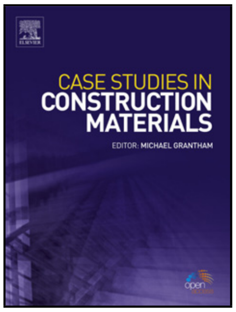

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Lime Stabilization for Compressed Stabilized Earth Blocks with Reduced Clay and Silt

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Abstract: Compressed stabilized earth blocks (CSEBs) are comparatively new earth-based materials similar to rammed earth, adobe, and bricks. Additionally, CSEBs can overcome the problems of fired bricks. The most common stabilizers used for CSEB production are cement and lime. Lime is environmentally friendlier than cement. This study was performed with the aim of finding the suitability of lime and lime-cement combinations as the stabilizer for CSEB production with reduced clay and silt contents. The soil selected for this study was modified to obtain clay and silt contents of 5%, 10%, and 15%. River sand was used to change the clay and silt contents of the soil. Lime percentages of 5%, 10%, and 15% by weight as the stabilizer were selected. The stabilized blocks were tested for dry density, water absorption, and 28-day wet and dry compressive strengths and were compared with the SLS 1382 standards. Cement-stabilized blocks with 10% and 8% cement by weight were prepared for comparison purposes. The study showed that lime alone did not give sufficient properties as specified in SLS 1382. From the percentages tested, 10% lime showed the maximum performance; hence, this optimum percentage of lime was replaced by cement contents of 3%, 5%, and 7%. Lime-stabilized blocks can be used for single-story buildings, while the combination of lime and cement stabilizers helped to obtain higher compressive strengths than that of lime alone. The other properties of the CSEB also meet all the specification values. Grade 2 block strength was achieved with the contents of 15% and 10% clay and silt with 5% lime: 5% cement combined stabilizer and 5% clay and silt contents with 3% lime: 7% cement combined stabilizer.

Keywords: Compressed stabilized earth blocks, Lime stabilization, Lime: cement combined stabilization

1. INTRODUCTION

Masonry constructions were introduced during the Mesopotamian civilization period (ca. 5000-3500 BCE). At that time, bricks and alluvial deposits were used for construction purposes (Deboucha and Hashim 2011). Currently, bricks are the most common building material used for masonry construction. According to a survey by the Department of Census & Statistics, in Sri Lanka, approximately 6.09 billion bricks were used in 2015 for construction works (Department of Census & Statistics 2016). Compressed stabilized earth blocks (CSEBs) are newly introduced blocks due to the issues identified with fired clay bricks. The primary issue regarding bricks is CO_2 emission during the manufacturing process of bricks, which leads to many environmental problems, such as acid rain and global warming.

The unfired bricks need less energy than the fired bricks, and the CO_2 emission to the atmosphere is 80% less than that of the fired bricks (Nagaraj et al. 2014). When CSEBs are used, CO_2 emissions can be controlled, and the adverse effects on the environment can be reduced. Additionally, the manufacturing costs of unfired bricks are low compared with those of fired bricks (Nagaraj et al. 2014). A comparison of CO_2 and energy emissions among different types of bricks is shown in Table 1.

Table 1: Energy emission comparison among different types of blocks

Type	Initial Embodied Energy per m³ of Wall	Pollution Emission (kg of CO_2) per m³ of Wall
CSEB wall	631 MJ / m³	56.79 kg / m³
Kiln-fired Brick	2,356 MJ / m³	230.06 kg / m³
Country-fired Brick	6,358 MJ / m³	547.30 kg / m³

(Source: www.earth-auroville.com)

Walker (1995) explained that most of the soil types have a lack of strength, durability, and stability in natural conditions. Hence, the properties of the soil must be improved by using both mechanical and chemical stabilization in CSEBs. Mechanical stabilization is compacting the soil material to reduce voids, and the chemical stabilization is adding stabilizers to the soil. Commonly used stabilizers are cement, lime, waterproof agents, chemical binders, bitumen, asphalt and natural and industrial byproducts (Walker 1995).

Lime and cement are the most common stabilizers used for stabilization in compressed stabilized earth block manufacturing (Deboucha and Hashim 2011). Lime has been used since ancient times as an earth stabilizer (Bell 1996) and is currently used for CSEB manufacturing (Raheem et al. 2010). Cement is the most popular stabilizer for earth block stabilization. Considering the manufacturing processes of cement and lime, energy and CO_2 emissions are high for cement as shown in Table 2 for 1 m³ of material (Alavez-Ramirez et al. 2012). Therefore, lime was selected as the stabilizer for this study.

