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Investigation of the mechanical effects of coconut coir reinforcement on Compressed Stabilized Earth Blocks

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Abstract

Compressed stabilised earth blocks (CSEBs) are produced from inorganic soil compacted under high pressure to create a solid block. This study explores the potential benefits of incorporating coconut coir into CSEBs to enhance their mechanical properties and water absorption. It focused on optimising the mix design of CSEBs with coconut coir reinforcement to achieve maximum compressive strength and minimise water absorption. The study employs a quadratic model to analyse the effects of moisture ratio, cement ratio, and coconut coir content on compressive strength. The results indicate that the moisture content and cement ratio significantly affect compressive strength, while coconut coir content is insignificant. However, the findings suggest that adding coconut coir can reduce water absorption in CSEBs. The analysis of variance reveals that the model is significant, with a predicted R-squared of 0.5884 and an adjusted R-squared of 0.6592. The results contribute to the growing research on using coconut coir as a reinforcement material in CSEBs, offering practical recommendations for their application in building construction.

Keywords: Compressed Stabilized Earth Blocks; Coconut Coir; Coconut Fiber Reinforcement; Compressive Strength; Water Absorption

1. Introduction

In recent years, using earth as a construction material has become an attractive alternative to traditional building materials due to the increasing demand for safe and durable structures. Green buildings are designed to save energy costs by reducing energy consumption. The Kyoto Protocol committed the developed countries to reduce greenhouse gas emissions to tackle global warming and climate change. Some of the measures of the governments to achieve this goal are to promote new building constructions and to retrofit existing buildings while satisfying low energy criteria. This means improving the energy efficiency of buildings and energy systems, developing sustainable building concepts and promoting renewable energy sources. (Samer, 2013).

Compressed Stabilised Earth Blocks (CSEBs) have emerged as a promising solution, offering a unique combination of environmental and economic benefits. CSEBs are produced by compacting a mixture of soil, stabiliser (such as cement or lime), and water into blocks and then curing them (Omotainse *et al.,* 2022). One way to improve the properties of CSEBs is by reinforcing them with natural fibres. Coconut fibres, or coir, have been investigated as a potential reinforcement material for CSEBs due to their availability, low cost, and good mechanical properties (Velasco-Aquino *et al.,* 2020).

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The study aims to rigorously investigate the effects of incorporating coconut fibres into the CSEB mix design. The researchers recognise the potential benefits of this approach, including improved mechanical properties and enhanced sustainability. By conducting this research, they hope to contribute valuable insights that can guide the development of more durable and environmentally friendly construction materials.

2. Material and methods

The materials selected for this study were laterite, fibres (coconut coir), 42.5R Ordinary Portland Cement (a finely ground powdered product that acts as a stabiliser's agent) and water. The type of soil used in this research was laterite because it is readily available on the university premises.

2.1. Soil preparation

The soil was sundried for a couple of days. When it was perceived to have been adequately dried, it was crushed due to larger moulds and sieved through a 5mm mesh sieve to have a uniform and homogeneous soil mix. Before production of the blocks commenced, the laterite was taken to the laboratory for physical and mechanical testing. These properties include Grain size distribution (Percentages of Sand, Silt and Clay), Atterberg's limits (Liquid limit, Plastic limit, Plasticity index), Proctor test (Maximum dry density, Optimum moisture content) and Particle density (Specific gravity). The standard used was ASTM D 422 - Standard Test Method for Particle-Size Analysis of Soils.

The standard used was the ASTM D 2216, BS 1377 - Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures.

The water content level in the soil was calculated using Equation 1

$$M.C = \frac{Ma - Mb}{Mb - Mc} \ldots\ldots\ldots\ldots\ldots..(1)$$

Where, M_a is the mass of moist soil and wet can, M_b is the mass of moisture can and dry soil, M_c is the mass of moisture can only and M.C is th moisture content.

The specific gravity of soil is used in the phase relationship of air, water and solids in a given volume of the soil. The standard used was ASTM D 854-00 – Standard Test for Specific Gravity of Soil Solids. The Atterberg limit based on the moisture content was used to determine the plasticity index, plastic limit and liquid limit of the soil sample and the termite hill clay.

