MAKERERE UNIVERSITY

ASSESSING THE STRUCTURAL POTENTIAL OF CEMENT STABILIZED RAMMED EARTH WALLS AS AN ALTERNATIVE TO BURNT CLAY BRICK WALLS FOR LOW-COST HOUSING CONSTRUCTION IN UGANDA

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A RESEARCH REPORT SUBMITTED TO THE

DEPARTMENT OF CONSTRUCTION ECONOMICS AND MANAGEMENT

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF A DEGREE OF BACHELOR OF SCIENCE IN QUANTITY SURVEYING

FEBRUARY 2022

DECLARATION

This study is original and has not been submitted for any other degree award to any other University before.

Signature…Baud……………………………………………………

Date…14/02/2022……………………………………………………

This dissertation has been submitted for examination with the approval of the following supervisor

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APPROVAL

This is to approve that this research work is the student's original work, has been carried out under my supervision and is ready for submission.

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DEDICATION

I would like to dedicate this report to my parents, without whose continued financial and emotional support, I would not have accomplished the completion of this research successfully.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisor, Ms. Pamela Achieng Opio for the guidance and knowledge availed to me during the undertaking of my project.

I would also like to extend my sincere appreciation to Mr. Mangoye Rogers and Mr. Ntume William who helped me with their laboratory expertise while doing the tests in the project.

Special gratitude goes to my loving parents, who rendered financial and emotional support towards the completion of this project. May the Almighty God bless you all abundantly.

ABSTRACT

Uganda, as a developing country in Africa is suffering from an enormous housing deficit that currently stands at about 2.4 million units per year, with a projection of up to about 3 million units by 2022(UN-HABITAT, 2017) .These numbers reflect the rapid population growth, being the fourth highest in the world (World Bank, 2018). In addition, the costs for conventional construction methods are very high owing to the fluctuations in the prices of clay bricks and cement. This has made it significantly difficult for the 34% of Uganda's population who are living below the poverty line as of 2013(World Bank, 2016) to build a decent residential house.

Earth as the main walling material is an abundant resource, which is not the same for the Burnt Clay Bricks. While the prices of Burnt Clay Bricks on the market is affected by the demand from the construction industry, earth remains a free resource readily accessed by everyone regardless of their income levels. This opens up opportunities of using earth as a walling material to help every Ugandan achieve their dream of building a house.

This however is met with concerns such as the load bearing capacity of earth walls, which has been considered to be low. Therefore, this research comparatively analyses the compressive strength and durability of small sized Burnt Clay Brick and CSRE wall panels at 21 days. The Rammed Earth wall panels were built with two soils sourced around Makerere University stabilized with Tororo Portland Pozzolana cement across percentages of 6%, 8% and 10%. The BCB panels were built with bricks sampled from a brick laying site in Mpererwe, a residential area in Uganda. In addition, a comparative cost study of both walls is carried out to determine any cost savings available when each of the walling materials is used for a typical two-bedroom house model in Uganda.

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ACRONYMS

ASTM – American Society for Testing and Materials

BCB – Burnt Clay Brick

BS - British Standard

CEDAT – College of Engineering, Design, Art and Technology

CSRE - Cement Stabilized Rammed Earth

MDD – Maximum Dry Density

NZS – New Zealand Standard

OMC – Optimum Moisture Content

PPC – Portland Pozzolana Cement

SADCSTAN – Southern African Development Community Cooperation in Standardization

UDL – Uniformly Distributed Load

USCS – Unified Soil Classification System

UTM – Universal Testing Machine

CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

The housing deficit in Uganda is one of the biggest issues of concern especially in her urban areas. Despite the fact that the construction industry contributes to about 5% of Uganda's Gross Domestic Product as of 2019/2020(UBOS, 2020), the housing sector continuously suffers from an enormous housing deficit currently that currently stands at about 2.4 million units per year with a projection of up to about 3 million units by 2022 (UN-HABITAT, 2017). This housing deficit is associated with high construction costs.

According to (Nuwagaba, 2020), the high construction costs can be traced to the building code inherited from the British, in which buildings are over-engineered to meet the U.K. building code standards. These standards incorporate more cementitious materials than necessary causing wastage(Nuwagaba, 2020).This has made it significantly difficult for a majority of Ugandans to build a decent residential house owing to the increased poverty rates i.e. statistics showed that about 34.6% of the population was living on $1.90 per day or less in 2013(World Bank, 2016).

