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Potential use of Shea nutshell ash as partial replacement of portland cement in interlocking earth blocks

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Abstract
Before the discovery of new building materials, earth was the basic building material. These buildings provided shelter and protected the people from weather. However, earth material is characterized with low strength, high shrinkage and sorptivity. To enhance the characteristics of earth blocks, several methods like cement and lime stabilisation of earth have been investigated. Due to the high cost and environmental impact of these stabilisers, a number of investigations have been carried out, including the possibility of using pulverized and combustible industrial and agricultural waste as partial replacement for cement in stabilised earth blocks. This study, therefore centered on analysing the potential use of Shea nutshell ash (SNSA) in stabilised interlocking earth blocks (IEBs). SNSA is obtained from the calcination of Shea nutshell, an agro-based waste. The quantity of cement used for the stabilisation of earth blocks was partially supplanted by SNSA from 0 to 6% by mass with a step of 2. The impacts of SNSA and cement on water absorption, dry density and compressive strength of IEBs were assessed. The results show a gain in compressive strength for 2% of replacement (4%C+2%SNSA) especially at 28 and 56 days (4.79% and 34.62% respectively). Moreover, SNSA improved the dry density of IEBs and the best result (1773.51 kg/m^3) was obtained for blocks with (0C+6SNSA) at 56 days. Although SNSA enhanced the compressive strength and dry density of IEBs, it did not improve the resistance of IEBs to water. Water absorption of the blocks was not satisfactory. Based on these results, SNSA is suitable for use as a stabiliser in earth blocks. It is an environmental friendly and low carbon material, affordable and it can contribute to sustainable and low-cost houses construction.

Keywords
Interlocking earth blocks, Shea nutshell ash, Water absorption, Dry density, Compressive strength.

1.Introduction
Earth is an ancient construction material. Our ancestors used it and it is still used today in developing countries and even in the super-modern world. Although earthen materials are environmental friendly, affordable and accessible to all, earth blocks have low strength and high water absorption capacity. Its low compressive strength has limited use in construction. Without proper maintenance, earth houses do not last for long, sometimes may collapse and cause loss of life [1]. However, when compared to cement blocks, studies have revealed that earthen structures suit better to the climate [2, 3].

That is why nowadays, people are still interested in using earth as construction material. To enhance the properties of earth blocks, several methods are used. For instance, properties improvement of earth block is achieved through cement or stabilisation [4, 5]. However, these binders are costly and unaffordable for the greatly destitute populace. Yet, the need for adequate housing has been perceived as an indispensable component of the right to a satisfactory standard of living [6, 7]. In addition, the conventional binders (cement, lime) are the source of environmental destruction through the emission of greenhouse gases.

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Studies have noted the CO_2 emissions generated by different types of blocks as follows: Concrete blocks emit 143 kg CO_2/tonne while compressed stabilised earth blocks (CSEB) emit 22 kg CO_2/tonne and burned clay bricks 200 kg CO_2/tonne[8]. It has moreover been demonstrated that amid the production process of CSEB, 1 kg of cement utilized produces 0.894 kg of CO_2[9, 10] Ekinci et al. [11] reported in their study that around one tonne of CO_2 is discharged into the environment for each tonne of cement produced.

In order to address all of the above issues, studies have been conducted in order to discover others innovations for the stabilisation of earth blocks using alternative cementitious materials [2, 12, 13]. As the United Nations Secretary-General once said, making peace with nature is the defining goal of the twenty-first century. Everyone, everywhere should make it a high priority [14]. This article, therefore investigates the potential use of Shea nutshell ash (SNSA) as a cement substitute in stabilised earth blocks while adopting the new technology of interlocking blocks.

The technology of interlocking blocks consists of producing blocks that fit together during construction, without need of using mortar. This technology reduces the requirement for talented labour and abbreviates time of construction [15]. Anand and Ramamurthy [16] found that using interlocking blocks reduces the cost of wall construction by 80%. It has also been shown that because of their interlocking nature, interlocking earth blocks (IEBs) are more stable and can withstand strong vibration earthquakes. With this technology, the use of plaster or paint is not necessary as the interlocking appearance gives the wall a more aesthetic look. All the advantages of this technology added to the replacement of cement by SNSA, an agricultural waste, allows obtaining more stable, ecological and cheaper blocks.