2.2. Coconut coir production

Coconut fibre or coir was obtained from whole coconut fruits, and the husk was manually removed before retting. The fibres were carefully separated from the husk and soaked in water to separate the fibres further. Coconut coir's physical and mechanical properties will also be tested and documented. These properties are the Length of a single fibre (mm), average diameter (mm), Tensile strength (MPa) and the modulus of elasticity (GPa).

2.3. CSEBs production

The response surface method was used for the experiment design to quantify relationships among one or more measured responses and the vital input factors. The Design Expert software was used to develop the experimental plan for RSM. The same software was also used to analyse the data collected. The design had three factors: moisture ratio, cement ratio, and coconut coir, at five levels each. The dry materials were mixed first until they achieved a uniform colour, then water was added and mixing continued until a homogeneous mix was obtained.

The compressive strength test was carried out for all block samples, and this was done using the Universal Testing Machine (UTM) to crush the bricks at the end of the curing periods (7, 14, 21 and 28 days). The compressive strength was obtained using Equation 2;

$$Compressive\ strength = \frac{crushing\ load\ (kN)}{area\ (m^2)} \ldots\ldots\ldots\ldots..(2)$$

3. Results and discussion

3.1. Engineering properties of the soil (laterite)

Some preliminary study was done to ascertain the physical and mechanical properties of the laterite soil used in this study. The study, which includes determining the moisture content, the Atterberg limits and the specific gravity of the laterite soil, is summarised in Table 1. The standard used was the ASTM D 2216, BS 1377 - Standard Test Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures, while the Atterberg limit was done in line with ASTM D 4318. Upon visual inspection, it was found to be light red clayey silt. The soil had a moisture content of 21%, a plasticity index of 7.63 and a specific gravity of 3.05. This shows that the laterite soil has intermediate plasticity (Liquid limit between 35 and 50%). The breakdown of the sieve analyses of the laterite soil used, which was carried out in line with ASTM D 422 - Standard Test Method for Particle-Size Analysis of Soils, is shown in Figure 1. The samples fell under the general classification of silty or clayey gravel and sand mineral because their percentages passing 75μm sieve were all less than 35%.

Table 1 Physical properties of the laterite soil

Test	Result
Moisture content (%)	21.0
Liquid limit	36.46
Plastic limit	28.59
Plasticity index	7.63
Specific gravity	3.05

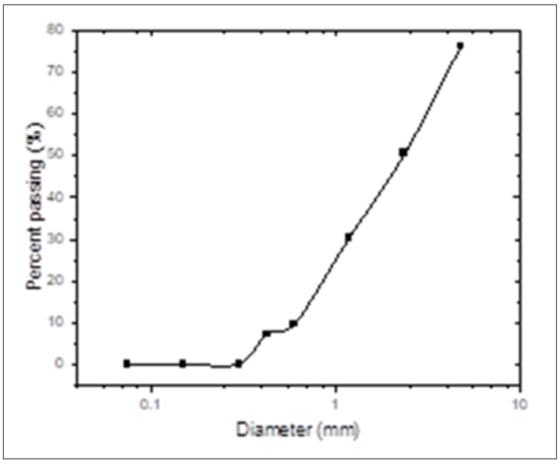


Figure 1 Graph of the Particle size distribution

3.2. Mechanical property of the coconut coir

The mechanical properties of the coconut coir were investigated using a Universal Testing Machine (Testometric material testing machine) and a digital veneer calliper. Random samples of the coir were selected, prepared and tested. The coir was irregular in shape, having a mean cross-sectional area of 0.204 mm^2 and a cut length of 100 mm. The testometric material testing machine was pre-tensioned to 0.500 N at a 10 mm/min speed. The coir samples were divided into two sets, the dry coir and the wet coir. The minimum, mean, maximum, standard deviation, coefficient of variation, lower control limit and upper control limit for the yield elongation, yield force, yield strain, yield stress, and young modulus were recorded and presented in Tables 2 and 3 for the dry and wet samples. The dry coconut coir had a minimum force at yield of 1.770 N, a maximum force at yield of 14.310 N and a mean force at yield of 8.934 N. The mean elongation at yield of 2.156 mm, stress at yield of 43.794 N/mm^2, strain at yield of 2.153 %, and the mean Young's modulus was 2506.793 N/mm^2. For the wet coconut coir, the minimum force at yield was 1.210 N, the maximum force at yield was 8.690 N, and the mean force was 5.911 N. The mean elongation at yield 1.633 mm, stress at yield 28.975

