Hindawi
Advances in Materials Science and Engineering
Volume 2023, Article ID 2933398, 12 pages
https://doi.org/10.1155/2023/2933398

*Research Article*

# Experimental Study on the Production and Mechanical Behavior of Compressed Lime-Cement-Stabilized Interlock Soil Blocks

**Besukal Befikadu Zewudie**

*Faculty of Civil and Environmental Engineering, Jimma Institute of Technology, Jimma University, Jimma, Ethiopia*

Correspondence should be addressed to Besukal Befikadu Zewudie; besubefk@gmail.com

Received 14 September 2022; Revised 10 December 2022; Accepted 27 December 2022; Published 12 January 2023

Academic Editor: Teresa M. Piqu



Compressed stabilized soil block is a sustainable building material primarily made up of stabilized damp soil compressed under pressure. Soil properties and the type of the stabilizer used in producing compressed soil blocks have a significant impact on the quality and behavior of the soil blocks. This study presents the physical and mechanical behavior of lime-cement-stabilized compressed interlock soil blocks produced from two types of natural soil. The two types of soil have different index properties and mineral oxide compositions. Lime-cement combination and cement standalone was used as a binder in the production of test sample blocks depending on the index properties of the soil. 2%lime + 6%cement, 3%lime + 8%cement, and 4%lime + 10%cement were used for the soil block produced from silty clay soil of medium plasticity index. On the other hand, 6%, 8%, and 10% cement by dry mass of soil were used to stabilize silty sand soil. The behaviors of the blocks, such as dry density, the initial rate of water absorption, saturated absorption of water, compressive strength, and stress-strain relation, were examined. The result shows that the compressed soil blocks produced from lime-cement-stabilized silty clay soil has a low rate of initial water absorption and a low dry unit weight when compared to cement-stabilized sandy soil blocks. Soil blocks produced from cement-stabilized silty sand soil attain greater compressive strength by more than 50% of the compressive strength of silty clay soil blocks stabilized by a combination of lime and cement at 60 days after production. The initial tangent modulus of the soil blocks produced using a manual compressing machine from a clay soil stabilized by the lime-cement proportions of 2%L + 6%C, 3%L + 8%C, and 4%L + 10%C is about 1,700 MPa–2,300 MPa with a dry density greater than 1,660 kg/m$^3$.

## 1. Introduction

Using wattle and daub soil reinforced by grass, straw, husks, and other agricultural waste is the traditional and indigenous construction material for low-cost buildings in semiurban and rural parts of Ethiopia. Nowadays, with the advancements in technologies and innovative techniques in manufacturing construction materials, using compressed stabilized soil blocks is becoming a common construction material over wattle and reinforced daub soil in major parts of Ethiopia.

Moreover, due to the global warming issue, the need for energy-efficient technology in manufacturing construction materials and the high demand for low-cost construction materials boost the focus on the consideration of traditional construction materials in a more systematic fashion [1]. Compressed stabilized soil block is a building material made primarily from damp soil stabilized with a chemical binder such as cement, lime, gypsum, or an alkali-activated solution and compressed at high pressure [2, 3].

In comparison to fired clay bricks and hollow concrete blocks, using compressed stabilized soil blocks for low-cost building and low-load bearing masonry offered numerous advantages. The main advantages of compressed stabilized soil blocks include faster and simpler construction, good thermal insulation properties, less carbon emissions and embodied energy in the manufacturing phase, and an extremely low level of waste that cannot cause environmental pollution [4–6].

In its natural state, the soil lacks the required constructional properties such as strength, durability, and dimensional stability. Hence, these deficiencies of natural soil can be addressed by compacting and stabilizing soil with chemical binder agents like cement, lime, gypsum, bitumen, fly ash, and alkali-activated solutions [3, 7, 8]. Walker [7] revealed the effect of the constituent proportions of clay, sand, and cement on the compressive strength, durability, and shrinkage of manually compacted cement-stabilized soil blocks. Another research study by Venkatarama Reddy and Gupta [9] on the characteristics of a soil-cement block of highly sandy soil revealed the influence of cement on the strength, water absorption, elastic properties, and porosity of a cement-stabilized highly sandy soil block. In addition, Piattoni et al. [10] have conducted an experimental investigation of the mechanical behavior of earthen brick made up of different fractions of earth, sand, and straw fibers and proposed an empirical linear correlation between compressive strength and elastic modulus. Chaibeddra and Kharchi [11] have investigated the performance of compressed stabilized earth block under sulphated medium attack to conclude that the effect of sulphates on compressed Earth block depends upon the nature of the base soil, degree of compaction, and type of treatment.

In addition to the abovementioned, numerous types of research have been presented on a means of enhancing the strength of stabilized earth blocks. Previous studies by Binici et al. [12, 13] revealed the influence of waste plastic fiber, straw, and polystyrene fiber on the compressive strength and thermal isolation of mud bricks. From these studies, it was found that stabilized mud blocks reinforced by waste plastic fiber showed higher compressive strength than mud bricks reinforced by straw and polystyrene fiber. Consoli et al. [14] have investigated the influence of fiber inclusion on the behavior of sandy soil under load and found that reinforcing sandy soil with fiber improves both residual triaxial and peak strength and also changes the cemented sandy soil's brittle behavior to a more ductile nature.

Besides, examining the mechanical properties of compressed stabilized soil blocks made from different blended soils Walker [15], Venkatarama Reddy, and Gupta [16] have presented an investigation on the compressive strength, erosion resistance, stress-strain relationship, and elastic properties of masonry built from compressed stabilized soil blocks.

In addition to using cement, lime can also be used as a stabilizing agent, specifically in cases where the soil is very clayey with a plasticity index greater than 15% [1, 17]. The addition of lime to clay soil modifies the important engineering properties of the clay soil [18–20]. The optimum addition of lime in the range of between 1% and 3% by weight to clay soil enhances important engineering properties of clay soils by satisfying the affinity of clay minerals [18]. Optimum admixture of lime along with silica fume improves shear strength and angle of internal friction of soft kaolin clay soil [21].

The common trend in manufacturing compressed stabilized soil blocks is reconstituting the natural soil by blending external sand into the soil to make granular material suitable for cement stabilization. Most of the previous studies presented on the behavior of compressed stabilized soil blocks emphasize on cement-stabilized soil blocks produced by reconstituting natural soil by blending with external sand [7, 10, 11, 17, 22–24]. Investigation on the effectiveness of using stabilized natural soil at its essence in compressed stabilized soil blocks is limited. Furthermore, the mechanical behavior of compressed soil blocks produced from natural soil using different stabilizer agents is not fully revealed. In addition, investigations on the performance of lime-cement-stabilized compressed clay soil blocks relative to cement-stabilized sand soil blocks are few in number and scope. Few studies have been reported on the behavior of compressed stabilized soil blocks produced from natural soil without blending external sand. James et al. [25, 26] investigated the water absorption, compressive strength, and efflorescence behavior of soil blocks produced from stabilized natural clay soil blended with sugarcane bagasse ash. Therefore, there is a need to investigate the important mechanical behavior of compressed stabilized soil blocks made up of natural soils without reconstituting them by blending them with external sand. This investigation aimed to reveal the important mechanical behavior of manually compressed lime-cement-stabilized soil block produced from two types of natural soil. The behavioral difference between lime-cement-stabilized compressed clay soil block and cement-stabilized silty sand soil block is elucidated in this study.

