

RESEARCH ARTICLE

Construction Materials

Proposed mix design improvements of compressed stabilized earth blocks (CSEB) with particle packing optimization and coir reinforcement

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Abstract: The use of the earth as a building material has been practiced since the beginning of human civilization. Unburnt bricks, rammed earth, adobe, and burnt bricks are some of them. As a result of technological development, adobe has developed into a compressed stabilized earth block (CSEB). The clay percentage of the soil significantly affects the strength of the CSEB. This study focused on controlling the clay percentage by adding larger particles externally using building construction waste and reinforcing them with coconut coir. Different coir amounts by weight from 0.1% to 0.5% with different lengths of 2 cm, 4 cm, 6 cm, and 8 cm were considered for block production. For dry compressive strength and wet compressive strength, the combination of 0.3% coir amount with 6 cm coir length gave the maximum strength, and it also satisfied the required water absorption limit as per the Grade 1 category of the SLS 1382, part 1. After that, using the above combination, the industrial scale (350 × 100 × 175) mm size block was prepared, and its strength also satisfied the SLS 1382 Grade 1 requirements. According to the study, the manufacturing cost for the CSEB is lower than that of cement blocks and clay bricks. The cost for a 1 m² wall panel preparation using CSEB is 41.52% lower than preparing using burnt clay brick and 8.56% lower than preparing using cement blocks. Therefore, the CSEB can be used as a load-bearing walling material at a low cost and with eco-friendliness.

Keywords: Coconut coir, compressed stabilized earth blocks (CSEB), compressive strength, cost-effectiveness, particle packing optimization.

INTRODUCTION

Masonry is one of the most popular building construction materials because of its durability, cost-effectiveness, availability, and sound and heat insulation. Nowadays the consumer demand is for environmentally friendly construction materials. Compressed Stabilized Earth Block (CSEB) is a relatively new eco-friendly construction material. Generally available sandy soil and gravel soil are used as the main raw material while stabilizing with cement, lime, or other different additives to improve the properties of CSEB (Kongkajun *et al.*, 2020). The main advantage of the CSEB is its eco-friendliness due to low cement usage, and it is an unburnt block (Riza *et al.*, 2010). The manufacturing cost of CSEB is significantly lower than that of fired clay bricks and conventional concrete blocks.

Though CSEB is a sustainable building material, there are some issues associated with durability and strength (Abdullah *et al.*, 2017). The best known method for enhancing the properties of CSEB is stabilization. Stabilization agents such as cement, fly ash (Gurumoorthy & Shanmugapriyan, 2020), bottom ash (Danso *et al.*, 2015) and lime (Malkanthi *et al.*, 2020) can be added to enhance the properties of the soil. According to past

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studies (Hall *et al.*, 2012), the inclusion of cement significantly causes an increase in the strength of the soil, but higher cement content will increase the manufacturing cost of the CSEB. Walker (1995) highlighted that the use of more than 10% cement is not very economical during this process. Alam *et al.* (2015) and Segetin *et al.* (2007) also suggested that the 5–10% and 3–10% range of cement stabilization is more effective, respectively. Further, the availability of suitable material is a major concern in this CSEB production because it is an earth-based product. So, the variation of the soil properties highly affects CSEB production. The dry density and compressive strength decrease due to the poor bond of cement with soil particles, as well as finer clay and silt particles (Walker, 1995). Also, water absorption is higher when the clay and silt content is in the high range (Guettala *et al.*, 2002). The higher water absorption decreases the durability of the blocks. Some researchers have suggested different methods like soil washing to overcome this issue (Malkanthi & Perera, 2018) and adding larger particles to modify the soil (Malkanthi *et al.*, 2021). The use of recycled waste, such as building construction waste, can reduce the finer percentage in the mix and increase the number of larger particles. However, there is a limit to adding other sources. With that limit, further enhancement of the properties of CSEB can be carried out by reinforcing with fibres such as coconut coir (Thanushan *et al.*, 2021).

This study used building construction waste to modify the soil according to the particle packing concept and coconut coir as a reinforcement to enhance the properties of CSEB. Further, the study focused on the cost-effectiveness of the CSEB with coconut coir.