Table 2: Energy emissions in the production of cement and lime blocks (Alavez-Ramirez et al. 2012)

Material	CO_2 emissions (kg)	Energy emissions (MJ)
Cement	73	772
Lime	54	583

1.1. Role of Lime Stabilization

Stabilization is used to improve the properties of CSEBs (Bell, 1993). Lime is the oldest material used in soil stabilization. When lime is added to clayey soil, the soil properties change. According to Bell's explanation, when the calcium ion in lime reacts with clay soil, metallic ion and cation exchange between them occurs. Therefore, the clay particles are surrounded by a diffuse hydrous double layer. This causes an alteration in the electrical charge density around the particles that makes the particles closer and forms flocks in a process called flocculation. This is the primary influence on the change in the engineering properties of lime-treated clay soils.

Past researchers have used different ranges of lime percentages as stabilizers. Alavez-Ramirez et al. (2012) used lime alone, lime combined with sugarcane bagasse ash (SBA) and cement alone for the stabilization of CSEBs. Sandy soil was used for CSEB production. The plasticity index and the liquid limit for the soil were 12% and 25.28%, respectively, and the clay percentage and silt percentage of the soil were 23.1 and 4.3, respectively. Alavez-Ramirez et al. (2012) achieved 28-day dry compressive strengths of 16.5 MPa with 10% lime and 23.5 MPa with 10% cement. Raheem et al. (2010) used laterite soil samples for lime stabilization with a 5%-25% lime percentage, and the highest 28-day compressive strength achieved was 1.25 MPa for 10% lime content. Guettala et al. (2002) used 8% lime as the stabilizer and changed the sand percentage between 0 and 40%. For 40% sand (clay 21.6%), 15 MPa dry compressive strength and 5 MPa wet compressive strength were obtained. Bell (1996) used 0-10% lime as the stabilizer, and concluded that the optimum percentage of the lime ranged between 4% and 6%. Ngowi (1997) used a 0-15% lime percentage as a stabilizer and obtained 15% as the optimum percentage. Akpokodje (1985) used different types of soil with different clay and silt percentages and used lime as the stabilizer. The lime percentage was selected as 0-12%, and the optimum percentages of lime for clay and silt percentages of 41%, 85%, 64%, 30%

and 29% were 10%, 12%, 6%, 12%, and 12%, respectively. Bogas et al. (2018) indicated from a review of past research that 6%-12% lime is the average advantageous percentage.

1.2. Role of the Combination of Lime and Cement as Stabilizers in CSEB

Combined lime-cement stabilization can be used to improve the long-term strength, which cannot be achieved with cement or lime alone. Nagaraj et al. (2014) used cement and lime combined as the stabilizer for CSEBs. The combinations used were 6% cement: 2% lime and 4% cement: 4% lime. A long-term high strength was obtained at the proportion of 4% cement: 4% lime. The combination of cement and lime was beneficial because the cement helps to stabilize the sand portion and the lime helps to stabilize the clay portion. Due to this, strength and durability can be increased (Nagaraj et al. 2014). Rahman et al. (2016) used clayey soil, sandy soil and a mix of clayey and sandy soil for block preparation. As the stabilizer, cement, lime and a combination of lime and cement has been used. They have shown that clayey and sandy soil mixed with cement stabilization gave the maximum compressive strength compared to other stabilization methods. However, for economic considerations, the combination of lime and cement for stabilization is better than cement alone.

Many studies have been conducted with different stabilizers for CSEB. The suitability of those stabilizers for soil with low contents of clay and silt (less than 15%) remains an area of research. The aim of this research is to determine the feasibility of using lime as a stabilizer for CSEB production using soil with low contents of clay and silt as a sustainable construction material. The objectives of this research are to determine the optimum percentage of lime as a stabilizer in CSEB and replace the optimum lime percentage with a percentage of cement to enhance the properties of the CSEB.

2. METHODOLOGY

2.1. Materials

In this study, soil, sand, lime, and cement were used to make CSEB. The soil was obtained from nearby borrow pits in Happugala, Galle, Sri Lanka. Geotechnical analyses were performed to determine the characteristics of the soil. The ASTM C136-06 Sieve analysis test and the ASTM D4318 Atterberg limit test, were conducted to identify the particle size distribution and plasticity index. Wet sieve analysis as per ASTM 117 was conducted to determine the clay and silt (fines) content accurately. The clay and silt content was 17.7%. A specific gravity test was also performed to identify the physical properties of the soil. The physical properties of the soil and sand are shown in Table 3. River sand was used to modify the fines proportion of the soil. The results of sieve analyses for three modified soil samples with fines contents of 5%, 10% and 15% and the original soil sample are shown in Figure 1. Combinations of the sand and soil by weight are shown in Table 4.