Walling, being, one of the most significant elements in residential construction, requires more raw materials to construct i.e. bricks, earth, mortar among others with the biggest proportion being bricks. In Uganda, the most commonly used material for walls is the Burnt Clay Brick that occupies almost 85% and 50% of all walls in urban and rural areas respectively (Nuwagaba, 2020).

The Burnt Clay Brick is a walling material formed in a mould and is then fired in a kiln at high temperatures or sundried to achieve its final desired strength(Sahu & Singh, 2017).It is widely used for walling because it is regarded as a symbol of durability, modernity and progress even in the most remote communities(Perez, 2009). In addition, the Burnt Clay Brick emerges as the popular wall-material choice when the unit cost is the sole consideration(Ahimbisibwe & Ndibwami, 2016).

Although it is considered a durable material, the Burnt Clay Brick is associated with problems such as mortar wastage. This is as a result of using excessive quantities of mortar for bonding during wall construction. Excessive mortar usage is linked to rapid construction timelines, uneven brick sizes, negligence and low mason skill levels(Ahimbisibwe &

Ndibwami, 2016). In addition, there is an increasing scarcity of appropriate clay for making the Burnt Clay Brick due to the high demand for clay materials by the construction industry in Uganda(UHSNET, 2015).

To address the problem of high construction costs whilst tackling the housing deficit in Uganda, the construction industry has to focus on exploring materials outside the conventional(traditional) techniques. This can be done by exploiting the abundant and readily available materials for walling construction such as earth. Earth technologies like Rammed Earth have the potential to replace the widely used Burnt Clay Brick for walling construction in residential homes.

Rammed Earth construction is a technique that involves the compaction of moist earth comprising varying proportions of clay, sand and gravel into rigid formwork, in successive layers until the desired height of the wall is reached(Middleton, G.F. & Schneider, 1987).Worldwide, Rammed Earth walls have been incorporated into ancient architecture for example they were used in the ancient cultures of the Middle East and Latin America for construction of a part of the Great wall of China and the Alhambra in Spain. These structures have stood the test of time and are proof that Rammed Earth is a durable construction material. In recent years, it has been widely used for building low rise and low-cost housing structures in the urban and rural areas of some parts of Europe, South Africa, Zambia, Zimbabwe and Ghana among others. In Uganda, the most notable use of Rammed Earth construction is at the Children's Surgical Hospital in Entebbe designed by EMERGENCY, an international NGO.

Despite its popularity in the above-mentioned regions, research on the use of Rammed Earth walling on a large scale for residential dwellings in Uganda is still very scanty tending to none.

The use of Rammed Earth would be a suitable construction method to explore towards the mission to address the housing deficit problem in Uganda, being that it is durable, readily available, cheap and with good thermal properties(Dabaieh & Sakr, 2014**.** This will however be curtailed by the existing Burnt Clay Brick that has long been perceived as the cheapest option and has therefore not left much room for evaluation of other possible alternatives(Ahimbisibwe & Ndibwami, 2016).

This study seeks to assess the structural potential of Rammed Earth walls as an alternative to Burnt Clay Brick walls for low-cost housing construction by comparing their loading strengths, durability and possible cost savings.

1.2. PROBLEM STATEMENT

Usually, the discussion about alternative construction methods has limited information on cost and performance as compared to the conventional methods(Ahimbisibwe & Ndibwami, 2016) most especially in developing countries like Uganda. Much as the conventional Burnt Clay Brick is widely preferred by Ugandans for wall construction, the high demand for clay materials by the construction industry is causing a gradual decline in the availability of appropriate clay in the country(UHSNET, 2015). In addition, the Burnt Clay Brick is associated with high construction costs commencing from the manufacturing stage up to the building stage. There is therefore a need to take into consideration the naturally abundant materials such as earth for construction i.e., the Rammed Earth, as an alternative to the Burnt Clay Brick.

1.3. AIMS AND OBJECTIVES

1.3.1. Main Objective

To assess the structural potential of Cement Stabilized Rammed Earth walls as an alternative to Burnt Clay Brick walls for low-cost housing construction in Uganda.

1.3.2. Specific Objectives

- To compare the compressive strength of Burnt Clay Brick and Cement Stabilized Rammed Earth wall panels
- To evaluate the durability of Burnt Clay Brick and Cement Stabilized Rammed Earth wall panels using the wet to dry strength ratio
- To assess the cost variations between using Rammed Earth and Burnt Clay Brick in wall construction.