The Shea nutshell (*Figure 1*) is the envelope in which the sea nut from the fruit of this tree (Shea) is enclosed. Shea trees grow naturally within the savannah of Africa. From the Sapotaceae family, Shea tree (Vitellaria Paradoxa or Nilotica Paradoxa) has been nicknamed "the tree of a thousand virtues" and is the source of the famous Shea butter [17−19]. The most often used component of the tree has been the kernel that is transformed into butter. It is during this process of transformation into butter that the shells are removed and, in most cases thrown away as waste [20]. However, in recent years, some researches have been done to prove the benefits of Shea nutshells. Thus, to twofold the benefits of butter and protect the environment, Shea nutshells have been suggested to be used as fuel [20]. Exploited mostly by women, Shea tree is also called women's gold. It has been proved that the Shea industry provides income for women, with an estimated of 16 million women involved in the production and processing of Shea nuts in producing regions in Africa [19]. Environmentally, a multi-impact assessment of the shea industry conducted by Bockel et al. [21] revealed that Shea has enormous climate change mitigation potential. It is reported that each tonne of Shea kernels produced has a negative carbon footprint (the amount of greenhouse gases) of 1.04 tonnes of CO_2. Therefore, using SNSA to improve the performance of IEBs would be exceptionally advantageous from an economic and environmental point of view. This study investigated the effect of SNSA on IEBs. In the blocks manufacturing process, cement was partially replaced with SNSA. Then water absorption, dry density and compressive strength of these blocks were measured.

Figure 1 Shea nutshells

This paper is organized as follows. Literature review has been presented in section 2. Section 3 and 4 covers the methods and results. Discussion based on the results is in section 5. At the end, concluding remarks have been pointed.

2.Literature review

Although SNSA is less used in the construction field, it has been proved to have various advantages in recent studies. Dejean et al. [22] evaluated the impact of biomass and charcoal supported catalyst synthesis parameters on the catalytic action of Shea nutshells. They found that Shea nutshells are endowed with catalyst properties producing good quality activated carbons for ethanoic biodiesel production. The study conducted by Quainoo et al. [23] on the elimination of harmful metals on ecological and economic aqueous phase Shea nutshell biochar shows that Shea nutshells were effective in removing toxic metals, including magnesium, iron, zinc and copper from soils.

In construction, an experimental study was conducted by Zieve et al. [24] on the potential use of Shea nutshells, as the substitution of cement in concrete. Cement in the concrete mix was replaced partially by mass with SNSA at 0%, 10% and 20%. The results showed minimal reduction in the concrete cube compressive strength compared to the control cubes at 14 and 28 days of curing. However, an important improvement in the strength of the concrete cubes was observed at 90 days of age compared to the control cubes. It was concluded that the SNSA is effective in developing the long-term concrete strength [24]. The same study found that SNSA has pozzolanic and cementitious properties allowing its use as a supplementary cementitious material for the construction of durable and affordable concrete. Another study was conducted by Tsado et al. [25] on the use of SNSA to replace 0%, 5%, 10%, 15% and 20% cement in mortar. Results showed an increase in properties such as compressive strength, setting time and density. Shea nutshell ash mortar gave satisfactory compressive strength for 0-15% substitution at 28 days. Also in this study, the chemical compositions of SNSA indicated that it is a good pozzolanic material according to the requirements of American Society for Testing and Materials (ASTM) Standard [26]. It was recommended by Tsado et al. [25] that SNSA could be used effectively in the production of masonry blocks.

The ability of SNSA to improve concrete and mortar performance and its ability to act as a binder may be due to the presence of silica (SiO_2) and alumina ($ALSO_4$) in its chemical composition. This reaction would be possible through polycondensation in which SiO2 and $ALSO_4$ interconnect and share their oxygen ions to form aluminosilicates (AL-O-Si) that act as binders [27]. In addition to this, according to Quainoo et al. [23], Shea nutshells can remove toxic metals from soils. However, Anifowose [28] found that the presence of iron in the soil leads to low compressive strength in the soil stabilisation process. The low compressive strength is caused by the production of sulfuric acid (H_2SO_4) through the oxidation of iron sulfide (FeS_2). The sulfuric acid produced can react in the presence of calcium carbonate to form gypsum (calcium sulphate hydrate), as demonstrated in Equations 1 and 2. The calcium sulphate hydrate formed can attack stabilised material in the same way as sulphate [29]. Since there are conceivable outcomes of utilizing SNSA in concrete and mortar as demonstrated by previous studies, there is a lack of information on its use in stabilised earth blocks. Therefore, this study focuses on the investigation of the effects of SNSA for stabilising interlocking earth blocks.

$$2F_eS_2 + 2H_2O + 7O_2 \longrightarrow 2F_eSO_4 + 2H_2SO_4 \quad (1)$$

$$C_aCO_3 + H_2SO_4 + H_2O \longrightarrow C_aSO_4, 2H_2O + CO_2 \quad (2)$$

3.Materials and methods

3.1Materials

This study was carried out in the Civil Engineering Laboratory of Jomo Kenyatta University of Agriculture and Technology (JKUAT) in Juja, Kenya. Lateritic soil, Shea nutshells and cement were the materials utilized in this research.

