 28 days). On the other hand, when the amount of SM combined with MKG for stabilizing CEBs is more than 4%, the compressive strength of the SCEBs drops.

Additionally, it should be pointed out that the combination of MKG with SM effectively addresses the high porosity of CEBs stabilized with MKG alone and makes them more compact and denser. As a result, the dry density of the SCEBs is increased as the percentage of SM increased. Alternatively, the stability in water of these CEBs stabilized by combining MKG and SM is improved more than that of CEBs stabilized with just MKG. The best result is obtained with the partial replacement of 4% of the optimum MKG content by SM. The water absorption value of 8.73% is thus obtained for SCEBs with 6% MKG + 4% SM at 28 days old. Beyond 4% of SM, the SCEBs crumbled in water. Thus, the CEBs stabilized with 5% MKG + 4% SM and 6% MKG + 4% SM may be recommended for construction purposes since they have a compressive strength greater than 2.5 MPa, a dry density within a range of 1500 to 2000 kg/m$^3$, and a water absorption value of less than 15% at 28 days.

# 5. Declarations

## 5.1. Author Contributions

Conceptualization, I.D., R.N.N.M., and R.O.O.; methodology, I.D., R.N.N.M., and R.O.O.; validation, I.D., R.N.N.M., and R.O.O.; formal analysis, I.D., R.N.N.M., and R.O.O.; investigation, I.D.; resources, I.D., R.N.N.M., and R.O.O.; writing—original draft preparation, I.D.; writing—review and editing, R.N.N.M., and R.O.O.; visualization, I.D., R.N.N.M., and R.O.O.; supervision, I.D., R.N.N.M., and R.O.O.; project administration, I.D., R.N.N.M., and R.O.O. All authors have read and agreed to the published version of the manuscript.

## 5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

## 5.3. Funding

This research has received funding from the African Union Commission (AUC) and, especially, the Pan African University of Sciences, Technology, and Innovation (PAUSTI) in Kenya.

## 5.4. Acknowledgements

The authors would like to thank the staff of the Pan African University of Sciences, Technology, and Innovation (PAUSTI) for their unwavering and constructive support throughout this research study.

## 5.5. Conflicts of Interest

The authors declare no conflict of interest.

# 6. References

[1] Niroumand, H., Zain, M. F. M., & Jamil, M. (2013). Various Types of Earth Buildings. Procedia - Social and Behavioral Sciences, 89, 226–230. doi:10.1016/j.sbspro.2013.08.839.

[2] Bahar, R., Benazzoug, M., & Kenai, S. (2004). Performance of compacted cement-stabilised soil. Cement and Concrete Composites, 26(7), 811–820. doi:10.1016/j.cemconcomp.2004.01.003.

[3] Montgomery, D. E. (2002). Dynamically-Compacted cement stabilized soil blocks for low- cost Housing. Phd Thesis, School of Engineering, University of Warwick, Coventry, United Kingdom. Available online: http://212.19.134.34/docs/Bricks/Dynamically-Compacted_Cement_Stabilised_Soil_Blocks_For_Walling_2002.pdf (accessed on January 2022).

[4] Gooding, D., & Thomas, T. (1997). Soilcrete blocks: Experimental work to determine whether cement or compaction pressure is more effective. Building Research and Information, 25(4), 202–209. doi:10.1080/096132197370327.

[5] Millogo, Y., Hajjaji, M., & Ouedraogo, R. (2008). Microstructure and physical properties of lime-clayey adobe bricks. Construction and Building Materials, 22(12), 2386–2392. doi:10.1016/j.conbuildmat.2007.09.002.

[6] El Wardi, F. Z., Ladouy, S., Khabbazi, A., Ibaaz, K., & Khaldoun, A. (2021). Unfired Clay-Cork Granules Bricks Reinforced with Natural Stabilizers: Thermomechanical Characteristics Assessment. Civil Engineering Journal, 7(12), 2068–2082. doi:10.28991/cej-2021-03091778.