Table 3: Physical properties of the soil and sand

Properties	Soil	Sand
Plastic limit (%)	26.3	-
Liquid limit (%)	37	-
Plasticity index (%)	10.7	-
Specific gravity	2.49	2.58
Clay and silt (%)	17.75	0.04

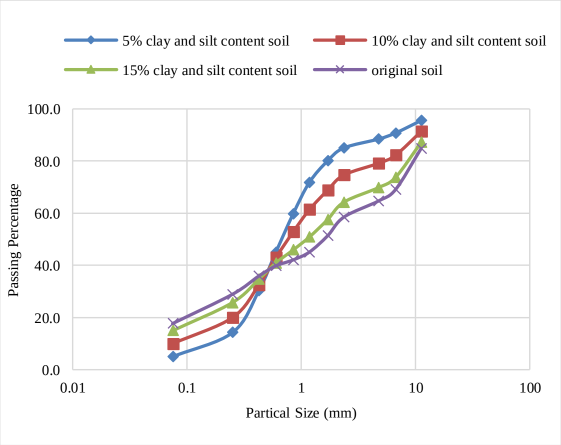

Figure 1: Sieve analyses for the modified soil and original soil samples

Table 4: Combination of the soil and sand Percentages for the modified soil

Percentage of silt and clay in modified soil	Soil percentage	Sand percentage
15	84.1	15.9
10	55.3	44.7
5	26.5	73.5

Both lime and a combination of lime and cement were used to stabilize the blocks. Cement-stabilized blocks were used to compare the results. Ordinary Portland cement was used with proportions of 10% and 8% by weight. Lime was added to each modified soil sample with 5%, 10% and 15% by weight, and the optimum lime percentage (10%) was replaced in each modified soil sample by 3%, 5% and 7% cement to make the CSEB specimens.

2.2. Manufacturing of the Test Blocks

First, the modified soil samples were prepared by mixing the dry soil and river sand. Then, the stabilizer was added to the modified soil samples in a dry state. A concrete mixture was used to mix the components. Then, gradually, water was added to the mix up to the optimum level. The optimum level of the water was ensured by the drop test according to SLS 1382 part 2. Nine blocks were cast from each mix proportion. Molds were used for block casting with dimensions of 150×150×150 mm. The mix was put into the mold in 3 layers, and every layer was compacted by 35 blows with a steel rod. The prepared blocks were cured for 7 days in a gunny bag on a damp-proof floor. Figure 2 shows the soil mixture and cast blocks.

Figure 2: Soil mixture and cast blocks

2.3. Testing of the blocks

The cast blocks were tested to determine their dry and wet compressive strengths, dry density and water absorption, as per SLS 1382 (Part 2). Each soil block was placed carefully in the testing machine below the center of the upper bearing block, and the load was added until failure. Using the load at failure, the compressive strength could be determined. Figure 3 shows the testing procedure of the cast blocks.

Figure 3: Block testing procedure

The dry density of the blocks was determined after keeping the blocks in the oven for more than 24 hours at 105^{0}C. Each specimen was oven-dried to a constant mass, weighed and measured to determine the dry density.

$$D_d = \frac{Drymass(Kg)}{Volume(m^3)} \times 10^6$$

To determine the water absorption of the blocks, oven-dried test specimens were immersed in water for 24 hours, and the increase in the mass of each oven-dried test specimen was calculated and expressed as a percentage of the initial dry mass of the specimen.

$$W = \frac{Saturated\ surface\ dry\ mass(g) - Oven\ dry\ mass(g)}{Oven\ dry\ mass(g)} \times 100$$

3. RESULTS AND DISCUSSION

3.1. Dry Compressive Strength

When considering lime stabilization, 10% lime addition helped to achieve the optimum block strength among the lime percentages used in this study (5%, 10%, and 15%). Hence, 10% lime was replaced with 3%, 5% and 7% cement to observe the increase in compressive strength with the combined stabilizers. Table 5 shows all the 28-day dry compressive strength results.

Table 5: 28-day dry compressive strength (N/mm^2) with various fines percentages and stabilizer percentages

Stabilizer	5% fines	10% fines	15% fines
15% lime	1.0	1.2	1.4
10% lime	1.6	1.6	1.7
5% lime	1.1	1.2	1.3
10% cement	3.2	2.3	2.1
8% cement	2.9	2.1	2.0
7% lime, 3% cement	1.4	3.5	1.2
5% lime, 5% cement	2.5	5.5	4.0
3% lime, 7% cement	4.1	3.0	0.8

The results in Table 5 are presented in Figure 4 and Figure 5 for better understanding.