Applicability of particle packing concept for CSEB production

The particle packing concept states that the particles should be selected to fill the voids between soil particles to achieve the maximum packing density (Senthil & Santhanam, 2003). This theory has been used in concrete technology (Wong *et al.*, 2013) and later to produce interlocking blocks (Hettiarachchi & Mamppearachchi, 2019). It is a very useful concept to select the most suitable soil and densify the improper soils by adding the required particle sizes in CSEB production. Several past studies on particle packing density with this optimization concept are available. The particles are considered as a continuous distribution in Fuller's curve theory (Fennis & Walraven, 2012).

According to Malkanthi *et al.* (2021) and Malkanthi & Perera (2019), native soil extracted from different activities can be modified by adding larger particles according to the theoretical curves, as explained in the particle packing concept. This helps to achieve the maximum packing density. At the same time, this helps to reduce the clay content in the soil. The theoretical curves developed according to Fuller's equation (Equation 1) and Funk and Dinger's equation (Equation 2) (Fennis & Walraven, 2012) were used to modify the soil grading with the purpose of reducing clay content and maximizing the packing density.

$$P_d = (d / d_{\max})^q \quad (\dots01)$$

$$P_d = \frac{d^q - d_{\min}^q}{d_{\max}^q - d_{\min}^q} \quad (\dots02)$$

where,

P_d = size cumulative distribution function

d = considered particle diameter

d_{\max} = maximum particle diameter in the mixture

d_{\min} = minimum particle diameter in the mixture

q = parameter (0.33-0.5), which adjusts the curve for fineness or coarseness.

Fibre-reinforced compressed stabilized earth blocks

For the purpose of increasing the strength and durability of the cement-stabilized earth blocks, different materials like glass fibre, synthetic fibre, and natural fibres (coconut husk fibre, banana fibre, oil palm, wool, straw, etc.) are used as the reinforcing material of CSEB (Bahar *et al.*, 2004; Thanushan *et al.*, 2021). Further, most of the researchers have shown that the properties of CSEB have improved with the addition of coconut fibre in different quantities (Raj *et al.*, 2017; Rangkuti & Siregar, 2020; Thanushan *et al.*, 2021).

Nowadays, synthetic fibres are gaining more popularity than natural fibres. There are experimental investigations on the application of natural fibres due to environmental concerns. This research mainly focused on CSEB reinforced with coconut. Coconut coir is a low-cost, widely available material that can be easily incorporated with cement soil mixture and increase the durability and strength of the CSEB. Researchers state that the average coconut fibre diameter is approximately 0.2 mm, cut into 15 mm pieces to mix better with soil. In Sri Lanka, the cost of 1 kg of coconut fibre varies from 300 to 650 LKR (Sri Lankan Rupees) according to its grade.

Coconut fibre is a readily available material that can be obtained from the husk of the coconut fruit. Countries like Sri Lanka, India, Thailand, Vietnam, etc. supply coconut coir to the world. Generally, there are two types of coconut fibre. They are brown fibre and white fibre. Brown fibres are thick and strong and are obtained from matured coconuts, and the white fibres which are extracted from immature coconuts are smoother, finer, and weaker (Wazir, 2020). Commercially, coconut coir is available in three forms: Bristle fibre – long fibres, mattress fibre – short fibres, and Decorated fibre – mixed fibres. According to Dharmaratne *et al.* (2021), the average diameter and the density of the coir fibre are 0.31 mm and 1.018 g/cm³. These values may change from region to region. In the tensile test, ultimate tensile strength, Young's modulus, and elongation of the coir fibre ranged from 94–159 MPa, 1.2–1.8 GPa, and 21–67%, respectively. Also, Sri Lankan coir fibres are thermally stable below 220 °C.