The lateritic soil was sourced from the JKUAT farm. In arranging to the dodge inclusion of humus, this soil was collected from a profundity of 600 mm underneath the ground level. The soil was sieved through 5 mm size sieves. Shea nutshells were collected in the northern region of Uganda because of their unavailability in Kenya. The pozzolanic cement (CEM) IV/32.5R was used conforming to current Kenyan standard [30]. Potable water that complies with the Kenyan water regulations [31] was used to mix different materials. It was sourced from the JKUAT water supply system.

3.2Methods

3.2.1Calcination of Shea nutshells

Being agricultural waste, Shea nutshells once gotten, were sorted to remove other waste materials and after that subjected to open burning to decarbonise the shells (*Figure 2(a)*). This open burning is controlled by constantly turning the shells with a long metal rod to ensure that all shells are burnt. Once the burning is complete, the ash is collected and is sieved through a 0.3 mm sieve. The ash obtained from the open burning ((*Figure 2(b)*) was subjected to calcination in a furnace at 650°C for 3 hours (*Figure 2(c)*) to improve its pozzolanic properties, as recommended by the ASTM [26]. After calcination, the chemical characteristics of SNSA were analysed at the Ministry of Mines laboratory. X-ray fluorescence (XRF) method was adopted to obtain the main chemical elements present in the SNSA (*Table 1*). Once the pozzolanic properties were confirmed, SNSA ash was used for block manufacturing.

Different types of blocks produced are shown in *Table 2*.

a) Open air burning of Shea Nutshell (b) Ash after combustion c) Ash after calcination

Figure 2 Calcination of Shea nutshells

Table 1 Chemical compounds of SNSA

Compounds	Symbol	Results (%)
Calcium	CaO	7.873
Silica	S_iO_2	57.973
Aluminium	AL_2O_3	11.597
Carbon	LOI	0.48
Iron	Fe_2O_3	3.548
Magnesia	M_gO	4.663
Potassium	K_2O	10.302
Phosphorous pentoxide	P_2O_5	1.966
Nitrogen	Ni	0.002

3.2.2Blocks production

The manufacturing procedure for blocks consisted of four main steps (*Figure 3*). Firstly, the soil was sieved on a 5mm sieve and put in bags then transported to the laboratory. The second step was to mix the lateritic soil with various ratios of stabilisers and water according to the mix proportion in *Table 2*. The amount of water used corresponded to the optimum moisture content (OMC) obtained during the compaction test. The third step was the production of blocks. A manual press machine was used for this process. The mould of the machine was lubricated by drain oil to prevent the materials from sticking to it. After that, the homogeneous mixture of soil with binder was poured into the mould of the manual press. The mould, cover was then placed and the block, once pressed, was ejected. The fourth step was to dry the block. Polythene was used to cover the blocks once produced for 7 days before further drying at room temperature.

Table 2 Mix proportion of interlocking earth blocks

Soil type	Binder		Water	Code
	Cement	SNSA		
Lateritic	0%	0%	OMC	0C+0SNSA
	6%	0%	OMC	6C+0SNSA
	4%	2%	OMC	4C+2SNSA
	2%	4%	OMC	2C+4SNSA
	0%	6%	OMC	0C+6SNSA