N/mm², strain at yield 1.631 %, and the mean Young's modulus was 1793.475 N/mm². The results from the mechanical properties of the coconut coir suggest that the dry coir fibres had higher mean values than those of the wet coir fibres. Dry coconut coir fibre was used to produce the CSEBs.

Table 2 Dry coconut coir mechanical properties

	Force at yield (N)	**Elongation at yield (mm)**	**Stress at Yield (N/mm²)**	**Strain at Yield (%)**	**Youngs modulus (N/mm²)**
Minimum	1.770	0.241	8.676	0.241	1416.549
Mean	8.934	2.156	43.794	2.153	2506.793
Maximum	14.310	3.023	70.147	3.020	3900.529
Standard Deviation	3.421	0.754	16.769	0.753	654.837
Coefficient of Variation	38.291	34.975	38.291	34.964	26.123
Lower Control Limit	6.487	1.616	31.798	1.615	2038.342
Upper Control Limit	11.381	2.695	55.790	2.692	2975.243

Table 3 Wet coconut coir mechanical properties

	Force at yield (N)	**Elongation at yield (mm)**	**Stress at Yield (N/mm²)**	**Strain at Yield (%)**	**Youngs modulus (N/mm²)**
Minimum	1.210	0.268	5.931	0.267	1088.533
Mean	5.911	1.633	28.975	1.631	1793.475
Maximum	8.690	2.975	42.598	2.971	2387.374
Standard Deviation	2.472	0.802	12.118	0.801	485.772
Coefficient of Variation	41.823	49.101	41.823	49.102	27.086
Lower Control Limit	4.143	1.059	20.306	1.058	1445.968
Upper Control Limit	7.679	2.206	37.645	2.203	2140.982

3.3. Mechanical property of the compressed stabilised earth blocks (CSEB)

The mechanical properties of the compressed stabilised earth blocks (CSEB) were investigated using a Universal Testing Machine to investigate the compressive force and measuring tape to calculate the surface area for both the treated CSEB and the controlled after 28 days of curing. For the treated CSEB, we got the highest Compressive strength of 6.17 MPa at a Moisture Ratio of 12%, Cement Ratio of 10% and Coconut Coir 0.75%. The highest compressive strength for our control CSEB after 28 days was achieved for samples with 10% cement content. Table 4 shows the obtained compressive strength values for the controlled CSEBs.

3.4. Water Absorption of the Blocks

After 28 days of curing, a water absorption test was carried out. The block with the lowest average water absorption rate among the treated CSEBs contained a mix ratio of 8% cement and 1.25% coconut coir, which had an absorption rate of 18.539 %. The highest water absorption was obtained from the block containing the mix ratio of 10% cement and 0.75% coconut coir, which had a water absorption rate of 24.226%. From the control block samples, the highest water absorption was obtained from the block with the mix ratio of 8% cement with an absorption rate of 34.603% and the lowest absorption was obtained from the block containing the mix of 10 % cement with a water absorption rate of 17.762%.

Table 4 Compressive strength of the Compressed Stabilized Earth Blocks (Control samples)

Cement %	7 days Compressive Strength (MPa)	14 days Compressive Strength (MPa)	21 days Compressive Strength (MPa)	28 days Compressive Strength (MPa)
2	1.833±0.28	2.449±0.11	1.343±0.14	1.533±0.08
4	2.221±0.19	3.109±0.20	3.148±0.16	3.088±0.21
6	2.595±0.31	4.254±0.08	2.505±0.08	3.284±0.63
8	2.641±0.72	3.426±0.20	4.313±0.03	3.938±0.47
10	3.077±0.39	3.842±0.46	3.984±0.06	4.831±0.32

