Article

Affordable and Sustainable Housing in Rwanda

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Abstract: Baked clay bricks (Impunyu) is the dominant wall construction material in Rwanda. Clay deposits in the country's lowlands are utilized for baked clay bricks. Despite the ongoing campaign, the use of wood by some local brick producers is unfriendly to the environment. Recent research has called for alternative methods in order to reduce the cost and impact on the environment. Earlier efforts with compressed earth blocks were saddled with weight and a substantial use of cement for good surface texture and adequate resistance against surface erosion. This research explored the potentials of using an appropriate dose of clay (from Muhanzi), volcanic light aggregate (Amakoro, (from Musanze)), and cement to produce unbaked shelled compressed earth blocks (SCEB). SCEB is a compressed earth block with an outer shell and inner core of different cement content or materials, compressed into a unit block. The result is a masonry unit with a higher surface resistance, durability, and desirable architectural effect produced with a 60% reduction in cement content. A weight reduction of 12% was achieved with an optimum content of 33% of the volcanic lightweight aggregate. A cost reduction of 25% was recorded over conventional compressed earth brick walls and a 54% over sand-cement block walls. Possible future trends were also identified with appreciable prospects in earthen architecture.

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1. Introduction

In Rwanda, about 75% of buildings are constructed with baked clay bricks [1]. The industrial subsector Masterplan for Construction Materials for Rwanda identified an abundance of available local construction materials, such as clay, wood, sand, and stone [2]. The hilly terrain of Rwanda creates a natural movement of surface water from the hills to the valley. Soils on the hills are generally stony, while clay and silt are washed from the highlands into the valleys, leaving large deposits of clay in some valleys. The efforts to utilize the existing local materials may well explain the popularity of baked clay bricks in the construction industry. While the formal brick industries are conscious of environmental issues posed by choice of firing materials by the use of rice or coffee husks (waste biomaterials), the informal local brick producers most often use wood with environmental effect on the forests. Furthermore, most firing burners are inefficient with incomplete combustion and substantial carbon emission. In the informal sector, the baked brick production can be seen to be cumbersome and labor intensive. Humanitarian News [3] reported of environmental concern as brick makers quarry near banks destroying natural vegetation. Since poor people directly depend on natural resources and natural services for their survival, a clear link between poverty reduction and environmental degradation is established [4].

While the baked bricks have firing issues, the cement stabilized soil blocks require 7 to 12% cement of content to produce a block of adequate resistance against surface erosion. The opinion that the addition of cement to earth raised fundamental sustainability questions against earth construction was laid to rest by the analysis made by Walker and Standards Australia [5], which indicated that clay bricks consume between 1.0 and 7.0 GJ

per ton, of which 80% to 90% is used in drying and firing, thus replacing firing with cement stabilization and reducing the energy consumed in the block production process by at least 50%.

Attempts were made at solving the limitations of ‘earth’ as a building material [6–9]. The prospect of durability of earth walls is dependent on how well the forces of erosion on its surface are resisted. This is of the utmost importance to social acceptability and the future of earthen architecture [10]. Rammed earth and compressed earth are areas of focus of modern research in a continuous efforts to explore and improve sustainable earthen architecture.

The analysis of Egenti et al. [11] is shown in Table 1; it takes 43.5 kg of cement to produce blocks for 1 m² of compressed earth wall of 200 mm thickness with 12% stabilization. The subject of cement content in compressed earth walls, for desirable effect and durability should be addressed critically and minimized.

Table 1. Summary of the analysis of Egenti et al. [11].