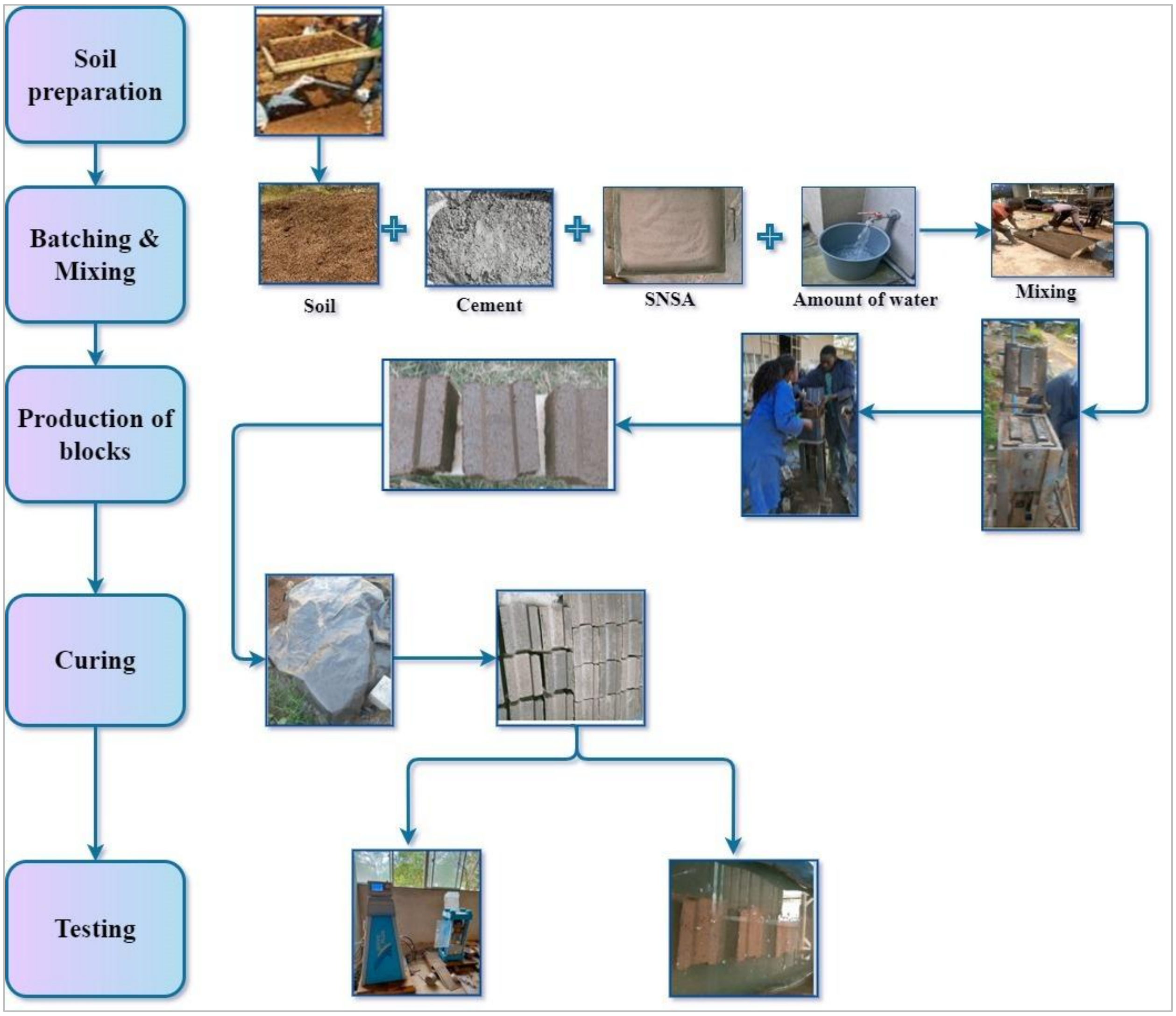


Figure 3 Process of blocks production

3.2.3Determination of water absorption

In order to evaluate the resistance of blocks in wet environment, the water absorption test was performed according to British Standard [32]. This can influence the suitability of the blocks and the quality of bond between the blocks and the mortar in a masonry structure. Although mortar will not be used for the interlocking blocks, it is important to ensure that block can resist to water. The water content of the soil as a percentage of its dry weight was determined. The procedure for this test consisted of: first, in a 105 °C ± 5 °C oven, the specimens were dried for 24 hours and weighed (W_b). The specimens were soaked in water for 24 hours then removed and reweighed (W_a). The percentage water uptake (W_u) was calculated using Equation (3).

$$W_u = \frac{(W_a - W_b)}{W_b} \times 100 \tag{3}$$

3.2.4Determination of the dry density

Directly related to compressive strength, the dry density test is of utmost importance. It provides an indication of the effect of the binders on block mass after drying. The determination of dry density was done according to the Nigerian industry standard [33] at 7, 14, 28 and 56 days. The blocks were dried in a 105 °C ± 5 °C oven. Once removed from oven, the blocks were left to cool before weighing. Equation (4) was used to calculate the dry density of the blocks. γ_d is the dry density (kg/m^3), V, the volume of the block (m^3), and W_d, the weight of the dried block (kg).

$$\gamma_d = \frac{W_d}{V} \times 100 \tag{4}$$

3.2.5Determination of compressive strength

Blocks are generally used to construct load-bearing masonry walls, columns and footings which are mostly under compressive loads. It is therefore necessary to determine the compressive strength of blocks to ensure their sustainability for construction. The compressive strength test of the IEBs was carried out in accordance with the British Standard [34] at 7, 14, 28 and 56 days. The test was carried out using the Universal Testing Machine (UTM). In order to get a flat surface due to the irregular shape of the interlocking blocks, metal plates (*Figure 4a*) were made to conform to the block shapes. The dimensions and weight of block were measured. The block was placed by coinciding its center with the loading axis of the UTM (*Figure 4b*). UTM was set by entering the rate of load application and the block dimensions. After that, load with a rate of 0.05 N/mm2/s was applied until the block broke. The maximum compressive strength and the maximum load were recorded. The different stages of the compression test are shown in *Figure 4.*

a) Block prepared for the test   b) Block between the two trays of UTM   c) Block after failure