## 2. Materials and Methods

*2.1. Material Characterization.* Two different types of soil from local areas of Jimma Town, Ethiopia, were selected and examined for the production of interlocking compressed stabilized soil blocks. The soil sample A is used by local people for the production of fired clay bricks and pottery works. Whereas soil sample B is used as selected material in subgrade fill locally. For this study, disturbed soil samples were extracted at a depth of 1.5 m below the natural ground level to avoid the unnecessary inclusion of organic debris. The index properties of the two-soil samples, such as grain size distribution, Atterberg's limit, specific gravity, and compaction test, were performed. A combined wet sieve and sedimentation analysis was carried out according to ASTM D 422 Standards [27] for particle size distribution analysis. The particle size distribution and the soil grading distribution of the two soil samples are depicted in Figure 1 and Table 1, respectively.

The compaction test as per the standard of ASTM D 698 [28] was performed on both soil samples. Figure 2 depicts the compaction test result for the two soil samples. The consistency limit test results according to ASTM D 4138 [29] and the specific gravity test results of the two soil samples were depicted in Table 2. According to the American Association of State Highway and Transportation Officials (AASHTO) soil classification system based on particle size

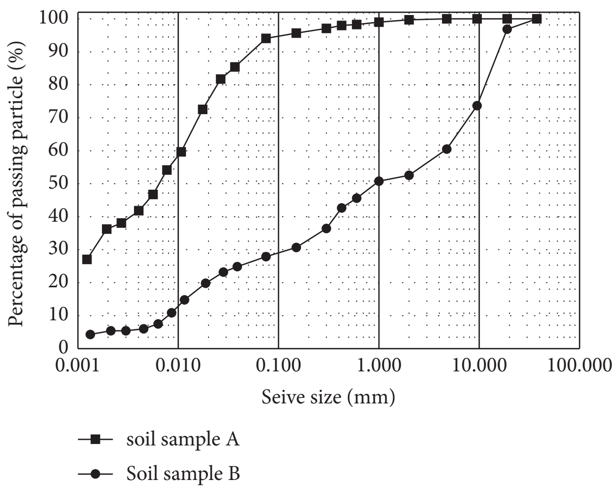



Figure 1: Particle size distribution curve.

Table 1: Soil grading distribution.

| Particle size range (mm) | Percentage of grading distribution (%) | |
|---|---|---|
| | Soil A | Soil B |
| Gravel (76.2 mm–4.75 mm) | — | 39.46 |
| Sand (<4.75 mm–0.075 mm) | 5.90 | 32.60 |
| Silt (0.074–0.005 mm) | 57.82 | 22.50 |
| Clay (<0.005 mm) | 36.28 | 5.44 |

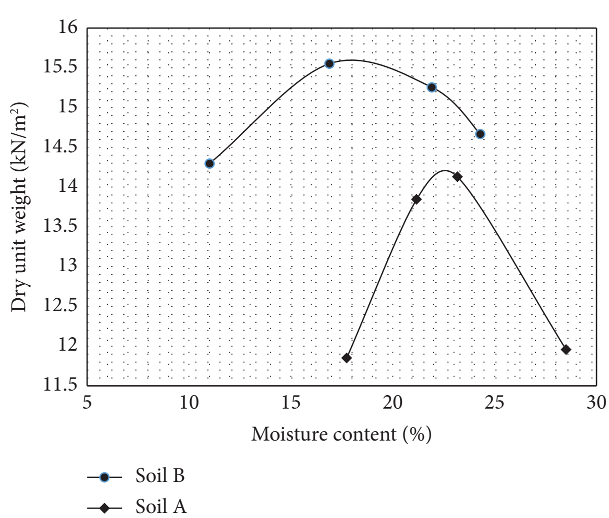



Figure 2: Compaction curve of the soil sample.

analysis and plasticity characteristics, the soil sample A was classified as silty-clay materials with significant constituents of clayey soils of group index 24 designated as A-7-6(24) and the soil sample B was grouped as silty gravel sand A-2-4. According to the unified soil classification system (USC), soil sample A is classified as inorganic clay of medium plasticity (CL), while soil sample B is grouped into silty sands (SM) with a plasticity index of less than 4.

Table 2: Soil consistency test result.

| Test | Soil A | Soil B |
|---|---|---|
| Liquid limit (LL %) | 46 | 30 |
| Plastic limit (PL %) | 22 | 27 |
| Plastic index (PI %) | 24 | 3 |
| Optimum moisture content (%) | 23.17 | 16.89 |
| Maximum dry unit weight (kN/m$^3$) | 14.13 | 15.25 |
| Specific gravity | 2.63 | 2.73 |

The major and minor chemical compositions of the two soil samples were examined using atomic absorption spectroscopy (AAS) by using the $LiBO_2$ fusion method, HF attack, gravimetric, and colorimetric analytical methods. Table 3 shows the chemical composition of the two soil samples. The result shows that soil sample A has a high composition of silica quartz ($SiO_2$) and a high loss of ignition percentage compared to soil sample type B, as shown in Table 3. Soil type B is mainly composed of quartz ($SiO_2$), alumina ($Al_2O_3$), and hematite ($Fe_2O_3$).

The crystalline phase of the two soil samples was identified by an X-ray diffractometer (XRD). Figure 3 depicts the peak-identified crystalline phase of the two soil samples. As can be seen from Figure 3, the crystalline phases identified in soil sample A were silica quartz ($SiO_2$), dolomite, and crystalline compound $C_{20}Cl_{10}$ $N_6$. While the main crystalline phases observed in soil sample B were silica quartz ($SiO_2$), tugtupite, and periclase (MgO). In addition, the identified XRD crystalline phase analysis of hydrated lime used as the stabilizer in this study constitutes mainly of silica quartz ($SiO_2$) and calcite (CaO, MgO).

*2.2. Stabilizer.* Portland pozzolana cement (PPC) and hydrated lime were used as stabilizer agents, depending on the index properties of the soil samples in this study. For soil B, which is coarse silty sandy soil with a low plasticity index, cement alone is preferred to achieve greater strength quickly [1, 6, 30]. Soil with a high plasticity index and constituting a considerable proportion of clay requires lime for immediate reduction of plasticity [18, 19, 31]. The lime added to clay soil first satisfies the affinity of clay minerals for lime ions to be ready for pozzolanic reactions [19, 31].

Therefore, 2%–4% lime by mass of soil with cement was used as a stabilizer for clay soil sample A. Table 4 shows the proportion of stabilizer in terms of the dry mass of the soil used for producing test specimens of compressed stabilized soil blocks.

