Particle Packing Application for Improvement in the Properties of Compressed Stabilized Earth Blocks with Reduced Clay and Silt

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Abstract—**Soil as a building material has been used in different forms such as mud, adobe, rammed earth and bricks. The present study focuses on producing Compressed Stabilized Earth Blocks (CSEBs) giving attention to the particle size distribution in the soil mixture. The literature established that compressive strength significantly depends on clay and silt content and 25% of clay and silt produce optimum results while no attention has been given to the amount of other, larger particles. Soil grading refers to the combination of different-size particles in a soil mixture. The correct selection of sizes in the correct proportion may cause improvements in CSEB properties. This paper explains the application of particle packing technology for the improvement of CSEB properties. The theoretical concepts provide a continuous particle size distribution, and the soil used for the experiments also has a continuous particle size distribution. The soil used in the experiments was subjected to washing to reduce the clay and silt content. Separated clay and silt and large particles of different sizes were added to the mixture to match particle size distribution to the optimization curves as explained in particle packing theories. The experimental results show that the CSEB properties can be significantly improved by modifying particle size distribution to fit the suggested optimization curves. According to the results, the compressive strength improved by more than 50% with different amounts of cement stabilization. Significant improvements in the dry densities and water absorption ratios of blocks were observed with this particle size modification.**

Keywords-cement stabilized earth blocks; soil washing; particle packing; optimization curves; compressive strength

I. Introduction

Earthen materials are been used in civil engineering construction worldwide with different forms, such as mud, adobe, rammed earth and bricks. CSEBs are earthen materials made of soil that are stabilized with different additives, such as cement, fly ash, and lime. CSEBs have been investigated as a building material for their advantageous properties. Compressed earth blocks represent a cost-effective and environmentally friendly alternative building material to traditional masonry elements [1]. In practice, CSEBs are made of earth stabilized with up to 10% cement and pressed either using a hand-operated press or a hydraulically operated, machine-driven press [2]. CSEBs are available as bricks, blocks, interlocking blocks and hollow blocks. Earthen constructions have many advantages, such as thermal comfort, local employment creation and minimal impact on the environment [3]. The use of earthen constructions is not limited to developing countries, even in developed countries, such as Australia, approximately 20% of the new building market is occupied with earth-based construction projects [4]. Clay and silt content, cement percentage, and soil grading used for CSEB production influence the properties of CSEB [5]. Soil grading refers to a combination of different size particles in a soil mixture. The selection of the correct sizes in the correct proportion may improve CSEB properties. Correct sizes and proportion can be better explained with the theory of particle packing. With this background, the aim of this paper is to explain the application of particle packing technology for the improvement of CSEB properties. To achieve this aim, the following objectives were considered:

- The properties of CSEBs made with different soils and different particle size distributions were tested.
- The soil grade was modified to fit the optimization curve for CSEB production, and the improvements in block properties with different amounts of cement stabilization were assessed.

II. Literature Review

A compressed earth block (CEB), also known as a pressed earth block or a compressed soil block, is a building material made primarily from soil compressed at high pressure to form blocks. A mechanical press is used to form blocks out of an appropriate mix of fairly dry inorganic subsoil, non-expansive clay and aggregates. If the blocks are stabilized with a chemical binder such as Portland cement, they are called CSEBs [6]. There are different methods of producing building walls using soil, such as with CSEBs, wattle and daub materials, rammed earth walls, and cob, or in the recent past, mud blocks [7]. Compared to major masonry units such as burnt bricks and cement blocks, CSEBs have considerable advantages related to

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environmental effects. Author in [8] mentions low energy consumption and the use of recyclable material. Authors in [3] explained the advantages of using CSEB in developing countries, as the bricks do not need plastering because they have a finish that is the same as that for wire-cut bricks, hence significantly saving in cost. The major challenges with CSEB have been researched by many studies considering strength and durability. The amounts of clay and silt are the main factors that act both positively and negatively with the properties of CSEBs.

A. Strength of CSEBs

Compressive strength has become a fundamental and universally accepted unit of measurement to specify the quality of masonry units. Authors in [9] showed the relationship between the clay and silt content and the compressive strength for different soil-cement ratios. In the test results of [9], the compressive strength displayed an increasing tendency with decreasing clay content and, as expected, it was high for high cement contents. However, other researchers used a minimum clay content limited to 15% [2, 10]. Based on their experiments, the compressive strength has tendency to increase with decreasing fines content for different amounts of cement. Author in [9] concluded that high compressive strength can be achieved when the plasticity index is low and with 10% cement. However, he tested blocks made with soil having a minimum clay content of 15%. It was also shown in [5], that a compressive strength of more than 10N/mm^2 can be achieved, even with a low plasticity index, when the clay content is between 10% and 15%. The mechanical properties of soil blocks with fiber reinforcement for two different soil types have been investigated in [11]. Both soils had more than 40% clay and silt content. For these soil types, the maximum compressive achievement was limited to 3N/mm^2, even with fiber reinforcement. Authors in [12] reported compressive strengths of 1.2, 1.9 and 2.4N/mm^2 with 5%, 8% and 10% cement, respectively, when the soil plasticity index is 13.4. Authors in [13] reported compressive strength results of 2.8 and 1.2N/mm^2 for CSEBs with 7.5% cement and soil having a plasticity index of 12.6 and 14.4 respectively. However, they did not consider any durability issues. In general, CSEBs with a minimum clay content of 15% have been tested in many studies, but the amount of larger particles has not been considered, which is the main focus of this paper.