Figure 4 Compressive strength test on the blocks

4.Results

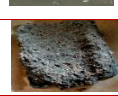
4.1Impact of SNSA and cement on the physical properties of interlocking blocks

4.1.1Water absorption

Water absorption, as mentioned by Salih et al. [35], is important for the evaluation of the strength of earth blocks in a humid environment. It indicates the resistance of the blocks to immersion. It is advised that the materials constituting a block should have the lowest water retention capacity [36]. The results of water absorption test with various ratios of binders at different ages are presented in *Table 3.*

The percentages of absorption for blocks stabilised with 6% cement at 7 and 14 days were 16.33% and 15.26% respectively. At 28 and 56 days, IEBs stabilized with 6% of cement had a water retention capacity of 14% and 12% respectively. For the blocks stabilised with SNSA as partial replacement for cement, only the combination of 4% cement and 2% SNSA (4C+2SNSA) at age 56 days resisted immersion for 24 hours; with an absorption capacity of 17.62%. The other combinations crumbled in water, making it impossible to measure.

Table 3 Water absorption of interlocking earth blocks

Age (days)	Binder percentage	Water absorption (%)	block appearance	Remark
7	0C + 0SNSA	Not measurable		Blocks disintegrated in water and could not be lifted
	6C + 0SNSA	16.33		Small cracks
	4C + 2SNSA	Not measurable		Blocks disintegrated in water and could not be lifted
	2C+ 4SNSA	Not measurable		Blocks disintegrated in water and could not be lifted
	0C+ 6SNSA	Not measurable		Blocks crumbled after removing from after

Age (days)	Binder percentage	Water absorption (%)	block appearance	Remark
	0C + 0SNSA	Not measurable		Blocks disintegrated in water and could not be lifted
14	6C + 0SNSA	15.26		Good condition
	4C+ 2SNSA	Not measurable		Blocks crumbled after removing from the water
	2C+ 4SNSA	Not measurable		Blocks mostly disintegrated in water
	0C+ 6SNSA	Not measurable		Blocks disintegrated in water and could not be lifted
	0C + 0SNSA	Not measurable		Blocks disintegrated in water and could not be lifted
	6C + 0SNSA	14.66		Good condition
28	4C+ 2SNSA	Not measurable		Blocks crumbled after removing from the water
	2C+ 4SNSA	Not measurable		Blocks disintegrated in water and could not be lifted
	0C+ 6SNSA	Not measurable		Blocks disintegrated in water and could not be lifted
	0C + 0SNSA	Not measurable		Blocks disintegrated in water and could not be lifted
	6C + 0SNSA	12.88		Good condition
56	4C+ 2SNSA	17.62		Small cracks
	2C+ 4SNSA	Not measurable		Blocks crumbled after removing from the water
	0C+ 6SNSA	Not measurable		Blocks disintegrated in water

4.1.2 Dry density

The dry density test was performed to observe how the binders affected the mass of the blocks after drying. The dry density values of each mix proportion at different ages are presented in *Figure 5*. It is noted that the blocks had a dry density ranging from 1488.42 kg/m^3 to 1773.51 kg/m^3. The highest dry density (1773.51 kg/m^3) was obtained at 56 days with the blocks stabilised with 6% of SNSA and 0% cement followed by the blocks with 4% of cement and 2% of SNSA (4C+2SNSA), 1732.8 kg/m3. On the other hand, dry density increased with age for most proportions. This increase is significant for blocks stabilized with (4C+2SNSA) and (0C+6SNSA) at 56 days (5.66% and 13.10%, respectively).

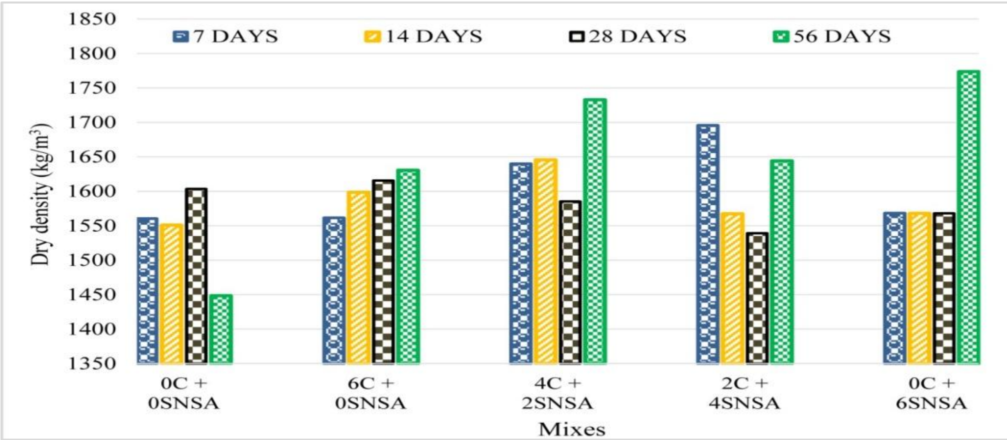


Figure 5 Dry density of interlocking earth blocks for different mixes

4.2The impact of SNSA and cement on the mechanical property of interlocking earth blocks: compressive strength