3.5. Compressed Stabilised Earth Blocks Analysis of Variance

The data set was analysed by applying the square roof transformation as suggested by the software. A quadratic model was used as it was the model of best fit, and the interceptions of moisture ratio denoted as “A”, Cement ratio denoted as “B”, coconut coir denoted as “C, their interactions with each other and their squares were analysed. The results obtained from the analysis of variance with compressive strength as the response showed that the model was significant with a p-value less than 0.0001. The moisture content and the cement ratio, which had values of "Prob > F" less than 0.0500, indicate model terms were also significant. However, the coconut coir was insignificant as "Prob > F" values were greater than 0.0500. The result shown in Table 5 shows their sum of squares, differential factor, mean square F-value and P-value. From the results, all interactions between the term and their squares were insignificant except for the square of moisture content, where the model term was significant. The predicted R-squared of 0.5884 was in reasonable agreement with the adjusted R-squared of 0.6592.

A regression model equation was also generated from the analysis to calculate the square root of the compressive strength. The equation is shown in Equation 3.

$$\sqrt{\mathrm{CS}} = -7.76576 + 1.33453 \times \mathrm{MR} + 0.21165 \times \mathrm{CR} + 2.05306\ \mathrm{CC} - 0.00526374\ \mathrm{MR} \times \mathrm{CR} - 0.10445\mathrm{MR} \times \mathrm{CC} + 0.074362\ CR \times CC - 0.050921 MR^2 - 0.013541 CR^2 - 0.65719 CC^2 \ldots\ldots\ldots\ldots..3$$

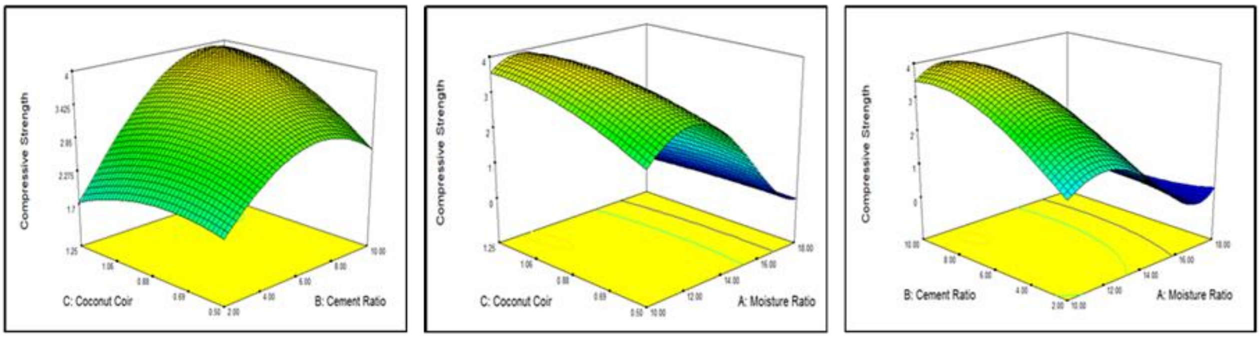
Where, CS is the compressive strength, MR is the moisture ratio, CR is the cement ratio and CC and coconut coir ratio.

Table 5 Analysis of variance of the treated CSEB

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob>F	Significant
Model	15.90	9	1.77	20.77	<0.0001	
A - Moisture Ratio	9.61	1	9.61	113.02	<0.0001	
B – Cement Ratio	0.34	1	0.34	4.05	0.0475	
C – Coconut Coir	0.031	1	0.031	0.37	0.5447	
AB	0.021	1	0.021	0.25	0.6182	
AC	0.13	1	0.13	1.54	0.2182	
BC	0.066	1	0.066	0.78	0.3796	
A^2	3.60	1	3.60	42.33	<0.0001	
B2	0.25	1	0.25	2.99	0.0873	
C2	0.15	1	0.15	1.72	0.1931	
Residual	7.06	83	0.085			