B. Application of Particle Packing Technology for CSEBs

Soil properties are the dominant factor of CSEBs' properties. Different researcher groups found different soil particle combinations, ingredients, etc. Particle packing technology is an important aspect of concrete technology to select appropriate sizes and shapes of aggregates. The purpose of this section is to review particle packing technology, its application in different areas, and to match it to CSEBs. Particle packing technology considers optimizing the right sizes and amounts of various particles to increase particle density [14]. Additionally, the packing of aggregates for concrete is the degree of how well the solid particles of the aggregates are packed in terms of packing density [15]. The packing density is defined as the ratio of the solid volume of the aggregate particles to the bulk occupied volume. At first, large particles fill the container with large voids and smaller particles are added to reduce the voids. Then, tiny particles are filled to further reduce voids and increase density [16]. When well-graded soil is used for CSEBs, it increases the strength property of the soil blocks. Smaller particles should be selected to fill the voids between large particles to increase packing density. The concept of particle packing optimization has been used in the field of concrete technology, such as high-performance concrete [17] and interlocking paving block development [18]. Authors in [17, 18] focused on an ideal grading curve that represents the grading with the greatest density. These ideal curves help to perform mixture proportion optimization since it is easy to modify the total particle size distribution by adjusting the ingredient proportions. Most studies on particle packing use one of the following particle optimization methods:

- Optimization curves: Groups of particles with a specific particle size distribution are combined in a way that the total particle size distribution of the mixture is closest to an optimum curve. The following are such optimization curves [14, 19]:

$$P(d) = \left(\frac{d}{d_{max}}\right)^q \tag{1}$$

where $P(d)$=size cumulative distribution function, d=considered particle diameter (m), d_{max}=maximum particle diameter in the mixture (m), q=parameter (0.33-0.5) which adjusts the curve for fineness or coarseness.

Authors in [19] utilized (1) with q=0.5 and as per [14]. Others have suggested values of q in the range of 0.33-0.5. Equation (1) was modified with the adjustment factor q=0.37 for optimum packing [20]:

$$P(d) = \frac{d^q - d^q_{\min}}{d^q_{\max} - d^q_{\min}} \tag{2}$$

Author in [21] proposed a maximum density line that provides a guide to blend aggregates and obtain maximum density [21]. Authors in [14] showed that when the packing density is high, high compressive strength can be achieved.

- Particle packing models: These models are analytical models that calculate the overall packing density of a mixture based on the geometry of the combined particle groups. These models are discrete, hence, they consider the definite sizes of different particles.
- Discrete element models: These models simulate the virtual particle structure from a given size distribution.

Considering the nature of the above-mentioned three optimization methods, an optimization curve is used to compare the soils used in this study.

III. RESEARCH METHODOLOGY

As the main consideration of this paper, focus was given on particle packing concepts. First, different soil types were checked for clay and silt content. Specifically, a wet sieve analysis test was performed in accordance with ASTM 117 [22] to determine the clay and silt percentage of the tested soil samples. CSEBs were cast from all the tested soil types. Based on the research scope, one soil type was selected. The selected soil was washed in order to reduce clay and silt content. In this study, washed soil contained 5% clay and silt. This washed soil was used to produce CSEBs, and its grading was modified to match the particle packing concept by adding large-size particles that were separated from the same soil earlier. Then, previously separated clay and silt (fines) were added to create fine particle percentages of 5%, 7.5% and 10%. For each fines content, 4%, 6%, 8% and 10% cement content was used as stabilizer. For each combination, 10 blocks were cast, resulting in a total of 120 blocks. Blocks of 150mm×150mm×150mm were prepared using a commercially available cement sand block-making machine. Both vibration and compaction were applied for block casting. The vibration time was regulated based on the preliminary test conducted. Cast blocks were cured using wet gunny bags and sprinkling water for 7 and 28 days. The cast blocks were tested to determine their dry and wet compressive strengths, dry density and water absorption, as per SLS 1382 (Part 2) [23]. Each soil block was placed carefully in the testing machine below the center of the upper bearing block, and load was added until failure. Using the load at failure, the compressive strength could be determined. Figure 1 shows the testing procedure and cast blocks.