The compressive strength values for stabilised IEBs are presented in *Figure 6.* The compressive strength values of un-stabilised blocks (0C+0SNSA) at 7, 14, 28 and 56 days were respectively 2.22, 2.83, 2.53 and 2.46 MPa. A reduction in strength with age is observed after 14 days for these un-stabilised blocks. This reduction is of 10.6% and 13.07% at 28 and 56 days respectively. As for the replacement of the cement by the SNSA, the results show an increase in compressive strength at 7 days. The compressive strength was 3.16, 2.79 and 3.06 MPa for (4C+2SNSA), (2C+4SNSA) and (0C+6SNSA) respectively in comparison to the control blocks (6C+0SNSA) with 2.6 MPa compressive strength. At 14 days, an increase of 25.93%, 17.85% was observed for the blocks with (4C+2SNSA) and (0C+6SNSA) respectively. However, blocks with (2C+4SNSA) showed a slight reduction of 2.02% compared to the control blocks. At 28 days, an increase of 4.79% in compressive strength was observed for (4C+2SNSA). On the other hand, a decrease of 20.40% and 10.08% for (2C+4SNSA) and (0C+6SNSA) respectively was observed compared to the control blocks. At 56 days, the blocks stabilised with (4C+2SNSA) gained in compressive strength compared to the control (24.44%). However, compressive strength of others blocks decreased. This reduction is 26.22%, 19.56% for (2C+4SNSA) and (0C+6SNSA) respectively. The optimal replacement of cement by SNSA is therefore 2%, a significant compressive strength (5.6 MPa) at 56 days was recorded with blocks stabilized with (4C+2SNSA). This value is therefore 124% higher than the minimum recommended by the Kenyan standard. The replacement of cement by SNSA beyond 2% leads to a decrease in strength.

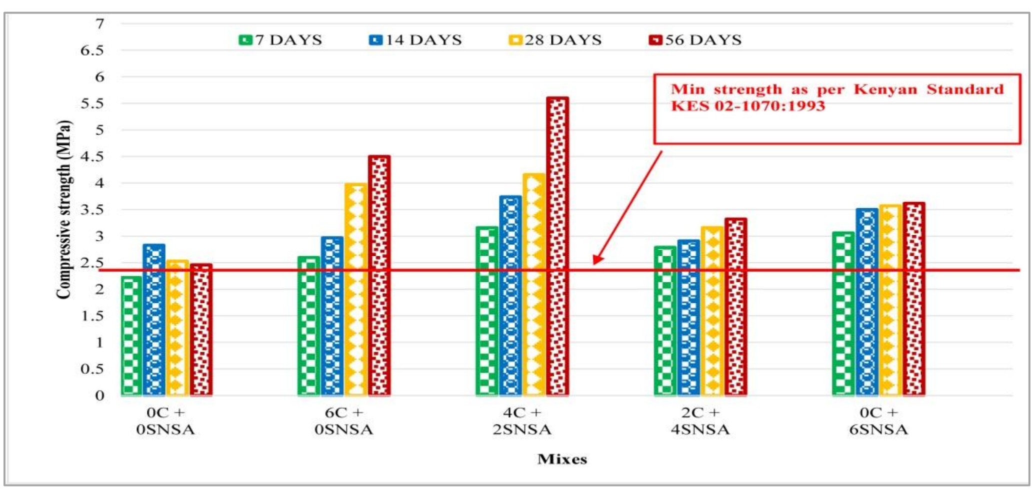


Figure 6 Compressive strength of interlocking earth blocks

5.Discussion

5.1Impact of SNSA and cement on the physical properties of interlocking blocks

5.1.1Water absorption

We can see from the results that only the blocks stabilised with 6% cement were measurable at all ages. However, the percentages of absorption at 7 and 14 days (16.33 and 15.26%, respectively) were above the 15% limit recommended by the Kenyan Standard [37]. Only the IEBs stabilised with 6% cement at 28 and 56 days had the water retention capacity below the specified requirement; 14% and 12% respectively.