3.6. Optimised Relationship Between Coconut Coir, Cement Ratio and Moisture Content

An optimisation was also carried out for the square root of the compressive strength to maximise the compressive strength. The moisture content, cement ratio and coconut coir percentages were left in the range. The numerical optimisation of the results, showed optimum values for compressive strength at moisture ratio 11.48%, cement ratio 8.73% and coconut coir 1.4% with a desirability factor of 0.855, and it was selected and that gave a compressive strength of 3.9662 MPa. The following desirable selection when all factors are left with a range for compressive strength at moisture ratio of 11.435 %, cement ratio of 6.590 % and coconut coir of 0.812 %. When the cement ratio is minimised, moisture content and coconut coir are within range and the compressive strength is maximised, the numerical optimisation of results showed that for optimum values for compressive strength, moisture ratio of 12.19%, a cement ratio of 2.57 % and coconut coir of 0.74 % with desirability factor of 0.750 which gave a compressive strength of 2.5078 MPa. Figure 2 (A) shows the relationship between coconut coir, cement ratio and compressive strength, it is observed from plot that the effect of coconut coir at lower levels of cement ratio is very gentle, as represented by the slight curve but as distortion to the curve is observed as the cement ratio increases with almost an inverse effect where it is observed that higher percentages of coconut coir gave higher values of compressive strength as the cement ration increased as opposed to coconut coir giving lower valves for compressive strength for lower values of cement ratio. Figure 2 (B) shows the relationship between moisture ratio, cement ratio and compressive strength, which gave a downward wavey plot. It is generally observed that for all levels of cement ratio, the compressive strength had a slight bump and then gently declined as the moisture ratio increased. However, there was a gradual increase in the compressive strength as the cement ratio increased for all levels of moisture ratio. Figure 2 (C) shows the relationship between moisture ratio, coconut coir and compressive strength, the compressive strength had a gentle rise before receding at all levels of the coconut coir ratio as the moisture ratio increased. The compressive strength, however, slightly increased for all levels of moisture ratio as the coconut coir ratio increased.



A B C

Figure 2 (A) Optimised relationship between coconut coir and cement ratio, (B) Optimised relationship between coconut coir and moisture ratio and (C) Optimised relationship between cement ratio and moisture ratio

4. Conclusion

The results from this study provide valuable insights into the potential use of coconut fibre reinforcement in CSEBs. The analysis of variance showed that the moisture ratio and cement ratio were significant factors affecting the compressive strength of the CSEBs. At the same time, the coconut coir content was not a significant factor. Optimisation of the CSEB mix design showed that the maximum compressive strength of 3.9662 MPa was achieved with a moisture ratio of 11.48%, cement ratio of 8.73%, and coconut coir content of 1.4%. The coconut fibre-reinforced CSEBs' water absorption was lower than the control samples, with the lowest absorption rate of 18.539% for the mix with 8% cement and 1.25% coconut coir.

The results of this study suggest that incorporating coconut fibres can improve specific properties of CSEBs, such as water absorption, but may not significantly enhance the compressive strength.

Compliance with ethical standards

Acknowledgments

The research was undertaken at the Agricultural and Bioresources Engineering Department and the Concrete Laboratory of the Civil Engineering Department, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria.

Availability of data and material

The laterite soil, coconut coir and cement were sourced within and around the university premises. The data were obtained using a standard testing machine and calculated using available standards.

Disclosure of conflict of interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Authors' contributions

- POO is the lead researcher of this paper and has made substantial contributions since the conception and towards the design of this research work. He also plays a vital role in acquiring materials, analysing and interpreting data, and drafting this paper.
- OUD contributed substantially to the conception and design of this research work. He also plays a vital role in acquiring materials, analysing and interpreting data, and drafting this paper.
- AAB contributed substantially to the conception and design of this research work. He also plays an essential role in acquiring materials, analysing and reviewing the draft of this paper.
- AAA contributed substantially to the conception and design of this research work. He also plays an essential role in acquiring materials, analysing and reviewing the draft of this paper.
- OJA made substantial contributions to the conception and design of this research work. He also plays an essential role in acquiring materials and analysing and reviewing the draft of this paper.

All authors have read and approved the final manuscript

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