Fig. 1. Cast blocks and compressive test procedure

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

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

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

$$W = \frac{Saturated\ surface\ dry\ mass(g) - Oven\ dry\ mass(g)}{Oven\ dry\ mass(g)} \times 100 \quad (1)$$

IV. Testing the Particle Packing Applicability

Initially, five soil types designated as S1, S2, S3, S4 and S5 were selected for preliminary testing. The S1 soil is industrially washed soil. The S3 and S5 soils are naturally available lateritic soils. The S2 and S4 soils were derived by washing of the S3 and S5 soils, respectively, to reduce clay and silt content. Table I denotes the soil grading distribution for each soil. Figure 2 shows a comparison with optimization curves based on the theoretical grading curves explained above. All the theoretical curves were considered within the particle size region of 0.075mm to 12mm.

TABLE I. SOIL GRADING DISTRIBUTION

Soil type	Particle size			
	0-0.075	0.075-2.0	2.0-6.0	6.0-12.0
S1	5	82	9	3
S2	23	24	23	30
S3	35	25	15	25
S4	19	28	20	33
S5	40	30	10	25

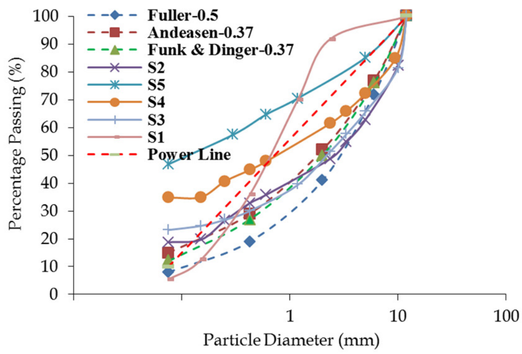

Fig. 2. Comparison of the particle distribution of the used soil with the theoretical distribution

These five types of soil with the same cement content added (6%) were used for block casting, and the cast blocks were tested after 28 days for wet and dry compressive strength, block density and water absorption. Considering the presented soil types and optimization curves, the particle size distribution of soil types S2 and S3 are closer to the optimization curves.

A. CSEB Properties vs Optimization Curves

Five selected soil types were used for CSEB manufacturing. Table II gives the tested properties for cast CSEBs. Among the studied soil types, blocks made with soil types S2 and S3 have comparatively high dry and wet compressive strength. However, the other properties of the blocks do not have the highest values but are within the acceptable range specified by [23-25]. These standards define compressive strength values under three grades and those are Grade 1 (strength value is above 6.0MPa), Grade 2 (4.0-6.0MPa) and Grade 3 (2.8-4.0MPa). The minimum density is 1750Kg/m^3 and the maximum water absorption is 15%. Blocks made with S1 soil type have high density but low strength. Therefore, blocks with S1 were tested with different cement contents, and the results are shown in Table III. The S1 soil has 5% fines after washing of the originally available soil. Figure 3 shows the graphical representation of these results.

TABLE II. BLOCK PROPERTIES (6% CEMENT)

Soil type	Fines %	Compressive strength (MPa)		Dry density (kg/m3)	Water absorption (%)
		28-day dry	28-day wet		
S1	5	1.06	0.55	1956	9.5
S2	19	3.01	1.55	1854	12.9
S3	23	2.95	0.82	1778	19
S4	33	1.98	0.69	1713	18.5
S5	40	0.99	0.25	1481	31

TABLE III. BLOCK PROPERTIES - VARYING CEMENT CONTENT

Cement %	Compressive strength (MPa)			Dry Density (kg/m^3)	Water Absorption (%)
	7-day dry	28-day dry	28-day wet		
4	0.56	0.71	0.47	1820	10.0
6	0.85	1.06	0.55	1956	9.5
8	1.95	2.26	1.27	1956	10.2
10	3.96	4.49	3.42	1940	8.75

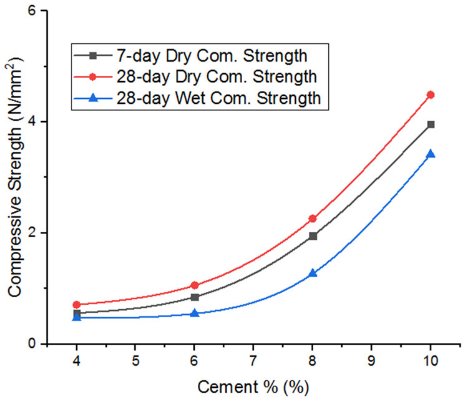

Fig. 3. Compressive strength of soil blocks with 5% fines, 20% quarry dust, and S1 Soil