Studies have shown that cement content required to obtain blocks with good water resistance varies from 5% to 10% [2, 38]. Thus, for the cement content below 5%, blocks are not water resistant. Sanewu [39] had also shown that increasing the dosage of CEM leads to a decrease in water absorption as cement has the ability to bind laterite particles together. This binding reduces the size of the pores through which water can flow. For IEBs obtained by partially substituting SNSA for cement, only the combination of 4% cement and 2% SNSA (4C+2SNSA) resisted immersion for 24 hours at 56 days; but water absorption was higher (17.62%) than the maximum of 15% recommended by the Kenyan Standard. The water absorption capacity of IEBs stabilised with SNSA is high because SNSA is very soft. This softness therefore promotes high porosity. A study conducted by Dejean et al. [22] confirmed the high porosity of coals catalysed by Shea nutshells. Previous researches on ashes had obtained similar results [39, 40]. From the viewpoint of water resistance, these blocks are only useful when there is no possibility of excessive wetting. For instance, they could be used to construct interior walls where excessive wetting is not a problem and exterior walls in less humid areas.

5.1.2Dry density

The dry density of the blocks is of great importance as it is directly related to the compressive strength and inversely to the water absorption, [35]. Studies have recommended that the density of stabilised earth blocks should be between 1500 and 2000 kg/m^3 [41, 42]. The dry density of blocks manufactured in this research were between this range of 1500 and 2000 kg/m^3 except the un-stabilised blocks at 56 days (1488.42 kg/m^3). It can be noted from the results that the highest dry density (1773.51 kg/m^3) was obtained at 56 days with the blocks stabilised with 6% of SNSA and 0% cement. This proves that the calcium silicate hydrate (C-S-H) that was produced from the SNSA was denser and in a larger quantity than the C-S-H formed from the cement only. It was reported that the increase in density of the materials is caused by the development of C-S-H which is able to bind the soil particles to each other [13, 41]. Thus, as in soil stabilisation where a high, dry density value provides stability [43], the high density of blocks stabilised with SNSA allows the blocks to be more stable.

In parallel with the pozzolanic reaction, the capacity of SNSA to remove toxic metals from the soil promoted the cohesion of the particles and thus, making the blocks denser [23]. An increase in density with age was observed for most percentage. These results are expected since pozzolanic reactions take time to occur [44]. Based on these results, it can be deduced that SNSA affects positively the dry density of the blocks [45]. However, some irregularities were observed due to the inconsistency of the compaction force applied during production and the water content.

5.2The impact of SNSA and cement on the mechanical property of interlocking earth blocks: compressive strength

It can be noticed from the test results that only the un-stabilised blocks (0C+0SNSA) had a compressive strength less than the minimum of 2.5 MPa required by the Kenyan standard [37]. However, on the basis of ASTM standard [46], where a minimum compressive strength of 2.06 MPa is recommended for blocks; un-stabilised blocks are satisfactory for all ages. This is because calcium ions (Ca^{2+}) and oxides SiO_2 and Al_2O_3 in the soil dissolve and react to form hydrated gels of C-S-H and congenital adrenal hyperplasia (C-A-H) (Equations 5 and 6). The hydrated gels bond the different particles of soil to each other and make it possible to have an acceptable resistance at earlier age [47, 48]. However, with time (after 14 days in this case), this reaction would appear to be reduced, certainly because of the presence of organic matter in the soil which decomposes over time causing the strength to decrease. This result is excepted because it was this problem of unsustainability of earth blocks that led to their stabilisation [1].

$$Ca^{2+} + 2(OH^-) + SiO_2 \longrightarrow \mathrm{C-S-H} \quad (5)$$

$$Ca^{2+} + 2(OH^-) + AL_2O_3 \longrightarrow \mathrm{C-A-H} \quad (6)$$

All the different types of stabilised blocks, on the other hand, had a compressive strength above 2.5 MPa. An increase in compressive strength is observed at all ages for the blocks stabilised with 4%

cement and 2% SNSA (4C+2SNSA) compared to the control blocks (6C+0SNSA). The fact that SNSA increases the compressive strength of the blocks can be explained by the reactivity of silica and/or alumina in the presence of water and alkali (calcium) during the pozzolanic reaction. This reaction generates C-S-H or differs of the aluminium-modified calcium silicate hydrate (C-A-S-H), which are the gels responsible for the strength of the blocks due to their bonding ability [48, 49]. From the chemical composition of SNSA presented in *Table 1*, the dominant element is silica (57.973%) followed by alumina (11.597%), which enabled the formation of C-S-H or C-A-S-H gels.