MATERIALS AND METHODS

Soil is the main raw material of the compressed stabilized earth blocks. In this study, the soil was collected from a borrow pit in the Karapitiya area (southern region of Sri Lanka) and ordinary Portland Cement was added to stabilize the soil. Considering past research findings, 10% of cement addition by weight was used in this study to achieve the required strength with cost-effectiveness. The clay percentage of the selected soil was 18.98%. It has a plasticity index of 3.5%, and this soil can be categorized as slightly plastic. Most of the research has shown that soil with a plasticity index of less than 15% is suitable for CSEB production (Raj *et al.*, 2017; Malkanthi *et al.*, 2020). The low clay percentage significantly increases the strength and durability of the CSEB. The reduction of clay percentage in the soil was achieved by adding larger particles using building construction waste according to the particle packing optimization. Construction waste mainly consists of crushed concrete waste. Further, coconut coir was used as reinforcement. There are three types of coconut coir available in Sri Lanka: bristle fibre, mixed fibre, and decorticated fibre. Bristle fibre was selected for the research because it is lengthy and stronger than the other two. The diameter of the coir is approximately 0.2 mm.

Using the particle packing concept, the soil was modified to fit the particle distribution of soil to theoretical particle curves. Particle packing theory says how to optimize the particle size to minimize the void ratio. According to the optimization curves, as explained

in particle packing theories, soil particles of different sizes are added to the mixture to improve the packing density by reducing the voids, as shown in Figure 1. It shows that the large particles have filled 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 the density.

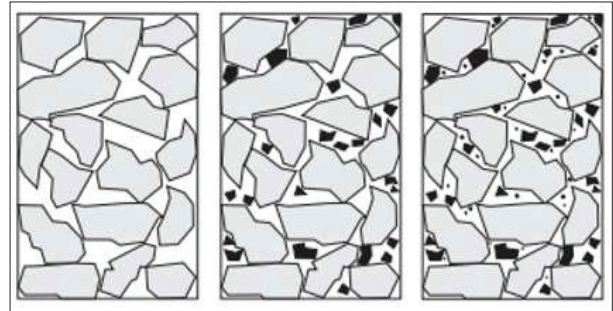


Figure 1: Particle packing concept (Senthil & Santhanam, 2003)

Figure 2 shows the graphical representation of Equation 1 and Equation 2. Further, it includes particle size distribution of the selected soil and construction waste. Finally, the particle size distribution of the modified soil by adding construction waste is illustrated. Coconut coir was added to the soil mixture as a reinforcement.

The clay reduction of the soil by adding building construction waste has limitations. The clay percentage of the selected soil was reduced from 18.98% to 12%. The governing factor for the properties of CSEB is the clay content, and most of the past studies have shown that limiting the clay content to 15% would give desirable properties to CSEB (Jayasinghe, 1999; Senthil & Santhanam, 2003; Reddy & Kumar, 2011a; 2011b). Further reduction of clay is not very practicable. So, further improvement of the CSEB was performed by adding coconut coir. After going through several research papers, the fibre length was varied as 2 cm, 4 cm, 6 cm, and 8 cm, with the amount of coir being 0.1%, 0.2%, 0.3%, 0.4%, and 0.5% of the total weight of the dry soil. The coir was combed using a wire brush to remove unwanted particles attached to the fibre and to get a straight fibre bundle. Then, those were cut into predefined lengths using a knife or scissors. All the materials were mixed by weight. For 10 kg of soil, 6.46 kg of construction waste and 1.0 kg of cement were used. Water addition was 8%-10% of the soil weight. The cubes (150 × 150 × 150 mm) were cast, and the properties of the cubes were tested. For each test, three specimens were used.

The optimum coconut coir combination, which showed the optimum desirable properties, was selected and using that combination, industrial scale $350 \times 100 \times 175$ mm

blocks were produced, and their properties were tested. Block preparation and testing were done following SLS 1382 Part 2: Test Methods.