Although the soil gradation does not match the available optimization curves, the strength can still be improved with cement addition. However, many past studies highlighted that more than 10% cement is not economical. Therefore, this study concerns soil grading near the optimization curve at low cement content. Therefore, the available S1 soil type was modified by adding larger particles to match the power line for CSEB production, and those blocks were tested. The final soil grading is shown in Figure 4 with the corresponding comparison to the optimization curves. This modified soil was used to cast blocks with varying cement content. Additionally, the influence of adding quarry dust was tested with 20% quarry dust and 0% quarry dust. Figure 5 shows the 28-day dry compressive strength for blocks made with modified S1 soil and 0% and 20% quarry dust for varying cement and fines content. We see that maximum compressive strength for all fines contents can be achieved with 10% cement content. Also, the use of quarry dust for the mixture does not have a significant influence on strength. The wet compressive strength, dry density and water absorption results for the tested blocks are shown in Table IV. The water absorption ratio clearly shows a notable improvement when optimizing particle packing. The dry density values also show that all the blocks made with upgraded soil arrangements achieve values of more than 1800kg/m^2. The SLS 1382 minimum value is 1750 kg/m^2.

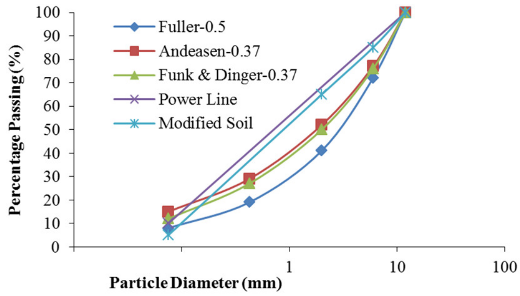

Fig. 4. Particle size distribution of the modified soil

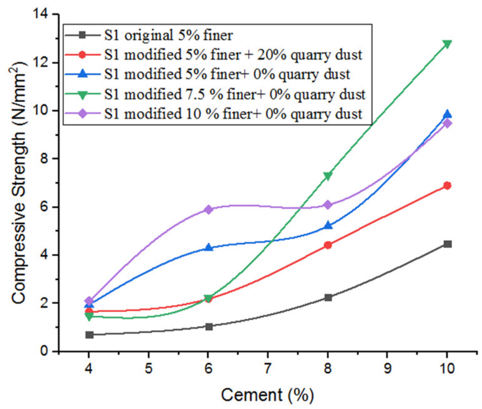

Fig. 5. 28-day compressive strength results of soil blocks with modified soil

TABLE IV. BLOCKS' DRY DENSITY AND WATER ABSORPTION

Soil type	Clay and silt %	Cement %	28-day wet compressive strength (MPa)	Dry density (kg/m3)	Water absorption %
S1 washed soil to obtain 5% fines, 20% quarry dust	5.0	4	0.47	1820	10.0
		6	0.55	1956	9.5
		8	1.27	1956	10.2
		10	3.42	1940	8.75
S1* and 20% quarry dust	5.0	4	1.17	2009	8.43
		6	1.26	2009	9.2
		8	2.75	2009	7.7
		10	5.26	2023	5.1
S1* and 0% quarry dust	5.0	4	0.88	1911	9.3
		6	2.73	2009	7.1
		8	4.54	2009	7.3
		10	5.65	2018	7.1
S1*	7.5	4	0.7	1890	11.3
		6	1.19	1961	10.1
		8	5.11	2009	7.5
		10	7.69	2055	6.8
S1*	10.0	6	3.2	1917	8.7
		8	3.8	1865	8.7
		10	5.9	1893	8.5

S1*: S1 modified to match the power line by larger particle addition

V. CONCLUSION

Compressed stabilized earth blocks (CSEBs) have been considered a key researched masonry unit over the past few decades. Many researchers have concluded that the compressive strength increases with decreasing clay and silt content. However, most researchers focused on the clay and silt content only. Their attempts focused on reducing clay and silt content by adding different soil, sand, etc. Further, studies of the influence of other larger particle sizes have not been extensively performed.

This study focused on rearranging the particle distribution of the soil to match the optimization curves while reducing the clay and silt content by soil washing. CSEBs produced with this rearranged soil showed improvements in their block properties. For this study, the soil was rearranged for three different clay and silt contents: 5%, 7.5% and 10%. The results show that high compressive strength can be achieved with 7.5% clay and silt content and 8% and 10% cement contents. Most of the compressive strengths are acceptable for Grade I blocks, as per SLS 1382. The dry density and water absorption ratio were also higher than the specified values in SLS 1382. This study mainly considered the strength characteristics of CSEBs. Many studies have been conducted on the durability of CSEBs with comparatively high clay and silt contents. Nevertheless, improvements are needed to enhance the durability of CSEB walls. Clay and silt content consist the main barrier to achieve the expected durability performance. Therefore, this research will be extended to test the durability issues of CSEBs with low clay and silt contents.

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