In addition to the pozzolanic reaction, the increase in compressive strength observed when cement is partially replaced by SNSA can be explained by the ability of Shea nutshell to remove toxic metals from soils [23]. According to the study conducted by Anifowose [28], it was revealed that iron in soil is the cause of the weak compressive strength in the process of soil stabilisation. This lower compressive strength is caused by the formation of gypsum (calcium sulphate hydrate) as shown in Equations 7 and 8. Makusa [29] mentioned that calcium sulphate hydrate can attack stabilised material in the same way as sulphate. In addition to this explanation, there is also the polycondensation in which SiO_2 and $ALSO_4$ interconnect and share their oxygen ions to form aluminosilicates (AL-O-Si) (Equation 9). The polymeric bonds (AL-O-Si) have a binding capacity [27].

$$2F_eS_2 + 2H_2O + 7O_2 \longrightarrow 2F_eSO_4 + 2H_2SO_4 \quad (7)$$

$$CaCO_3 + H_2SO_4 + H_2O \longrightarrow CaSO_4.2H_2O + CO_2 \quad (8)$$

$$S_i(OH) + ALSO_4 \longrightarrow S_i - O - S_i + AL - O - AL + AL - O - S_i \quad (9)$$

On the other hand, the replacement of cement by SNSA beyond 2% (4% and 6%) led to a decrease in compressive strength compared to the control blocks. The drop in compressive strength observed by partially replacing the cement with SNSA beyond 2% (2%C+4%SNSA) or total replacement (0C+6SNSA); allowed to conclude that the optimal percentage of SNSA to obtain good compressive strength is 2%. Higher dosage leads to a decrease in compressive strength. Vinai et al. [50] observed the same behaviour when studying a structured approach from waste sorting to binder composition development. This is because the higher dosages trigger rapid setting behaviour and do not ensure adequate strength development. This result is also consistent with the findings of Sanewu [39], who noted a reduction in compressive strength with increasing rice husk ash. This phenomenon can be explained by the fact that excess ash is unable to be easily mobilised for the pozzolanic process, thus taking up space in the soil and leads to a reduction in strength. In the case of blocks stabilised only with SNSA (0C+6SNSA), lower compressive strength was to be expected as the SNSA used in this research is class F. Furthermore, because class F ash is not a self-cementitious material it requires the addition of an activator, such lime or cement, in order to generate pozzolanic stabilised mixes[8].

5.3Limitations of the study

Several aspects were not investigated in this study. In particular, the thermal properties of IEBs stabilised with SNSA. Thus, it is suggested that further studies should be conducted on these blocks to determine their thermal performance. In addition, the impact of the calcination temperature of the Shea nutshells to obtain good pozzolanic properties has not been studied. This study only considered the temperature of 650°C. It is therefore important to verify the optimum temperature for obtaining ash with good pozzolanic properties. A complete list of abbreviations is shown in *Appendix I.*

6.Conclusion and future work

From this study, it can be concluded that the use of SNSA to partially replace cement in IEBs stabilisation is possible. Indeed, apart from the water resistance that did not give satisfactory results, the results for dry density and compressive strength are satisfactory. The study concluded that:

- The combination of (4%C+2%SNSA) was found to be optimal for obtaining the best performance of the stabilised blocks.
- The maximum compressive strength of 5.6 MPa (124% higher than the minimum recommended by the Kenyan Standard) was obtained with the optimum combination at 56 days of curing.
- Blocks with (4%C+2%SNSA) could be considered for possible use in construction, particularly in situations where wetting is minimal.

There are some suggestions for future work on the basis of this work, as follows:

- The effect of calcination temperature on Shea nutshells.
- Improvement of SNSA-stabilised blocks under the effect of water absorption.
- Evaluation of the thermal conductivity of SNSA-stabilised blocks.

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Conflicts of interest
The authors have no conflicts of interest to declare.

Author's contributions statement
Majoie R. Mbakbaye: Performed experimental work, including the production and testing of blocks, interpreted the results and wrote the paper. **Erick K. Ronoh:** Placement of the study plan with the other authors, supervision, revision and editing. **Isaac F. Sanewu:** Supervised the experimental work by providing guidelines for the blocks tests and reviewed the written paperwork.

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Appendix I

S. No.	Abbreviation	Description
1	AL-O-Si	Aluminosilicates
2	ASTM	American Society for Testing and Materials
3	Ca^{2+}	Calcium ion
4	$CaCO_3$	Calcium Carbonate
5	CEM	Pozzolanic Cement
6	CO_2	Carbon Dioxide
7	CSEB	Compressed Stabilised Earth Blocks
8	C-A-S-H	Differs of the Aluminium-Modified Calcium Silicate Hydrate
9	C-A-H	Congenital Adrenal Hyperplasia
10	C-S-H	Calcium Silicate Hydrate
11	FeS_2	Iron Sulfide
12	H_2O	Water
13	H_2SO_4	Sulfuric Acid
14	IEBs	Interlocking Earth Blocks
15	JKUAT	Jomo Kenyatta University of Agriculture and Technology
16	Kg	Kilogram
17	O_2	Oxygen
18	OMC	Optimum Moisture Content
19	SNSA	Shea Nut Shell Ash
20	UN	United Nations
21	UTM	Universal Testing Machine