[7] Zhang, J., Liu, G., Chen, B., Song, D., Qi, J., & Liu, X. (2014). Analysis of $CO_2$ Emission for the cement manufacturing with alternative raw materials: A LCA-based framework. Energy Procedia, 61, 2541–2545. doi:10.1016/j.egypro.2014.12.041.

[8] Shan, Y., Liu, Z., & Guan, D. (2016). $CO_2$ emissions from China's lime industry. Applied Energy, 166, 245–252. doi:10.1016/j.apenergy.2015.04.091.

[9] Raphaëlle, P. (2015). Formulation and durability of metakaolin-based geopolymers. PhD Thesis, Civile Engineering, University of Paul Sabatier, Toulouse, France. (In France). Available online: https://tel.archives-ouvertes.fr/tel-01297848/document (accessed on January 2022).

[10] Khale, D., & Chaudhary, R. (2007). Mechanism of geopolymerization and factors influencing its development: A review. Journal of Materials Science, 42(3), 729–746. doi:10.1007/s10853-006-0401-4.

[11] Imtiaz, L., Ur Rehman, S. K., Memon, S. A., Khan, M. K., & Javed, M. F. (2020). A review of recent developments and advances in eco-friendly geopolymer concrete. Applied Sciences, 10(21), 7838. doi:10.3390/app10217838.

[12] Zhao, J., Tong, L., Li, B., Chen, T., Wang, C., Yang, G., & Zheng, Y. (2021). Eco-friendly geopolymer materials: A review of performance improvement, potential application and sustainability assessment. Journal of Cleaner Production, 307, 127085. doi:10.1016/j.jclepro.2021.127085.

[13] Nazari, A., Bagheri, A., Sanjayan, J. G., Dao, M., Mallawa, C., Zannis, P., & Zumbo, S. (2019). Thermal shock reactions of Ordinary Portland cement and geopolymer concrete: Microstructural and mechanical investigation. Construction and Building Materials, 196, 492–498. doi:10.1016/j.conbuildmat.2018.11.098.

[14] Mucsi, G., & Ambrus, M. (2017). Raw Materials for Geopolymerisation. Proceedings of the MultiScience - XXXI. MicroCAD International Multidisciplinary Scientific Conference, University of Miskolc, Hungary, 20-21 April 2017. doi:10.26649/musci.2017.008.

[15] Carreño-Gallardo, C., Tejeda-Ochoa, A., Perez-Ordonez, O. I., Ledezma-Sillas, J. E., Lardizabal-Gutierrez, D., Prieto-Gomez, C., Valenzuela-Grado, J. A., Robles Hernandez, F. C., & Herrera-Ramirez, J. M. (2018). In the $CO_2$ emission remediation by means of alternative geopolymers as substitutes for cements. Journal of Environmental Chemical Engineering, 6(4), 4878–4884. doi:10.1016/j.jece.2018.07.033.

[16] Omar Sore, S., Messan, A., Prud'homme, E., Escadeillas, G., & Tsobnang, F. (2018). Stabilization of compressed earth blocks (CEBs) by geopolymer binder based on local materials from Burkina Faso. Construction and Building Materials, 165, 333–345. doi:10.1016/j.conbuildmat.2018.01.051.

[17] Zhang, M., Guo, H., El-Korchi, T., Zhang, G., & Tao, M. (2013). Experimental feasibility study of geopolymer as the next-generation soil stabilizer. Construction and Building Materials, 47, 1468–1478. doi:10.1016/j.conbuildmat.2013.06.017.

[18] Dukuly, A. A. (2021). Evaluation of Metakaolin-Based Geopolymer as a stabilizing agent for Expansive Soil. Master Thesis, Department of Materials and Science Engineering, African University of Science and technology, Galadima, Nigeria.