Block	Composition	Block Thickness	Area of Wall Covered	Cement (kg)
Compressed Earth Block (CEB)	12% cement	200 mm solid	1 m ²	43.5 kg

1.1. Shelled Compressed Earth Blocks

In a bid to reduce the amount of cement while maintaining quality of blocks, shelled compressed earth blocks (SCEB) was evolved by Egenti et al. [12] as shown in Figure 1. SCEB is a compressed earth block of two layers of different materials or percentages of cement content, compressed into a block. The inner layer/core may constitutes up to 60% of the total volume of a unit block and may be stabilized with 0–3% cement. The outer layer/shell of about 40% of total volume of unit block can be stabilized with higher (8–12%) cement content. All were mechanically compressed into a single unit block. The structure of SCEB and wall is illustrated in Figure 1. The structure gives adequate strength and surface resistance to the exposed part of the earth block with less overall cement content and cost. A quality earthen architecture can be achieved with substantial reduction in cement with SCEB.

Figure 1. The structure of shelled compressed earth block [12].

The SCEB wall is a framework of shell in a supportive and interwoven structure and the inner core in a protective confinement [12].

1.2. Earth Walls in Urban and Rural Areas

Earth walls are environmentally friendly with less use of cement and low embodied energy. While the challenges and desired characteristics of compressed earth building are simple and few in rural areas, they are more demanding in the urban areas as shown in Table 2.

Table 2. Desirable characteristics of compressed earth blocks (CEB) in urban and rural areas.

Desired Characteristics	Urban	Rural
Durability/Exposure to weather	✓	✓
Aesthetic appeal	✓	
High surface resistance	✓	
Multistorey housing	✓	
Low Cost	✓	✓
Self help		✓

This research aims to produce a model of compressed earth masonry units of high surface resistance with less cement and less weight for affordable and sustainable housing in Rwanda.

2. Materials and Methods

The materials and technique to explore or adopt are dependent on the environment and the ways relevant soil and natural deposits are constituted. Appropriate materials were fetched from locations in Rwanda and subjected to relevant standard tests.

2.1. Muhanzi Clay Soil

The clay soil sample used for this research work was taken from Muhanzi in the Muhanga district of Rwanda, a place popularly known for its production of fired bricks. Particle size distribution and plasticity index tests were conducted in accordance with BS EN ISO 17892-12:2018 [13].

2.2. Volcanic Aggregate (Amakoro), Musanze

Samples of volcanic aggregate was collected from Musanze (shown in Figure 2a) and used in this research as lightweight aggregate added to Muhanzi clay soil. The dramatic deposit of Volcanic sand/gravel in Musanze exists in two colors: black and golden yellow as shown in Figure 2b. A mountain of loose volcanic aggregate were clean and ready for use. Local settlers used this material as aggregate for building works. The particle size distribution was conducted in accordance with BS EN ISO 17892-12:2018 [13].

(a) Volcanic aggregate (Amakoro)

(b) Natural deposit of Volcanic aggregate (Amakoro), Musanze

Figure 2. Volcanic aggregate (Amakoro) and its natural deposit in Kinigi, Musanze.

2.3. Research Design/Analytical Approach

A research design was proposed in Table 3 and used within the framework of material requirements, available resources, past research works, and standards.

Table 3. Research design/analytical approach.

1. Conduct Particle Size Distribution of Earth and Amakoro. Design and Fabricate CEB/ shelled compressed earth blocks (SCEB) Kit	2. Establish Optimum Moisture content, Optimum Cement Content, and Optimum Aggregate Content	3. Analyze Cement Content and Weight of Hollow SCEB against Control	4. Architectural and Construction Opportunities of SCEB and OSCEB in Expanding the Limits in Earthen Architecture
Conduct particle size distribution of Muhanzi clay soil and musanze volcanic aggregate in accordance with BS EN ISO 17892-12:2018 [13]. Design and fabricate CEB/SCEB mechanical kit [12].	Produce laboratory test cube samples of compressed earth with same compaction pressure but varying moisture content and test for strength [14]. Produce laboratory test samples of compressed earth with same compaction pressure but varying cement content and test for surface integrity, initial rate of water absorption, and compressive strength in accordance with BS EN 772-11:2011 [15] and BS EN 772-1:2011 [16]. Make laboratory cubes of compressed earth with varying aggregate content; and test for strength and initial rate of water absorption.	Calculate and assess the cement requirement per unit block. Calculate and assess weight reduction per unit block. Calculate and assess cost reduction per square meter of wall, in comparison with other common wall materials.	Analyze results of tests in comparison with conventional masonry units. Establish architectural implications and opportunities.