*2.3. Sample Preparation.* Soil samples were excavated from a 1.5 m depth below the natural ground level of the site to avoid the unnecessary inclusion of organic debris. The extracted samples were air-dried for five days and sieved with a 4.75 mm sieve mesh size to achieve a smooth finish and good compaction as shown in Figures 4(a) and 4(b). For the known mass of soil, the stabilizer was added in proportion to the percentage of soil mass. The percentage of stabilizers used for the preparation of each specimen of the soil block is given in Table 4. After the soil was uniformly

TABLE 3: Mineralogical composition test result.

| Soil | Oxides composition in (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | MnO | $P_2O_5$ | $TiO_2$ | $H_2O$ | LoI |
| A | 73.38 | 6.88 | 4.70 | <0.01 | 0.14 | 0.10 | 1.86 | 0.06 | 0.10 | 0.42 | 3.41 | 8.43 |
| B | 66.04 | 14.50 | 8.46 | <0.01 | <0.01 | 0.70 | 4.23 | 0.08 | 0.14 | 0.22 | 1.73 | 3.88 |

*LoI stands for loss on ignition.

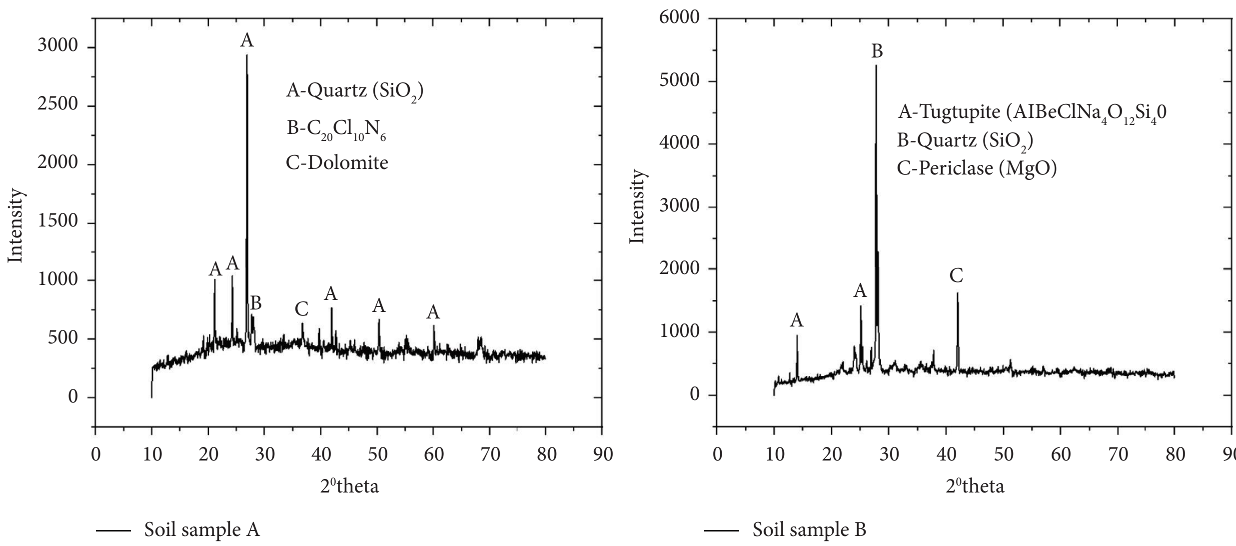



FIGURE 3: X-ray diffractometer test result of the soil sample.

TABLE 4: Proportion of stabilizer used for test sample.

| Binder proportion in % of the mass of soil | |
|---|---|
| Soil A (silty clay) | Soil B (silty sandy) |
| 2%lime + 6%cement | 6%cement |
| 3%lime + 8%cement | 8%cement |
| 4%lime + 10%cement | 10%cement |

(a) (b)

FIGURE 4: (a) Clay soil A and (b) silty sand soil B sample prepared for block production.

blended with the stabilizer, a measurable amount of water was added to the mix. The proportion of water was added to the mix on a trial-and-error basis until suitable moisture content and consistency were obtained. This can be checked after each trial by making a ball of mixed soil with water by hand and dropping the soil ball from the hand approximately from the height of 1 m. If the hand is not wet and the dropped ball of soil is not too fragile but also not too sticky, an optimum proportion of water is obtained in the mixture. From this trial-and-error, it was observed that a measurable amount of water in the range of 10–15% by mass of soil results in a consistent and suitable mixture for soil block preparation. For lime-cement-stabilized soil A, first lime was added and then mixed with water. After 10 minutes of the lime fixation reaction of clay minerals with lime ions, cement was added to the soil and mixed with water.

Stabilized wet soil was poured into the bucket of the manual lever arm compressing machine shown in Figure 5(a). The machine molds and compresses the soil into the interlock soil block unit of size 300 mm* 150 mm* 100 mm in length, width, and height, respectively. In this investigation, to achieve consistent compressive pressure, only a single identified person whose weight is 82 kg operates the compressing of the mold throughout the whole production of test specimens. Under this operation, the manual lever arm compressing machine develops compaction pressure in the range of 1 MPa–1.5 MPa on the mold. After compression, a fresh block extruded from the machine is placed on a base plate prepared for this purpose as shown in Figure 5(b). To ensure desired moisture and temperature for continued hydration and development of strength, the produced test specimens were daily moistened. Cement-stabilized soil block B was moisturized daily for 7 days and lime-cement-stabilized soil block A moistened daily for 10 days. After curing, the test block was covered by a plastic sheet for the first 15 days after production.

*2.4. Experimental Test Program.* In this investigation, the dry density, the initial rate of water absorption, the saturated water absorption of the block for 24 hours, and the dry compressive strength of the compressed stabilized interlocked soil blocks produced from soil A and B were examined and presented. All the tests conducted in this study were performed according to the ASTM C-67 standard for brick sampling and testing [32]. Tests were conducted on five blocks for each stabilizer combination for every test presented in this study, and the average results from the sample tests were taken for discussion of the test results. Figures 6(a) and 6(b) depicts the samples of the blocks prepared for the experimental test.

*2.4.1. Dry Density of the Block.* The mass of the test block was measured after the test blocks were oven-dried for 24 hours at 105°C and divided by the net volume of the block to obtain the dry density of the block. For this study, the dry density of the five blocks for each stabilizer proportion was computed and averaged to obtain the dry density of the blocks for each stabilizer proportion. The dry density is computed as:

$$D_{\text{ry de nsity}}\left(\frac{\text{kg}}{\text{m}^3}\right) = \frac{\text{Oven dried mass (gram)}}{\text{net volume of block}\left(\text{mm}^3\right)} * 10^6. \quad (1)$$

*2.4.2. Initial Rate of Water Absorption.* In this study, the initial rate of absorption of soil blocks produced from two different soil types using various lime-cement stabilizer proportions was investigated according to the ASTM C-67 brick testing standard [32]. The oven-dried base of the block sample was immersed in a 3 mm depth of the water-filled tray size of 0.5 m* 0.5 m for a 1 minute duration to determine the initial rate of water absorption of the soil block per base area of the block, as shown in Figure 7(a). The initial rate of absorption is computed, as IRA = $30W/LB$, where IRA is the initial rate of absorption, $W$ is the actual gain in weight of the specimen in grams, $L$ is the length of the specimen in inches, and $B$ is the width of the specimen in inches.