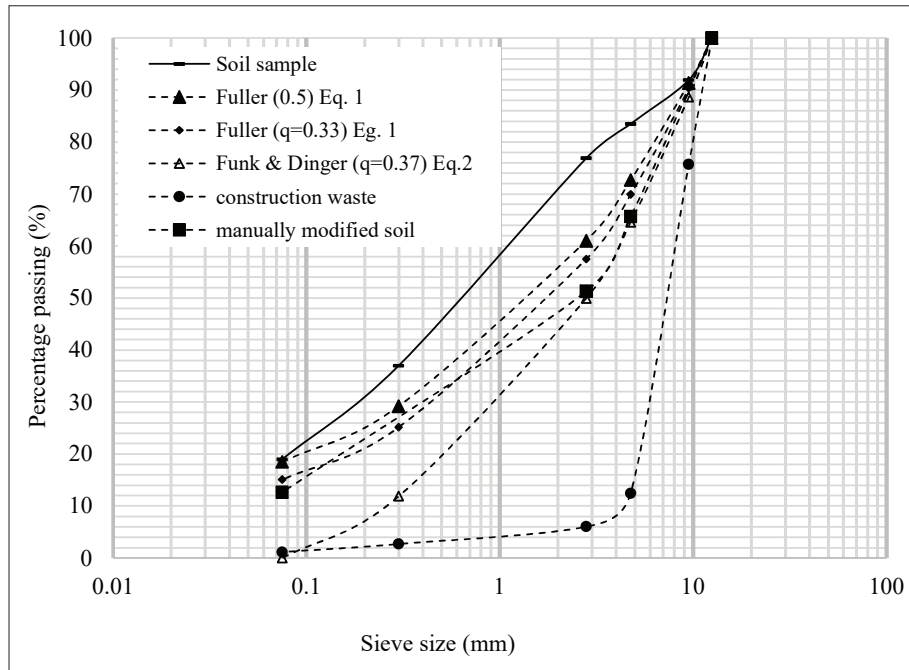


Figure 2: Particle size distribution of soil and theoretical particle packing curves

Finally, the cost of coir-reinforced CSEB was calculated considering the market rates of materials in August 2022. Furthermore, the cost of produced CSEB was compared with the market price of cement blocks of the same size. The unit rate of 1 m^2 of CSEB wall was calculated and compared to that of cement blocks and burnt bricks.

RESULTS AND DISCUSSION

The cubes were cast using modified soil with 10% Portland cement and different coir combinations. After 28 days of the curing period, cubes were tested and compared with Sri Lankan standards (SLSI, 2010a; 2010b). The 28 days of dry compressive strength values are shown in Figure 3. It shows that compressive strength first increases with the coir length and amount, and then it tends to decrease. When increasing the coir amount, the bond between soil particles and coir increases. Further addition of coir reduces the interfacial bond between soil particles and coir. In other words, the bond performance will loosen due to the high density of fibre. Similar behaviour has been shown in the studies done by Raj *et al.* (2017) and Thanushan *et al.* (2021).

According to Figure 3, the maximum dry compressive strength value was 8.0 MPa with the combination of 0.3% coir amount and 6 cm coir length. Also, it satisfies the SLS 1382, grade 1 strength condition (should be more than 6.0 N/mm^2). Based on the study done by Thanushan *et al.* (2021), the maximum compressive strength achievement was around 3.3 N/mm^2 when varying the coir amount from 0.0% to 0.6%. Raj *et al.* (2017) have achieved a compressive strength of 10.42 N/mm^2 at 0.8% of coir content.

The wet compressive strength variation with the different coir combinations is also shown in Figure 4. As for dry compressive strength, the maximum wet compressive strength was given from 0.3%, 6 cm coir combination, and the strength value was 5.60 MPa. Also, all wet compressive strength values are in Grade 1 as per SLS 1382 strength requirement (should be more than 2.4 N/mm^2).

Figure 5 shows the water absorption variation of the different combinations.