2.4. Mechanical Kit for Production of Laboratory Samples

A mechanical kit was fabricated for the production of laboratory samples of CEB with uniform compaction pressure. Standard masonry tests were conducted on specimens of SCEB. The mechanical kit, as shown in Figure 3, was fabricated similar to an earlier one described in Egenti et al. [12] and illustrated in Figure 4.

Figure 3. A mechanical kit for the production of laboratory samples of CEB and SCEB.

Figure 4. Description and use of the separator for production of SCEB.

2.5. Surface Resistance Test

Surface resistance of block was tested using ‘surface integrity test’ method in Egenti et al. [11]—(a simple hand test, evolved by curiosity and found to be effective in assessment of surface resistance/integrity of clay based masonry unit).

3. Results

3.1. Particle Size Distribution and Plasticity Index of Muhanzi Clay Soil

The particle size distribution of Muhanzi clay soil and its plasticity index are shown in Figures 5 and 6. The Muhanzi clay soil is composed of about 40% of silt and clay, combined with 60% of sand in range of fine, medium, and coarse (Figure 5a). The composition is within the African Regional Standards (ARS) range of suitable soil for compressed earth as shown in Figure 5b. ARS are compressed earth blocks standards intended to guide earth construction activities in the African regions.

(a) Particle size distribution of Muhanzi Clay Soil.

(b) Graph is within the African Regional Standard ARS range of suitable soil for compressed earth.

Figure 5. Particle size distribution of Muhanzi clay soil.

SOIL REF: Type 1		DESCRIPTION
LIQUID LIMIT: 31		A-4
PLASTIC LIMIT: 17		CASAGRAHDE
PLASTIC INDEX: 14		CLASSIFICATION

(b) Plasticity index is within ARS range of suitable soil for earth walls.

(a) Liquid Limit and Plastic limit of Muhanzi clay soil.

Figure 6. Liquid limit, plastic limits, and plasticity index of Muhanzi clay soil within range of ARS suitable soil.

The liquid limit and plastic limits of Muhanzi clay soil were 31 and 17, respectively, as shown in Figure 6a. The plasticity index of 14 falls within the ARS range of suitable soil for earth walls (Figure 6b).

3.2. Particle Size Distribution of Volcanic Aggregate (Amakoro)

The composition of the volcanic aggregate ranged between fine sand and medium gravel, with a high (90%) proportion coarse sand, fine, and medium gravel, as shown in the results in Figure 7a.

(a) Particle size distribution of volcanic aggregate (amakoro)—Musanze

(b) Optimum moisture content of Muhanze clay soil with 16% water producing maximum density.

Figure 7. Particle size distribution of volcanic aggregate (amakoro)—Musanze.

3.3. Optimum Moisture Content of Muhanzi Clay Soil

The result of the optimum moisture content test of Muhanzi clay soil shows that 16% gave the highest density as shown in Figure 7b. The optimum moisture content was adopted in the preparation of all laboratory specimens.

3.4. Results for the Shell of SCEB

3.4.1. Optimum Cement Content

The optimum cement content was determined based on the result of the surface resistance test, as well as the compressive strength and water absorption tests.

3.4.2. Surface Resistance

Figure 8a shows that the minimum cement content for a durable, non-eroding surfaces of block made from Muhanzi clay soil is 7%. However, 8% cement content is appropriate as a factor of safety due to mixing.

Soil	Cement content (%)					
	0	3	5	7	10	12
Muhanzi soil	S	S	S	US	US	US

S – Stained; US – Unstained.

- (a) Surface resistance test shows a minimum of 7% cement content for outer shell.

- (b) Initial rate of water absorption of Muhanzi clay soil with increase in cement content.

- (c) Compressive strength of Muhanzi clay soil with increase in cement content.

Figure 8. Results of preliminary tests for the shell of SCEB with Muhanzi clay soil.