*2.4.3. Water Absorption.* The soil block was dried in an oven at a temperature of 105°C for 24 hours to attain a constant dry mass. Once an oven-dry mass was recorded after cooling the specimen to room temperature, the test sample block was soaked in clean water for 24 hours, as shown in Figure 7(b), to obtain the wet mass of the test block. The percentage of water absorption computed for the test specimen is as follows:

$$\text{Water absorption}\,(W\,(\%)) = \frac{\text{wet mass of the block (g)} - \text{oven dry mass (g)}}{\text{oven dry mass}} * 100. \quad (2)$$

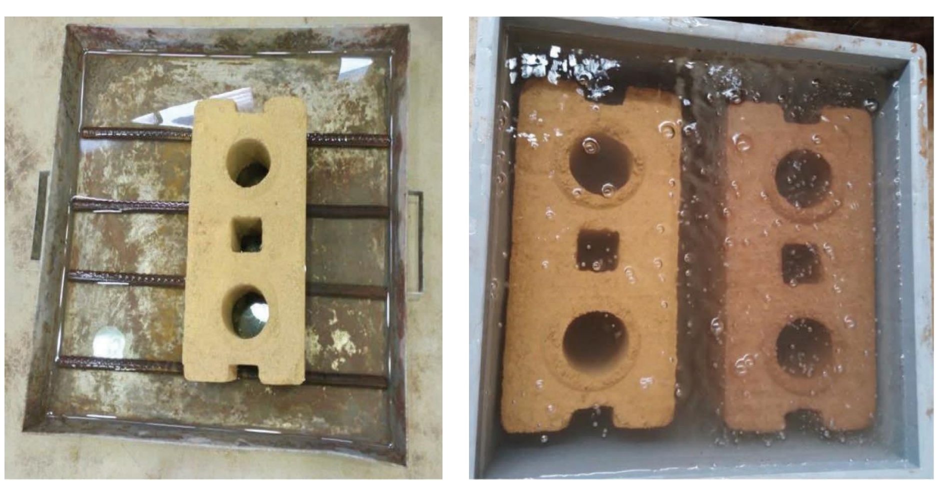
*2.4.4. Compressive Strength Test.* To evaluate the compressive strength and stress-strain relationship of the soil block, a compressive strength test was performed both on specimens of the full width and height but half-length plus 1 mm and on full-size soil blocks as per the ASTM C-67 [32] standard. The compressive test was performed at the age of 60 days after production to allow the lime-stabilized soil block to acquire sufficient time for hardening and the lime fixation reaction. The compressive strength test on a full-sized block was performed to check the impact of block size on the strength and fracture mode. The result on both full-size block and half-length specimens ensures the same compressive strength but differs in fracture mode as shown in Figures 8(a) and 8(b). Five oven-dried soil blocks from each stabilizer proportion of both types of soil blocks were tested using the UTEST compression test machine. To obtain consistent results, a load-controlled test was taken at a loading rate of 1 kN/sec. The vertical deformation with the corresponding compressive load of the test sample was recorded using a dial gauge reading. Figures 9(a) and 9(b) show the compressive test setup and test samples prepared for the compressive test, respectively. The compressive load

(a) (b)

Figure 5: (a) Compressing machine and (b) wet soil block placement.

(a) (b)

Figure 6: (a) Lime-cement-stabilized clay soil block A, (b) cement-stabilized silty sand soil block B.



(a) (b)

Figure 7: (a) Initial rate of water absorption and (b) saturated water absorption test-up.

(a) (b)

Figure 8: (a) Half-length block and (b) full size fracture mode soil block under compression test.

(a) (b)

Figure 9: (a) Compressive test set up and (b) test specimen.

obtained at each 0.05 mm interval of vertical deformation gauge reading is divided by the net cross-sectional area to determine the associated compressive stress. The strain at each interval was computed by dividing the vertical deformation change in mm by the initial height (100 mm) of the block.

## 3. Result and Discussion

The behavior of compressed stabilized soil blocks produced from lime-cement stabilized natural clay soil and cement-stabilized silty sand natural soil was investigated as the procedure described in Section 2.4. The result of the test is discussed and interpreted in the following section.

*3.1. Dry Density of the Block.* The dry density of the soil block depends upon the degree of applied compression pressure, the type of soil, and the moisture content of the soil at the time of applied compression [7]. Table 5 depicts the average dry density of the soil block produced from two different soil types with varied stabilizer proportions. As can be seen from Table 5, the block manufactured from cement-stabilized sandy soil B has a higher dry density than the block manufactured from lime-cement-stabilized clay soil A. in support of this previous study by walker [7] indicated that the dry density of the cement stabilized soil block decreases with the increase of clay proportion in the soil. The African standard for The earth block specification [33] limits the minimum required dry density of the soil block to at least 1,700 kg/m$^3$. From the test result, it was found that the soil block produced from natural clay soil with 2%L + 6%C did not meet the minimum the required specification for dry density as per the norm of African standards [33]. However, increasing the proportion of stabilizers from 2%L + 6%C to 3%L + 8%C improves the dry density of clay soil blocks and satisfies the minimum requirements of dry density for the soil blocks as per the African standards [33].

*3.2. Initial Rate of Water Absorption.* The average result of five tests on the initial rate of water absorption of the soil block base area of 30 in$^2$ (194 cm$^2$) in 1 minute for each stabilizer proportion is presented in Table 6. From the

Table 5: Dry density of the soil blocks.

| Block type | Block from soil A | | | Block from soil B | | |
|---|---|---|---|---|---|---|
| Stabilizer proportion | 2%L + 6%C | 3%L + 8%C | 4%L + 10%C | 6%C | 8%C | 10%C |
| Dry density (kg/m$^3$) | 1660 | 1799 | 1784 | 1986 | 1898 | 1951 |

L is for lime and C for cement.

Table 6: Soil block water absorption.

| Type of block | Block from soil type A | | | Block from soil type B | | |
|---|---|---|---|---|---|---|
| Stabilizer proportion | 2%L + 6%C | 3%L + 8%C | 4%L + 10%C | 6%C | 8%C | 10%C |
| Initial rate of absorption (g/min/30·in$^2$) | 40.32 | 29.16 | 25.53 | 52.08 | 46.49 | 40.87 |
| Saturated water absorption (%) | 22.77 | 20.68 | 19.56 | 20.5 | 19.25 | 18.96 |

result, it was observed that the initial rate of water absorption decreases as the proportion of the stabilizer increases in both types of soil blocks. In a line with this result, previous studies by Venkatarama Reddy and Gupta [9] showed that the initial rate of absorption of cement-stabilized highly sandy soil blocks decreased from 6.5 kg/min/m$^2$ to 1.6 kg/min/m$^2$ as the stabilizer proportion doubled from 6% to 12%. In this study, as depicted in Figure 10(a), the initial rate of soil block produced from lime-cement-stabilized clay soil decreases by 36.53% as the stabilizer proportion increases from 2%L + 6%C to 4%L + 10%C. While the initial rate of absorption decreases by 21.52% as the stabilizer proportion increased from 6% to 10% in the case of soil block produced from cement-stabilized silty sand soil. When it comes to comparisons, lime-cement-stabilized clay soil block A shows a low initial rate of water absorption in comparison to the soil block produced from coarse silty sand soil B stabilized by cement alone as depicted in Figure 10(a). High clay content in the compressed soil block decreases the initial rate of absorption because the fine nature of clay attributes low surface porosity of the soil blocks [34]. In the actual construction of masonry, the suction of water from fresh mortar due to the high initial absorption of the masonry unit negatively affects the development of the bond. ASTM C270-10 [35] specifies the maximum initial rate water of absorption of masonry units up to 30 g/min/30·in$^2$. Therefore, it's advisable to prewetting the base of soil block B produced from cement-stabilized silty sandy soil before placing it on fresh mortar. This ensures to maintain adequate moisture of grout mortar for cement hydration.