For the lime-stabilized blocks, when the percentage of fines increased, the 28-day compressive strength also slightly increased. Considering the cement stabilization, when the fines content increased, the 28-day dry compressive strength decreased, but it was greater than the strength achieved with lime stabilization. The combined stabilizers helped to achieve 28-day dry compressive strength greater than that of the cement stabilization and lime stabilization alone. Additionally, lime stabilization and cement stabilization alone did not achieve 28-day dry compressive strength greater than the minimum specification value in SLS 1382 (2.8 N/mm^2). The combined stabilizers achieved compressive strength greater than the specification value.

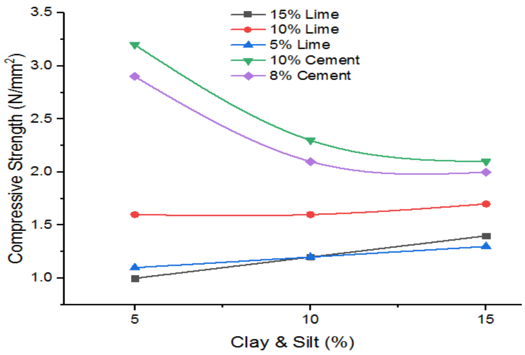

Figure 4: Variation in 28-day dry compressive strength for lime and cement stabilization

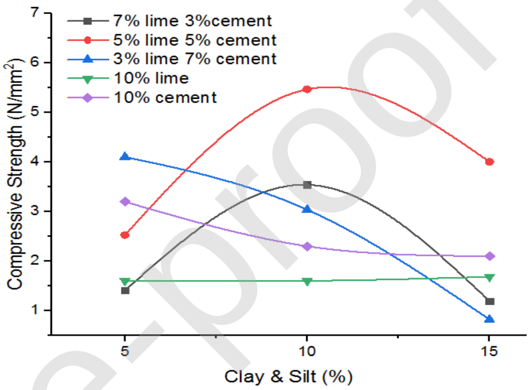

Figure 5: Variation in 28-day dry compressive strength for the combined stabilizers, 10% lime stabilizer and 10% cement stabilizer

3.2. Wet Compressive Strength

For the lime stabilization, 28-day wet compressive strength values for every percentage of fines in the soil blocks are less than or equal to 0.5 N/mm^2. However, the cement stabilization achieved a wet compressive strength greater than that of the lime stabilization, and 10% cement stabilization achieved a 28-day wet compressive strength greater than the specification value (1.2 N/mm^2). The variation in the 28-day wet compressive strength of the combined stabilizers was the same as that of the dry compressive strength. The optimum 28-day wet compressive strength was achieved at the same optimum percentage of the combined stabilizers as that of the 28-day dry compressive strength. Additionally, these strength values are greater than the specification value. Similarly, the soil blocks with 10% fines content achieved wet compressive strengths values greater than the specification value for all the combined stabilizer percentages. Figure 6 shows the variation in the 28-day wet compressive strength for lime and cement stabilization, and Figure 7 shows the variation in the 28-day wet compressive strength for the combined stabilizer, 10% lime stabilizer and 10% cement stabilizer.

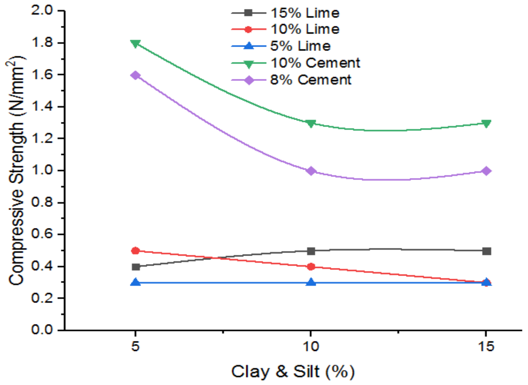

Figure 6: Variation in the 28-day wet compressive strength for lime and cement stabilization

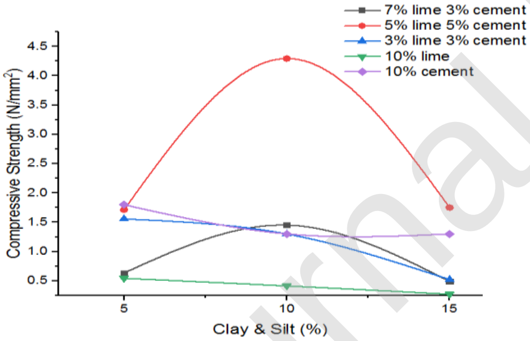

Figure 7: Variation in the 28-day wet compressive strength for the combined stabilizer, 10% lime stabilizer and 10% cement stabilizer