3.4.3. Initial Rate of Water Absorption

The initial rate of water absorption reduced when cement content increased, as shown in Figure 8b. The average absorption of 8% cement content is less than 15% absorption, which was a limit established by Abdullah et al. [17].

3.4.4. Compressive Strength

The compressive strength increased when the cement content increased, as shown in Figure 8c. Moreover, 8% passed the surface resistance test and gave a compressive strength of 6 N/mm², which is above average strength for earth masonry units.

3.5. Results for the Inner Core of SCEB

Optimum Aggregate Content

The compressive strength of compressed earth blocks reduced when the content of the volcanic aggregate increased, as shown in Figure 9a. The cement content was 3% and the compaction pressure of the samples was 2.5 N/mm². The initial rate of water absorption increased with increase in volcanic aggregate, as shown in Figure 9b. A 33% volcanic aggregate with a 3% minimal cement content for a core of SCEB produced the minimum compressive strength of 2 N/mm² (Figure 9a).

(a) Compressive strength with increase in volcanic aggregate (Amakoro) (b) Initial rate of water absorption with increase in volcanic aggregate (Amakoro)

Figure 9. Results of preliminary tests for the inner core of SCEB with Muhanzi clay soil and volcanic aggregate (Amakoro).

3.6. Summary of Results of Costs from Market Survey

The average cost per square meter of different wall materials in Rwanda are shown in Table 4.

Table 4. Average cost of block and number per square meter.

Masonry Type	Cost of Unit Block/Brick (rwf)	Number of Blocks in 1 m ² of Wall
Sand-Cement	500	15
Baked Brick (Industrial)	700	25
Compressed Earth	250	38
Shelled Compressed Earth (Calculated Material and Labor Costs)	180	38

4. Analysis of a Model Masonry Unit

Following the above results, the shell of a model of SCEB from Muhanzi clay soil was found to contain 8% cement content and thus could be safely adopted for a good surface resistance of shell. A 3% cement content is typically adequate in the inner core of block. Furthermore, 33% volcanic aggregate (amakoro) in a core is adaptable. The research results and data were applied to a typical standard block in order to calculate quantity of cement used and weight reduction in a proposed model of SCEB.

Block Configuration

The regular CEB size is $295 \times 140 \times 90$ mm ARS [18] and can be adapted for 10 mm of a mortar joint with $290 \times 140 \times 100$ mm block size. The dimensional structure of the block is as shown in Figure 10.

Figure 10. Dimensions of typical standard CEB. (All dimensions in mm).

The gross volume of the block is $(290 \times 140 \times 100)$ mm = 4,060,000 mm³

Volume of void = $2 (\pi \times 252 \times 100)$ = 141,390 mm³ (3.5% of gross volume of block)

Volume of shell = 1,050,400 mm³ = (26% of gross volume of block)

Volume of inner core = 2,868,210 mm³ = (70.5% of gross volume of block).

Table 5 shows the summary of measurements and computation of the amount of cement required for the unit block of SCEB in comparison with CEB. The comparison of CEB and SCEB with the optimum volcanic aggregate content in the core is shown in Table 6. The basic parameters for the calculations such as sample mass, sample cement content, and sample aggregate content were taken from the laboratory specimens of cubes cast and tested to research design requirements.

Table 5. Summary/comparison of cement content between CEB and model SCEB.

Description of Items	CEB—Muhanzi Clay Soil		Model SCEB—Muhanzi Clay Soil		
	Block	Void	Shell	Core	Void
Volume of unit block (mm ³)	3,918,610	141,390	1,050,400	2,868,210	141,390
Mass of unit block (g)	7445	0	1996	4589	0
Density (kg/m ³)	1880	0	1880	1598	0
Mass of cement required for unit block (g)	596	0	158	83	0
Total amount of cement required for unit block	596 g		241 g (60% reduction of cement)		

Table 6. Comparison of mass of CEB and SCEB (with volcanic aggregate in the core).