*3.3. Water Absorption.* The percentage of water absorption in a soil block indicates the durability of the block under extreme weather conditions and the presence of pores in the block. Table 6 depicts the percentage of absorbed water in terms of the dry mass of the soil block after soaking in water for 24 hours. The test result reveals that compressed lime-cement-stabilized clay soil block A absorbs more water than cement-stabilized sandy soil block B as shown in Figure 10(b). In support of this previous investigation on rammed earth construction, Kumar [36] revealed that the saturated water absorption of soil blocks increases with the percentage of clay proportion. In addition, the study presented by Baker et al. [37] on water absorption of interlock-compressed soil block produced using a hydraulic compression machine reveals that the maximum water absorption of interlock-compressed stabilized soil block is 15.09% in 24 hours and 17.18% for 5 hours of boiling water absorption. However, in this study, water absorption of 2%L + 6%C and 3%L + 8%C stabilized clay soil block is higher than 20%, the maximum allowable water absorption limit given in the specification of the earth block standard [33, 38]. The water absorption of cement-stabilized silty sand natural soil block B presented in this study is also greater than the water absorption of the reconstituted high sandy cement stabilized soil block discussed in the research work of Venkatarama Reddy and Gupta et al. [9]. Generally, high water absorption is observed in lime-cement-stabilized clay soil blocks. This limits the application of lime-cement stabilized compressed clay soil blocks in severe weather-exposed conditions.

*3.4. Compressive Strength.* The dry compressive strength test was performed on both full-size and half-length plus 1 mm test specimens according to ASTM C-67 [32] as described in subsection 2.4.4. Figure 11 depicts the average dry compressive strength of the soil blocks produced from soil types A and B with varied proportions of binding agents. It can be seen that the compressive strength of both soil blocks increases with stabilizer proportions, as revealed in previous related investigations [7, 9, 17]. When it comes to comparisons, the soil block B produced from cement-stabilized silty sand of low plasticity index, achieves greater compressive strength than the soil block produced from lime-cement-stabilized clay soil B of medium plasticity index at the early ages after production. Cement alone stabilized silty sand soil blocks attain higher compressive strengths at an early age due to the quick hydration of cement to form a cementitious gel to bind sand particles together. Lime added to clay soil builds strength over a long time due to gradual pozzolanic reactions between lime ions and clay minerals [18, 39, 40]. Nagaraj et al. [17] have reported a study on the effectiveness of lime cement over years in stabilized soil blocks produced from reconstituted sandy soil. Nagaraj et al. [17] found that lime-cement-stabilized sandy soil blocks built compressive strength after a year better than cement alone

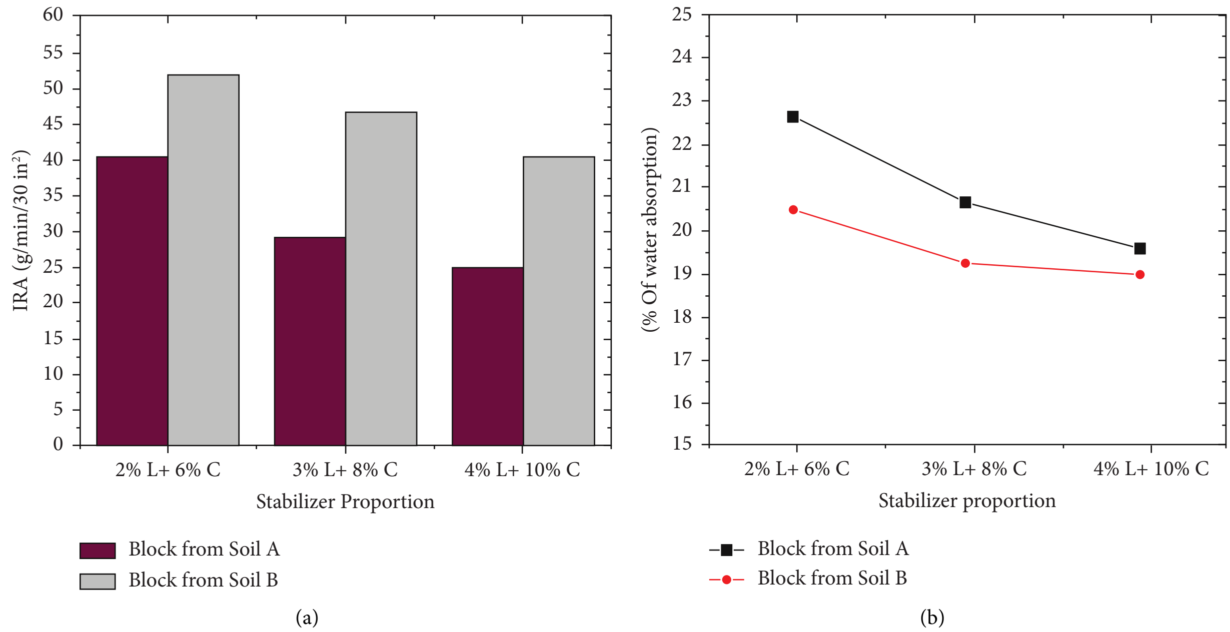



FIGURE 10: (a) Initial water absorption and (b) saturated water absorption test result.