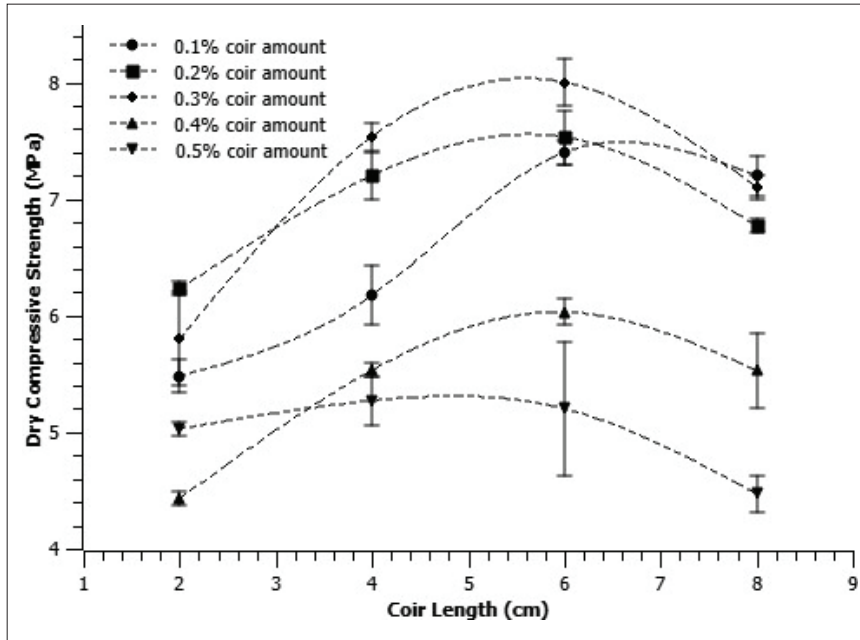


Figure 3: 28 days dry compressive strength vs coir length of CSEB

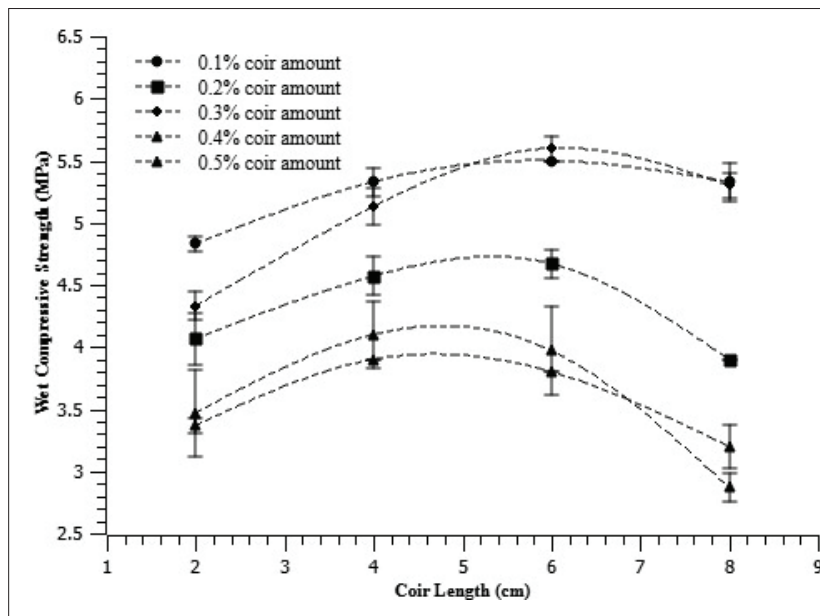


Figure 4: 28 days wet compressive strength vs coir length of CSEB

According to Figure 5, the water absorption of the CSEB increased with the coir length and the amount of coir. The maximum water absorption should be limited to 15% as

SLS 1382; Part 1. Finally, Table 1 shows the summary of the test results. Considering all the requirements, the standing of CSEB in SLS 1382 is also listed.