1.4. SIGNIFICANCE

This study shall contribute to the development of affordable housing construction in order to address the housing deficit in Uganda. The study will aim at investigating the structural and cost capabilities of Cement Stabilised Rammed Earth when used as an alternative for the conventional Burnt Clay Brick in Uganda. The results of this study will be useful to the housing construction industry and construction materials' researchers in the country.

1.5. SCOPE

This study focused on assessing both the structural and cost capabilities of Cement Stabilised Rammed Earth walls in comparison to Burnt Clay Brick walls in Uganda. The structural comparisons were done by comparing results from the compressive tests done on Burnt Clay Brick wall panels with those of 21-day cured Cement Stabilised Rammed Earth panels stabilized in the range of 6-10% from two soil samples sourced around Makerere University, Uganda. The cost variations between the two walling materials were assessed by the preparation of separate walling material schedules for a two-bedroom house model plan.

CHAPTER 2: LITERATURE REVIEW

In this section, I present the past and present background and forms of Rammed Earth used in construction worldwide. In addition, I explore the existing research on the structural and cost properties of Cement Stabilised Rammed Earth and how they compare with those of the widely accepted and approved Burnt Clay Brick.

2.1. BACKGROUND OF RAMMED EARTH

(Middleton, G.F.& Schneider, 1987) defined Rammed Earth construction as a building technology in which moist earth comprising of varying proportions of clay, sand and gravel was compacted into rigid formwork in successive layers until the desired height of the wall was reached. It was used as a construction material in the ancient cultures on some parts of the Great Wall of China and the Alhambra in Spain. In recent years, its construction has been re-explored in parts of Europe, Southern and Western Africa for example; urban and rural areas of South Africa, Zambia, Zimbabwe and Ghana. In Uganda, the most notable application of the Rammed Earth construction is at the Children's Surgical Hospital in Entebbe.

According to Walker et al. (2005), stabilised Rammed Earth is one which contains an additive, that changes the material's physical characteristics with cement being the primary additive. Cement stabilization of the soil increases the elasticity of the wall. It also prevents shrinkage in the walls once they gain sufficient strength(Jayasinghe & Kamaladasa, 2005). In addition, stabilization is necessary in situations where the Rammed Earth wall has a lot of exposure to water which can cause erosion. Therefore, both ramming and stabilization are combined to increase the durability of the walls.

Cement (Sand) and water are mixed with the soil in correct proportions. This mixture is then compacted using a pneumatic rammer or locally using a manual rammer in layers of 100mm up to 150mm deep. This is done until the specified height of the wall is reached. At this point, the setup is then moved to set another section of the wall. The process is repeated until the entire perimeter of the wall is completed. These walls can take any type of thickness depending on the design requirements. The majority of earthen buildings are low rise, single or two storeys, and consequently the stresses experienced by the thick earth walls are generally well within the modest capabilities of the material (Maniatidis & Walker, 2003) .

2.2. ADVANTAGES AND DISADVANTAGES OF CEMENT STABILSED RAMMED EARTH

Cement Stabilised Rammed Earth construction is credited for producing a finished product that is durable in nature and can last for vast periods of time. According to Bui et al (2009), unplastered Rammed Earth walls exposed to natural weathering in wet continental area for 20 years were observed to not have shown complete collapse at the time of the study. The use of stabilization during construction increases their ability to resist weathering effects in wet continental areas (Walker et al., 2005). Due to its wide availability as the main raw material, building with Rammed Earth is relatively cheaper than conventional techniques (Minke, 2006; Walker et al., 2005)**.** (Dabaieh & Sakr, 2014) further found that experimental low housing construction with Rammed Earth cost 30 to 40 Euros per square metre which was less than 50% of conventional techniques. This is because it employed simpler tools and less skilled labour than the conventional Burnt Clay Brick technique (Adam & Agib, 2001; Maini, 2005; Minke, 2006; Hadjri et al., 2007). The use of Rammed Earth is also associated to low carbon levels in the atmosphere. According to UNEP (2020), the construction sector contributed to about 38% off all energy related carbon dioxide emissions. The use of Rammed Earth can mitigate these emission levels because Rammed Earth contains 95% of unfired raw materials and also uses locally available raw materials hence minimal levels of transportation are required (Hall & Swaney, 2005)

However, Rammed Earth construction is associated with a few limitations such as inflexibility in construction that is it is an in-situ construction method(Walker et al., 2005). The construction process is longer than the Burnt Clay Brick method that is a lot of time is spent from soil excavation, soil testing, erection of formwork to soil compaction into the formwork. In addition, the soils favorable for Rammed Earth construction may not be available at every site of construction. At times, the soil will have to transported form one site to another hence elevating transportation costs.