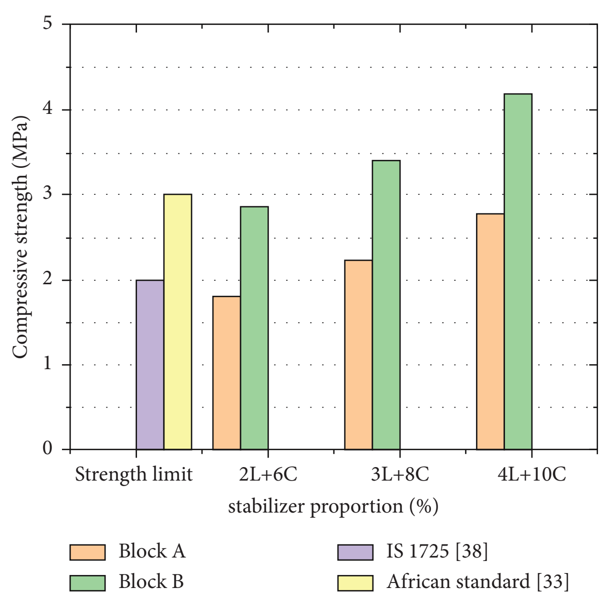



FIGURE 11: Compressive strength performance.

stabilized soil blocks. However, the effectiveness of the lime-cement combination in producing compressed stabilized soil blocks from silty clay soil has not been reported before as presented in this study. The contribution of lime to strengthening soil is time-dependent. Knowing the optimum ratio of lime to cement to produce compressed soil blocks from silty clay soil is crucial to achieving the minimum required compressive strength of soil blocks for load-bearing masonry structures. As can be seen from Figure 11 the compressive strength of soil block produced from soil type A stabilized with 2%L + 6%C by mass of soil gains less than 2 MPa compressive strength at the age of 60 days after production. But as the stabilizer proportion increases from 2%L + 6%C to 3%L + 8%C and 4%L + 10%C the compressive strength of the soil block produced from soil type A increases by 25% and 55.5%, respectively. Different standards give varied minimum requirements for the dry compressive strength of the soil blocks. The Indian standard for soil-based construction [38] limits the minimum required compressive strength of class 20 soil block to 1.96 MPa, while the African standard [33] limits the minimum allowable compressive strength of class C soil blocks to 3 MPa. Figure 11 shows the dry compressive strength of the soil block considered in this study along with the minimum dry compressive strength required for the two mentioned specifications. As can be seen from Figure 11 soil block A produced from lime-cement-stabilized clay soil did not meet the minimum strength requirement of class C block as of African standard [33]. However, except 2%L + 6%C stabilized clay soil blocks A, all the test blocks with the provided stabilizer proportion presented in this study adequately meet the minimum strength requirement of a class 20 soil block according to Indian standards [38].

The important mechanical behavior of the soil block produced from the two soil samples was determined from the stress-strain relation of the soil block under the uniaxial compression test as described in Section 2.4.4. The initial tangent modulus, secant modulus, yield strain, and ultimate strain of the soil block were derived from the stress-strain curve. Figures 12(a) and 12(b) show the typical stress-strain curve of 4%L + 10%C stabilized clay soil block and 10%C stabilized sand soil block, respectively. The initial tangent modulus is the slope of the tangent line to the elastic portion of the stress-strain stress curve, while the secant modulus is the slope of the line that passes through the origin of the curve and the

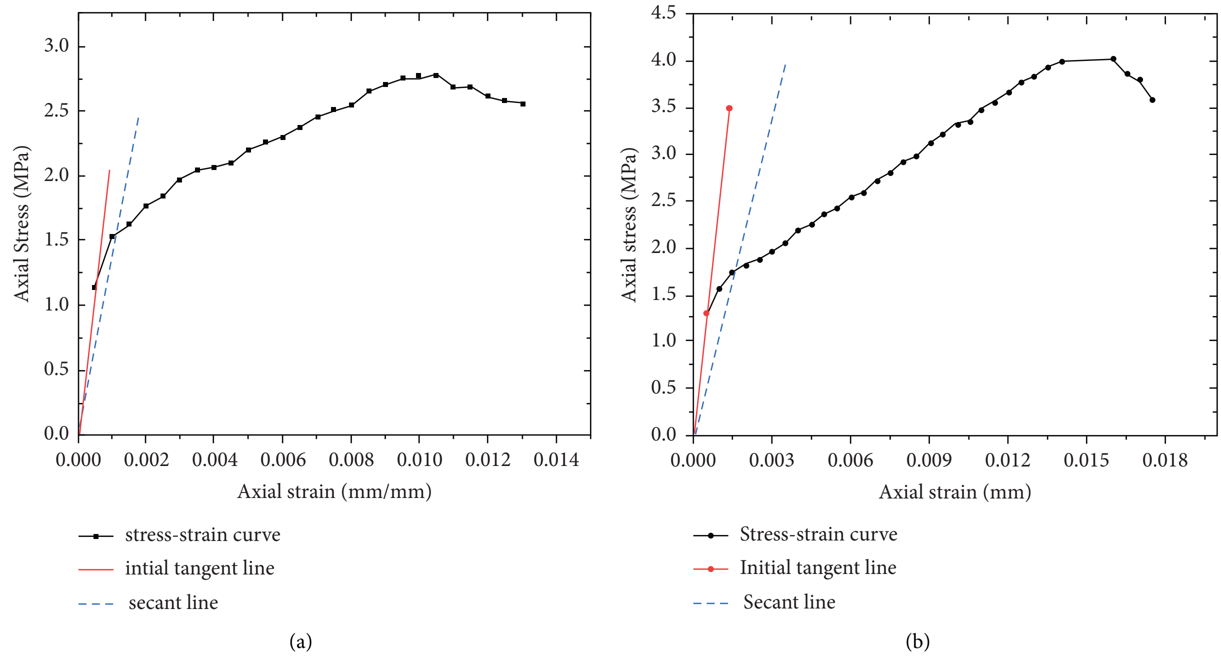



Figure 12: Stress-strain relationship of soil blocks. (a) Soil block from soil A (4%L + 10%C). (b) Soil block from soil B (10%C).

Table 7: Mechanical properties of soil blocks.

| | Block from soil type A | | | Block from soil type B | | |
|---|---|---|---|---|---|---|
| Stabilizer proportion | 2%L + 6%C | 3%L + 8%C | 4%L + 10%C | 6%C | 8%C | 10%C |
| Average compressive strength (MPa) | 1.8 | 2.25 | 2.8 | 2.87 | 3.38 | 4.2 |
| Mean initial tangent modulus (MPa) | 1721.5 | 2151.8 | 2305.5 | 2050.5 | 2155.67 | 2536.1 |
| Mean secant modulus (MPa) | 995.1 | 1227.7 | 1392.9 | 1147.8 | 1338.1 | 1122.0 |
| Standard deviation of initial tangent modulus ($\sigma_t$) | 2.55 | 2.85 | 3.1 | 2.20 | 4.20 | 5.62 |
| Standard deviation of tangent modulus ($\sigma_s$) | 1.47 | 1.77 | 2.1 | 2.30 | 3.87 | 4.83 |
| Average yield strain | 0.001 | 0.001 | 0.001 | 0.0015 | 0.0015 | 0.0015 |
| Average ultimate strain | 0.0085 | 0.0085 | 0.01 | 0.016 | 0.016 | 0.017 |

L stands for lime and C is for cement.

desired point on the stress-strain curve. For this study, the secant modulus is the slope of the secant line joining the origin to one-half (50%) of the peak axial stress point on the stress-strain curve. Table 7 depicts the mean and standard deviation of the initial tangent modulus and secant modulus of the five test samples for each stabilizer proportion. As can be seen from Table 7, the initial tangent modulus of the two blocks increases with the proportion of the stabilizer. The initial tangent of modulus of 4%L + 10%C stabilized clay soil block A is smaller than 10%C stabilized sandy soil block B by 9.09%. The previous related study by Venkatarama Reddy and A. Gupta [9] indicated that the initial tangent of modulus of 6% cement stabilized soil block produced from reconstituted sand soil by quarry dust is about 2,332 MPa which is greater than 2,050.54 MPa initial tangent modulus of 6% cement stabilized natural sand soil block presented in this study. The average ultimate strain of lime-cement-stabilized clay soil block A at the peak stress lies in the range of 0.0085–0.01 for the proportion of lime-cement stabilizer considered in this study. The ultimate strain at peak stress of cement-stabilized natural sand soil is about 0.016 and 0.017 for 6% cement and 10% cement stabilizer proportion, respectively.