[19] Samuel, R. A. (2019). Synthesis of Metakaolin-based Geopolymer and its Performance as Sole Stabilizer of Expansive Soils. PhD Thesis, University of Texas at Arlington, Arlington, United States.

[20] Zhang, M. (2015). Geopolymer, Next Generation Sustainable Cementitious Material−Synthesis, Characterization and Modeling. PhD Thesis, Worcester Polytechnic Institute, Worcester, United States. Available online: https://digital.wpi.edu/downloads/nc580m84s (accessed on January 2022).

[21] Malanda, N., Kimbembe, P. L., & Tamba-Nsemi, Y. D. (2018). Etude des caractéristiques mécaniques d'une brique en terre stabilisée à l'aide de la mélasse de canne à sucre. Sciences Appliquées et de l'Ingénieur, 2(2), 1-9.

[22] Karthik, A., Sudalaimani, K., & Vijayakumar, C. T. (2017). Durability study on coal fly ash-blast furnace slag geopolymer concretes with bio-additives. Ceramics International, 43(15), 11935–11943. doi:10.1016/j.ceramint.2017.06.042.

[23] Kamtchueng, B. T., Onana, V. L., Fantong, W. Y., Ueda, A., Ntouala, R. F., Wongolo, M. H., Ndongo, G. B., Ze, A. N., Kamgang, V. K., & Ondoa, J. M. (2015). Geotechnical, chemical and mineralogical evaluation of lateritic soils in humid tropical area (Mfou, Central-Cameroon): Implications for road construction. International Journal of Geo-Engineering, 6(1), 1–21. doi:10.1186/s40703-014-0001-0.

[24] Aurelie, T. K. R., Tome, S., Judicaël, C., Idriss, E., Spieß, A., Fetzer, M. N. A., Elie, K., Janiak, C., & Etoh, M.-A. (2021). Stabilization of Compressed Earth Blocks (CEB) by Pozzolana Based Phosphate Geopolymer: Physico-Mechanical, Structural and Microstructural Investigations. SSRN Electronic Journal, 1–22. doi:10.2139/ssrn.3855724.

[25] M'Ndegwa, J. K., & Shitote, S. M. (2012). Influence of cane molasses on plasticity of expansive clay soil. International Journal of Current Research, 4(1), 136-141.

[26] Riza, F. V., Rahman, I. A., Mujahid, A., & Zaidi, A. (2010). A brief review of Compressed Stabilized Earth Brick (CSEB). CSSR 2010-2010 International Conference on Science and Social Research, 999–1004. doi:10.1109/CSSR.2010.5773936.

[27] WD-ARS 1333 (2018). Compressed stabilized earth blocks-requirements, production and construction. The African Organization for Standardization (ARS), Nairobi, Kenya. Available online: https://www.arso-oran.org/wp-content/uploads/2014/09/WD-ARS-1333-2017-Compressed-stabilized-earth-blocks-Requirements-production-and-construction.pdf (accessed on January 2022).

[28] Ojo, E. B., Isah, A. K., Teixeira, R. S., Matawal, D. S., & Savastano, H. (2018). Geopolymer Stabilisation of Earth Building Materials for Sustainable Construction. NBRRI International Conference: Emerging Materials and Technologies for Sustainable Building and Road Infrastructure, 20-21 June 2018, Abuja, Nigeria, 1–13.

[29] Ranjbar, N., Kuenzel, C., Spangenberg, J., & Mehrali, M. (2020). Hardening evolution of geopolymers from setting to equilibrium: A review. Cement and Concrete Composites, 114(103729). doi:10.1016/j.cemconcomp.2020.103729.

[30] Muguda, S., Lucas, G., Hughes, P.N., Augarde, C.E., Perlot, C., Bruno, A.W., & Gallipoli, D. (2020). Durability and hygroscopic behaviour of biopolymer stabilised earthen construction materials. Construction and Building Materials, 259, 119725. doi:10.1016/j.conbuildmat.2020.119725.