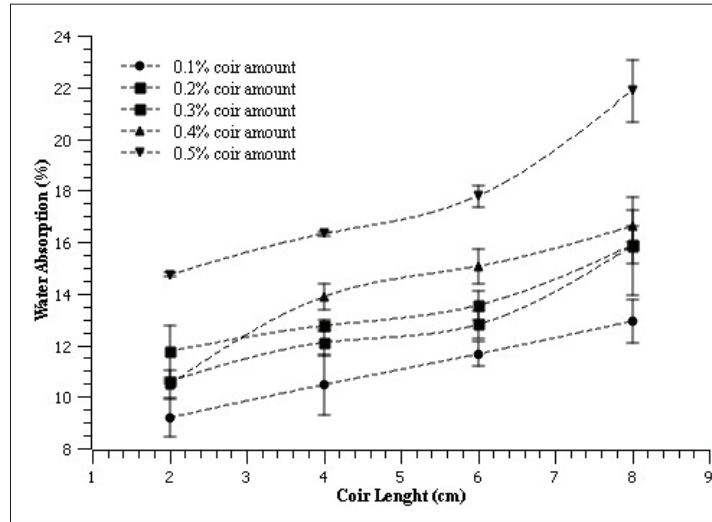


Figure 5: Water absorption of the CSEB with different coir combinations

Table 1: Summary of the test results

Coir amount	Length (cm)	28 days compressive strength (MPa)		Dry density (kg/m ³)	Water absorption (%)	Standing of CSEB in SLS 1382
		Dry	Wet			
0.1%	2	5.48	4.83	1,640	9.18	Grade 2
	4	6.17	5.33	1,649	10.46	Grade 1
	6	7.40	5.50	1,738	11.65	Grade 1
	8	7.20	5.33	1,719	12.93	Grade 1
0.2%	2	6.23	4.07	1,684	10.59	Grade 1
	4	7.20	4.57	1,669	12.09	Grade 1
	6	7.53	4.67	1,664	12.80	Grade 1
	8	6.77	3.90	1,610	15.83	Not satisfied
0.3%	2	5.80	4.33	1,763	11.75	Grade 2
	4	7.53	5.13	1,728	12.75	Grade 1
	6	8.00	5.60	1,723	13.54	Grade 1
	8	7.10	5.30	1,649	15.87	Not satisfied
0.4%	2	4.43	3.37	1,743	10.48	Grade 2
	4	5.53	3.90	1,649	13.87	Grade 2
	6	6.03	3.80	1,640	15.06	Grade 1
	8	5.53	3.20	1,546	16.61	Not satisfied
0.5%	2	5.03	3.47	1,615	14.72	Grade 2
	4	5.27	4.10	1,635	16.31	Not satisfied
	6	5.20	3.97	1,556	17.78	Not satisfied
	8	4.47	2.87	1,491	21.86	Not satisfied

6.0 MPa, 4.0 MPa, and 2.8 MPa are the dry compressive strength limits for Grade 1, Grade 2, and Grade 3, respectively. 2.4 MPa, 1.6 MPa, and 1.2 MPa are the wet compressive strength limits for Grade 1, Grade 2, and Grade 3, respectively. Water absorption should be less than 15% (SLSI, 2010a).

The optimum combination for the CSEB was selected as a 0.3% coir amount with a 6 cm coir length because that combination obtained the maximum dry and wet compressive strength with an acceptable water absorption

value. Then, using that combination, an industrial scale block (350 × 100 × 175 mm) was produced. The 28-day test results of the industrial scale CSEB block are shown in Table 2.

Table 2: Test results of the Industrial-scale block

Clay percentage (%)	Cement percentage (%)	28 days compressive strength (MPa)		Dry density (kg/m ³)	Water absorption (%)	Grade (As per SLS 1382)
		Dry	Wet			
12	10	Avg = 7.01	Avg = 4.41	1,677.64	12.79	Grade1
		SD = 0.07	SD = 0.08			

The industrial-scale block properties also satisfied SLS Grade 1 requirements.

The cost of the coconut fibre-reinforced compressed stabilized earth block is calculated for the laboratory cast block, which is 150 mm × 150 mm × 150 mm in size. After that, it was converted into an industrial-scale block. It is assumed that the manufacturing process for cement blocks can also be applied to this CSEB production. So, the same labour requirement was assumed. During the testing procedure, the average dry weight of a block is around 5.82 kg. Materials (dry soil, construction waste, cement, coir) requirement for one block production was calculated, and rates were calculated for these units of material considering market prices of August 2022. Finally, the estimated manufacturing cost for the compressed stabilized earth block was 91.00 LKR (Sri Lankan Rupees). If the CSEB market price is listed as Rs 105.00 with a 15% profit, the cost reduction by comparing with a normal cement block is Rs. 15, and

the estimated cost reduction percentage is 14.28%, considering the market value of cement blocks (average) was 120.00 LKR. So, the industrial-scale compressed stabilized earth block usage is more economical than the usage of normal cement block.