## 4. Conclusions

In this paper, the physical and mechanical behavior of compressed interlocked soil blocks produced from two natural soils without reconstituting with external sand was presented. The two soils were stabilized by a varied proportion of lime-cement combination and cement alone depending upon the index properties of the soil. In this study, the silty clay soil A with a medium plasticity index was stabilized by a lime-cement combination, while the coarse silty sand soil B with a low plasticity index was stabilized by cement alone. The index soil properties, chemical composition, and crystalline phases of the two natural soils used for producing the test sample blocks are experimentally examined and presented in this investigation. The soil block properties such as dry density, the initial rate of absorption, water absorption, initial tangent modulus, and stress-strain relation of the soil blocks made from lime-cement-stabilized clay soil and cement stabilized silty sand soil of low plastic index, were revealed and compared. Generally, the following main findings were drawn from this study:

(i) The compressed soil block produced from cement-stabilized silty sand soil has greater dry density than a soil block made up of silty clay soil stabilized by a combination of lime and cement.

(ii) The initial rate of absorption of lime-cement-stabilized clay soil block decreases by 26.67% and 36.68% as the stabilizer proportion increases from 2%L + 6%C to 3%L + 8%C and 4%L + 10%C, respectively. 3%L + 8%C and 4%L + 10%C stabilized clay soil block satisfies the maximum initial rate of water absorption of 30 g/min/30 $in^2$ adopted by ASTM C 270 [35].

(iii) The initial rate of water absorption of cement alone stabilized silty sand soil block is higher than lime-cement-stabilized clay soil block. 10%C stabilized sand soil block's initial rate of absorption is 37.56% higher than the initial rate of absorption of a 4% L + 10%C stabilized clay soil block. The initial rate of absorption of a cement-stabilized sand soil block is higher than 30 g/min/30·$in^2$ the maximum initial rate of absorption required for brick as per the norm of ASTM C 270 [35].

(iv) The saturated water absorption of the soil block decreases as the stabilizer proportion increases, but it is not very sensitive to the stabilizer proportion. The water absorption of lime-cement-stabilized clay soil blocks decreased by 9.18% and 14.09% as the lime-cement stabilizer proportion increased from 2%L + 6%C to 3%L + %C and 4%L + 10%C, respectively.

(v) The saturated water absorption of 2%L + 6%C and 3%L + 8%C stabilized clay soil blocks is slightly greater than 20%, the maximum allowable water absorption adopted in a different standard of soil block-based construction [33, 38]. This restricts compressed lime-cement-stabilized clay soil block application in severe weather-exposed masonry construction.

(vi) At the age of 60 days after production, the dry compressive strength of soil block produced from the sandy soil of low plasticity index stabilized by cement alone achieves greater compressive strength by more than 50% of soil block made up from lime-cement-stabilized clay soil of medium plastic index.

(vii) The compressive strength of 3%L + 8%C, 4% L + 10%C stabilized of medium plasticity clay soil block meets the minimum compressive strength required for Class 20 block as per the norm of Indian standard [38], but failed to meet the minimum dry compressive strength of class C block required as per the African standard [25].

(viii) The initial tangent modulus and ultimate strain of the soil blocks manufactured using a manual compressing machine from clay soil stabilized by the lime-cement proportion of 2%L + 6%C, 3% L + 8%C, and 4%L + 10%C fall in the range of 1,700 MPa–2,300 MPa and 0.0085–0.01, respectively, with a dry density greater than 1,660 kg/$m^3$.

(ix) The soil block made up of cement stabilized in the proportions of 6%, 8%, and 10% from natural silty sand soil of low plasticity index without reconstituted external sand has an initial tangent modulus in the range of 2,000 MPa–2,500 MPa and ultimate strain of about 0.015–0.017.

This investigation findings show the physical and mechanical behavior of lime-cement-stabilized compressed interlock soil blocks produced from natural clay soil and silty sand soil without reconstituting with the natural sand. The study results demonstrated the effectiveness of using lime-cement-stabilized clay soil with a medium plasticity index and cement alone stabilized silty sand soil in the production of compressed stabilized soil blocks without reconstituting with natural sand. This would add to our understanding of the behavior of soil blocks produced from natural soils at their essence and the effectiveness of using lime-cement stabilizer in the soil blocks' production. The long-term effect of lime-cement reaction and durability aspects of lime-cement stabilized compressed clay soil blocks are not covered in this study and are recommended for future studies.

## Data Availability

The data that support the findings of this study are available from the author upon request.

## Conflicts of Interest

The author declares that there are no conflicts of interest.

## Acknowledgments

The author would like to thank his former undergraduate students Nestanet Endale, Abdi Firdisa, Hawi Dabesa, Natnael Tesfaye, and Nestanet Lopiso for their active participation in sample preparation. The author is also grateful to Eng. Fikru Gabre for providing a block compressing machine.

## References

[1] M. E. Schlesinger, M. J. King, K. C. Sole, and W. G. Davenport, *Mud Stablized Blocks Production and Use Technical Manual*, United Nations Industrial Development Organisation, Vienna, Austria, 2015.

[2] T. Morton, *Earth Masonry Design and Construction Guidelines*, IHS bre press, Bracknell, Berkshire, 2008, http://www.ihsbrepress.com, 1st edition.

[3] J. F. Rivera, R. Mejía de Gutiérrez, S. Ramirez-Benavides, and A. Orobio, "Compressed and stabilized soil blocks with fly

ash-based alkali-activated cements," *Construction and Building Materials*, vol. 264, Article ID 120285, 2020.

[4] B. V. Venkatarama Reddy and K. S. Jagadish, "Embodied energy of common and alternative building materials and technologies," *Energy and Buildings*, vol. 35, no. 2, pp. 129–137, 2003.

[5] B. Surekha, M. N. Hegde, and K. S. Jagadish, "Energy and building materials," *International Journal of Civil Engineering*, vol. 5, pp. 13–24, 2016, http://www.iaset.us.

[6] F. V. Riza, I. A. Rahman, A. Mujahid, and A. Zaidi, "A brief review of compressed stabilized earth brick (CSEB), CSSR 2010 - 2010," in *Proceedings of the2010 International Conference on Science and Social Research (CSSR 2010)*, pp. 999–1004, Kuala Lumpur, Malaysia, December 2010.

[7] P. J. Walker, "Strength, durability and shrinkage characteristics of cement stabilised soil blocks," *Cement and Concrete Composites*, vol. 17, no. 4, pp. 301–310, 1995.