Description of Item	CEB Muhanzi Clay Soil		SCEB with 33% of Volcanic Aggregate in Core		
	Block	Void	Shell	Core	Void
Mass of unit block (g)	7445	0	1996	4589	0
Total mass of unit block	7445 g		6585 g (12% reduction in mass)		

The above analysis shows that with the SCEB, the cement content of the model block was reduced by 60%. Furthermore, with 33% of volcanic aggregate in the core, a reduction in mass of 12% was achieved.

A comparison of the cost profile of different wall materials was analyzed as in Table 7.

Table 7. Comparison of the cost profile of 1 m² of different wall materials.

Cost Items	Sand-Cement Wall (rwf)	Baked Brick Wall (Industrial) (rwf)	Compressed Earth Wall (Interlocking) (rwf)	Shelled Compressed Earth Wall (SCEB) (Interlocking) (rwf)
Cost of blocks or bricks per 1 m ²	7500 (15 Blocks at 500 rwf per block)	17,500 (25 blocks at 700 rwf per brick)	9500 (38 blocks at 250 rwf per brick)	6840 (38 blocks at 180 rwf per brick)
Cost of mortar per 1 m ²	3700	6400	1050	1050
Cost of Plastering	4500	NA	NA	NA
Painting (Basic emulsion)	1500	NA	NA	NA
Estimated Total Cost of 1 m² Area of Wall	17,200 rwf (218% of SCEB)	23,900 rwf (303% of SCEB)	10,550 rwf (134% of SCEB)	7890 rwf (SCEB)

NA—Not Applicable.

The estimated cost per square meter of a SCEB brick wall had a cost reduction of 54% compared to a sand-cement wall. Moreover, it had a 67% cost reduction compared to that of industrially fired bricks. The cost reduction of 25% over conventional CEB walls can be attributable to the reduction of cement in the core.

5. Architectural and Building Opportunities

Beyond cement reduction, the concept of a shelled block provides the opportunity for ornamental SCEB (OSCEB). The OSCEB adopts a wide range of compressible earth materials such as Kaolin (white clay), grey clay soil, red clay soil, volcanic sand, etc., to make blocks of desirable colors, textures, and effects, as shown in Figure 11. The possible application in earthen architecture is shown in Figure 12.

(a) Shelled compressed earth blocks (SCEB)

(b) Ornamental shelled compressed earth blocks (OSCEB)

Figure 11. Shelled and Ornamental Shelled Compressed Earth Blocks.

Figure 12. SCEB and OSCEB application in walls.

6. Compressed Earth Buildings in Rural Areas

The task of using compressed earth for affordable housing in rural areas is less challenging than it is in urban areas. Rural environments may have the advantage of on-site mining of earth and a family and friends labor force for a self-help building process. The conventional compressed earth blocks with 3–5% cement content is adequate for building stability with no attachment to polished wall surfaces. The challenges of compressed earth in rural area is limited to the compressed earth presses and technical know-how. Cooperatives and governmental agencies can make compressed earth presses and trained personnel available at sectorial offices for use in various cells in their respective jurisdiction.

7. Conclusions

Enhancing compressed earth masonry units can provide an alternative wall construction systems to baked clay bricks with an appreciable effect on environment and cost. The challenges of conventional compressed earth masonry units were explored and a model of shelled compressed earth block was evolved with a 60% reduction in the use of cement. The reduction in cement without a reduction in comfort and aesthetic appeal balances the triple bottom line of sustainability, i.e., environment, economic, and sociocultural. In this study, the use of lightweight volcanic aggregate (amakoro) reduced the weight of the unit block by 12%, which further reduced with bigger blocks of larger inner core. The estimated cost of the SCEB wall compared to common wall materials showed a reduction of 15% over conventional compressed earth block wall and a 54% cost reduction over sand-cement block wall. Therefore, shelled compressed earth provides opportunities for ornamenting blocks with more architectural uses for affordable housing in urban areas. In rural areas, compressed earth presses and technical know-how can be made available for people to build their own houses.

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