3.3. Water Absorption

The water absorption increased with the fines content for all stabilizer contents. For the soil with 15% fines content, 10% and 5% lime stabilizer and 5% lime: 5% cement combined stabilizer achieved water absorption less than the specification value (15%). For the soil with 10% fines content, only the 15% lime stabilizer content did not achieve water absorption less than the specification value. For the soil with 5% fines content, all the stabilizers achieved water absorption less than the specification value. The content of 5% lime stabilization achieved the minimum water absorption compared with that of other stabilizer contents. Table 6 shows the water absorption of CSEB with various clay percentages and different percentages of stabilizers.

Table 6: Water absorption (%) with various clay percentages and various stabilizer percentages

Stabilizer	5% fines	10% fines	15% fines
15% lime	10.8	15.7	18.6
10% lime	8.9	12.8	13.0
5% lime	6.2	10.2	12.4
10% cement	5.9	12.5	18.5
8% cement	7.2	14.3	19.1
7% lime 3% cement	11.7	12.0	17.3
5% lime 5% cement	9.1	10.1	14.2
3% lime 7% cement	9.1	10.2	15.9

3.4. Dry Density

SLS 1382 specifies that the compressed stabilized earth blocks should have a dry density greater than 1750 kg/m³. For all percentages of stabilizers, when the clay percentage decreased, the dry density of the soil blocks increased, except for 8% cement stabilization. The dry density specification value was not achieved by the 15% lime-stabilized blocks at all percentages of clay and silt content. For the soil blocks with 15% fines content, only 10% and 5% lime stabilizer, 8% cement stabilizer and 5% lime: 5% cement combined stabilizer achieved a dry density greater than the specification value. For soil blocks containing 10% fines, 15% lime stabilization and 8% cement stabilization did not achieve dry densities greater than the specification value. Other than at 15% lime stabilization, soil blocks containing 5% fines achieved dry density values greater than the specification value. Table 7 shows the dry density of CSEB with various clay percentages and different percentages of stabilizers.

Table 7: Dry density (kg/m3) with various clay percentages and various stabilizer percentages.

Stabilizer	5% fines	10% fines	15% fines
15% lime	1737.3	1676.1	1610.7
10% lime	1954.0	1841.6	1763.5
5% lime	1817.6	1805.1	1798.8
10% cement	1889.3	1771.1	1547.2
8% cement	1822.3	1642.4	1763.9
7% lime 3% cement	1889.1	1882.7	1678.4
5% lime 5% cement	1877.2	1890.7	1815.5
3% lime 7% cement	1922.1	1808.6	1603.5

4. CONCLUSIONS

This study focused on the manufacturing of compressed stabilized earth blocks with lime stabilization for soil with low contents of clay and silt. The study was able to reveal the following findings.

- The optimum level of compressive strength achieved for 10% lime stabilized blocks was below the values specified in SLS 1382.
- 10% Lime stabilized blocks can be used for single-story building units (according to SLS 855, part 1 specification, the limiting value is 1.2 N/mm^2).
- For soil containing 15% and 10% clay and silt, all percentages of lime stabilization achieved the same strength, which was greater than 1.2 N/mm^2.
- For soil blocks containing low proportions of clay and silt, the combination of cement and lime is more suitable than lime or cement stabilization alone.
- The maximum strength was achieved with 5% lime: 5% cement for soil blocks containing 15% and 10% clay and silt and 7% cement: 3% lime for soil blocks containing 5% clay and silt. These strengths satisfied the SLS 1382 specification of Grade 2 blocks.
- For soil blocks with 5% and 10% clay and silt contents, the water absorption is less than 15%, which is the specified level in SLS 1382.
- The dry density of the blocks made with 5% and 10% clay and silt are above the specification value (1750 kg/m^3) given in SLS 1382.

When the clay and silt percentage decreased, an increase in the cement stabilizer percentage was useful. When a small amount of clay and silt is in the soil, a small percentage of lime needed to be added to obtain good strength. This was observed in the results with 5% clay and silt content. The cement stabilizer alone achieved a compressive strength of 3.2 N/mm^2 but the combination of 7% cement and 3% lime stabilizer achieved a compressive strength of 4.1 N/mm^2.

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Author Declaration

We wish to confirm that there are no known conflict of interest with this publication and there has been no significant financial support for this work that could have influenced its outcome. We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us. We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property. We further confirm that any aspect of the work covered in this manuscript that has involved.

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