[8] N. K. Sharma, S. K. Swain, and U. C. Sahoo, "Stabilization of a clayey soil with fly ash and lime: a micro level investigation," *Geotechnical & Geological Engineering*, vol. 30, no. 5, pp. 1197–1205, 2012.

[9] B. V. Venkatarama Reddy and A. Gupta, "Characteristics of soil-cement blocks using highly sandy soils," *Materials and Structures*, vol. 38, no. 280, pp. 651–658, 2005.

[10] Q. Piattoni, E. Quagliarini, and S. Lenci, "Experimental analysis and modelling of the mechanical behaviour of earthen bricks," *Construction and Building Materials*, vol. 25, no. 4, pp. 2067–2075, 2011.

[11] S. Chaibeddra and F. Kharchi, "Performance of compressed stabilized earth blocks in sulphated medium," *Journal of Building Engineering*, vol. 25, Article ID 100814, 2019.

[12] H. Binici, O. Aksogan, and T. Shah, "Investigation of fibre reinforced mud brick as a building material," *Construction and Building Materials*, vol. 19, no. 4, pp. 313–318, 2005.

[13] H. Binici, O. Aksogan, M. N. Bodur, E. Akca, and S. Kapur, "Thermal isolation and mechanical properties of fibre reinforced mud bricks as wall materials," *Construction and Building Materials*, vol. 21, no. 4, pp. 901–906, 2007.

[14] N. C. Consoli, P. D. M. Prietto, and L. A. Ulbrich, "Influence of fiber and cement addition on behavior of sandy soil," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 124, no. 12, pp. 1211–1214, 1998.

[15] P. J. Walker, "Strength and erosion characteristics of earth blocks and earth block masonry," *Journal of Materials in Civil Engineering*, vol. 16, pp. 497–506, 2004.

[16] B. V. Venkatarama Reddy and A. Gupta, "Strength and elastic properties of stabilized mud block masonry using cement-soil mortars," *Journal of Materials in Civil Engineering*, vol. 18, pp. 472–476, 2006.

[17] H. B. Nagaraj, M. V. Sravan, T. G. Arun, and K. S. Jagadish, "Role of lime with cement in long-term strength of compressed stabilized earth blocks," *International Journal of Sustainable Built Environment*, vol. 3, no. 1, pp. 54–61, 2014.

[18] D. T. Hilt, G. Harrison, and Davidson, *Lime fixation in clayey soils*, pp. 20–32, Highway. Research. Board, 1961.

[19] M. Khemissa and A. Mahamedi, "Cement and lime mixture stabilization of an expansive overconsolidated clay," *Applied Clay Science*, vol. 95, pp. 104–110, 2014.

[20] M. Y. Fattah, À. A. Al-Saidi, and M. M. Jaber, "Characteristics of clays stabilized with lime-silica fume mix," *Italian Journal of Geosciences*, vol. 134, no. 1, pp. 104–113, 2015.

[21] A. J. Alrubaye, M. Hasan, M. Y. Fattah et al., "Stabilization of soft kaolin clay with silica fume and lime," *International Journal of Geotechnical Engineering*, vol. 11, no. 1, pp. 90–96, 2016.

[22] P. Walker and T. Stace, "Properties of some cement stabilised compressed earth blocks and mortars," *Materials and Structures*, vol. 30, no. 9, pp. 545–551, 1997.

[23] M. Sassu, A. Romanazzi, L. Giresini et al., "Production procedures and mechanical behaviour of interlocking stabilized compressed earth blocks (ISCEBs) manufactured using float ram 1.0 press," *Engineering Solid Mechanics*, vol. 6, pp. 89–104, 2018.

[24] S. N. Malkanthi, N. Balthazaar, and A. A. D. A. J. Perera, "Lime stabilization for compressed stabilized earth blocks with reduced clay and silt," *Case Studies in Construction Materials*, vol. 12, Article ID e00326, 2020.

[25] J. James, P. K. Pandian, K. Deepika, J. M. Venkatesh, V. Manikandan, and P. Manikumaran, "Cement Stabilized Soil Blocks Admixed with Sugarcane Bagasse Ash," *Open Access*, vol. 2016, Article ID 7940239, 9 pages, 2016.

[26] J. James and P. K. Pandian, "Valorisation of sugarcane bagasse ash in the manufacture of lime-stabilized blocks," *Slovak Journal of Civil Engineering*, vol. 24, pp. 7–15, 2016.

[27] ASTM D-422, "Standard Test Method for Particle-Size Analysis of Soils," pp. 1–8, 2007, https://www.astm.org/d7928-21e01.html Astm. D422-63.

[28] ASTM D-698-91, "Standard Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort," 1991, https://www.astm.org/d0698-12r21.html.

[29] ASTM D4318 and A. Astm D 4318-10, "D4318-05, standard test methods for liquid limit, plastic limit, and plasticity index of soils," *Report*, vol. 04, 2005.

[30] F. V. Riza, I. A. Rahman, and A. M. A. Zaidi, "Preliminary study of compressed stabilized earth brick (CSEB)," *Aust. J. Basic Appl. Sci.*, vol. 5, pp. 6–12, 2011.

[31] F. G Bell, "Lime stabilization of clay minerals and soils," *Engineering Geology*, vol. 36, pp. 1283–1293, 1996.

[32] ASTM C-69/C67M-18, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*, ASTM, West Conshohocken, Pennsylvania, USA.

[33] The African Organization for Standardization (ARSO), *Compressed Stabilized Earth Blocks-Requirements, Production and Construction*, ARSO, Nairobi, Kenya, 1st edition, 2018.

[34] B. V. Venkatarama Reddy, "Stabilised soil blocks for structural masonry in earth construction," in *Mod. Earth Build. Mater. Eng. Constr. Appl*, pp. 324–363, Woodhead Publishing Limited, Sawston, United Kingdom, 2012.

[35] ASTM International and C. Astm, *10 Standard Specification for Mortar for Unit Masonry*, pp. 19428–2959, ASTM International, West Conshohocken, PA, USA, 2010.

[36] P. p. Kumar, *Stabilized Rammed Earth for walls Materials Compressive Strength and Elastic Properties*, Indian Inistitute of Science, Bangalore, India, 2010.

[37] B. H. A. Bakar, S. Saari, and N. A. Surip, "AIP conference proceedings 1892," *Water Absorpt. Charact. Interlocking Compress. Earth Brick Units*, 2017.

[38] M. Kisan, S. Sangathan, and J. Nehru, *Indian Standard Specification for Soil Based Blocks Used in Construction*, Indian Standard inistitution, New Delhi, India, 1982.

[39] N. O. Attoh-Okine, "Lime treatment of laterite soils and gravels - revisited," *Construction and Building Materials*, vol. 9, no. 5, pp. 283–287, 1995.

[40] A. A. Firoozi, C. Guney Olgun, A. A. Firoozi, and M. S. Baghini, "Fundamentals of soil stabilization," *International Journal of Geo-Engineering*, vol. 8, no. 1, p. 26, 2017.