Furthermore, a 1 m², 4.5-inch thick wall panel with burnt clay brick needs 3136.86 LKR, and a 1 m², 4-inch thick wall with CSEB needs 2216.45 LKR, which is a 41.52% cost reduction over burnt clay brick usage. A 4-inch thick 1 m² wall with cement block needs 2,406.26 LKR, and it is 8.56% more costly than the CSEB wall cost. The unit rate calculations are shown in Table 3 and Table 4. The quantities were extracted from the Building Schedule of the Department of Buildings. Most of the CSEB walls are not plastered because of their external appearance, which results in further reductions in construction costs. Construction waste usage is also an eco-friendly method to reduce waste generation in the country.

Table 3: Unit rate calculation for CSEB wall and cement block wall

Item description	Unit	Quantity	Rate (Rs.)	Amount for CSEB (Rs.)	Amount for cement block (Rs.)
Hollow cement blocks (16" × 8" × 6")	No	112	105.00 for CSEB and 120 for cement blocks	11,760.00	13,440.00
Allow 5% for wastage	-	-		588.00	672.00
Cement	Bag	0.75	3,000.00	2,250.00	2,250.00
Sand	Cube	0.06	23,000.00	1,380.00	1,380.00
Mason	Day	1.5	3,000.00	4,500.00	4,500.00
U / SK laborer	Day	2.25	2,000.00	4,000.00	4,000.00
		Total for 1 square		24,478.00	26,242.00
		Rate for 1 m ²		2,631.40	2,821.00

Table 4: Unit rate calculation for brick masonry wall

Item description	Unit	Quantity	Rate (Rs.)	Amount (Rs.)
Bricks	No	550	25.00	3,750.00
Allow 5% for wastage	-	-		687.50
Cement	Bag	1.3	3,000.00	3,900.00
Sand	Cube	0.1	23,000.00	2,300.00
Water	Gal	50	0.30	15.00
Mason	Day	1.5	3,000.00	4,500.00
U / SK laborer	Day	2	2,000.00	4,000.00
		Total for 1 square		29,152.50
		Rate for 1 m ²		3,133.90

CONCLUSION

Green building techniques can help to create a better, environmentally friendly future. Compressed stabilized earth block is one of the eco-friendly building construction materials. The clay percentage of the soil significantly affects the strength of CSEB. The particle packing concept was used to modify the soil by adding different sizes of building construction waste to obtain the maximum packing density, and it helped reduce the clay percentage of the soil from 18.98% to 12%. Further reduction of clay percentage is not possible by adding waste particles. Therefore, fibre reinforcing of CSEB was done using coconut coir. It helps to improve the properties of CSEB. Both the coir length and the amount were varied.

To minimize the cost and to obtain the desired strength, 10% of Portland cement was used as the stabilizer. The maximum dry and wet compressive strengths were given with the combination of 0.3% coir amount and 6 cm coir length. The water absorption was increased with the increase of the coir amount and coir length. The 0.3%, 6 cm coir combination test results satisfied the SLS 1382 Grade 1 requirements. The cost reduction of industrial-scale CSEB was 8.56% compared to cement blocks and 41.52% compared to clay bricks. The use of CSEB for low-rise buildings is a cost-effective and eco-friendly solution.

This study focused on changing the coir amount and the length only. Due to the unavailability of facilities, other physical, mechanical, and chemical properties of coir, such as tensile strength, elastic modulus, and lignin of coir were not tested. Further, durability issues related to wetting expansion and drying shrinkage were not considered in the present study.

To enhance the properties of CSEB further, it is recommended to consider the durability of CSEB reinforced with natural fibres. Artificial fibre reinforcements also can be considered with different stabilization agents. The effectiveness of using fly ash, bottom, and plant resin can be tested as stabilizers.

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