2.3. RESEARCH ON EARLIER STRUCTURAL INVESTIGATIONS OF CEMENT STABILISED RAMMED EARTH VERSUS BURNT CLAY BRICK WALLS

2.3.1. Introduction

(Ahimbisibwe & Ndibwami, 2016) conducted a study to investigate alternative building materials to Burnt Clay Brick as well as cost. They built a display space (whose form considerations adhered to the commonly favoured row house seen in many rural communities) at Uganda Martyrs University. The display space was built with both Rammed Earth and site produced stabilized soil blocks to replace the commonly used Burnt Clay Brick. This study showed that incorporating a wall built with Rammed Earth onto a display space was structurally possible. However, the research did not consider Rammed Earth as the sole walling material for the display space.

2.3.2. Comparison of Compressive Strength

Compressive strength is the capacity of a material or structure to withstand loads tending to reduce size(Gadekar et al., 2018).

Past literature on comparisons of compressive strengths for both cement stabilised Rammed Earth and Burnt Clay Brick wall panels is scanty. However, the closest to this research was done by (C. Jayasinghe, 2007). For the comparative study, one brick thick wall panels of three bricks length and six courses high were constructed for both the Burnt Clay Brick and cement stabilized earth bricks (5% cement), both with the same thickness(225mm) and laid in English bond. The load deformation behaviour of both panels was monitored to judge whether adequate warning was given by the walls before failure at each loading step. It was observed that both these materials showed somewhat ductile behaviour with adequate warning before failure, which is a satisfactory result for masonry walls. From the results, the average ultimate strengths for the stabilized earth brick walls was found to be approximately 17% lower than that of the Burnt Clay Brick at 28 days after casting. This implied that earth also had the capability to withstand loads in low-rise buildings.

In contrast to the above research, (Pang et al., 2012) concluded that a cement mortar steel reinforced Rammed Earth wall showed somewhat a different failure behavior from that of brick masonry. Prior to this conclusion, an observation was made which showed that a

Rammed Earth wall may not give an adequate warning in the form of cracks while the brick masonry failed at much lower loads than their brick compressive strengths. (Pang et al., 2012) therefore, recommended that an adequate factor of safety be used for practical Rammed Earth wall application.

According to Tripura et al. (2015), the compressive strength of CSRE blocks increased with increasing cement content. On 21 to 28 days curing, the CSRE blocks can attain the compressive strength up to 37–50% higher than those cured for seven days.

2.3.3. Comparison of Durability

The durability of both Burnt Clay Brick walls and cement stabilized Rammed Earth walls can be determined with the wet-to-dry strength ratio.

There is no definite comparison study of durability between Burnt Clay Brick and cement stabilized Rammed Earth. Some of the relevant studies on durability of Cement Stabilized Rammed Earth include:

(Jayasinghe & Kamaladasa, 2005) determined the wet to dry strength ratios of Cement Stabilised Rammed Earth wall panels. The tests were performed on the panels with gravely and clayey soils since these were more susceptible to the strength decrease due to water. The wet strength of wall panels was determined after soaking the panels in water for 24 hours. (Jayasinghe & Kamaladasa, 2005) reported that the wet to dry strength ratios of these panels gave a ratio that was more than 33% which satisfied the range earlier established by research conducted by Heathcote (1995) in which a range of 33% - 50% was regarded as suitable for walls depending on the severity of rainfall.

Similarly, Jayasinghe & Kamaladasa (2007) stated that the wet-to-dry strength ratio of 46%–64% for clayey and hard laterite soil types was also adequate for Rammed Earth walls under adverse conditions.

(Guettala et al., 2006) stated that walls constructed with 5–8% cement soil blocks had a wet-to-dry strength ratio of 58%–69% and therefore showed no deterioration as observed in a comprehensive durability study of stabilized earth.

Furthermore, Tripura et al. (2015) observed that the ratios were higher in case of uncured cement stabilized earth blocks, which may be due to extra hydration of cement that was unable to hydrate fully due to an insufficient amount of water during compaction.

2.3.4. Cost Variations

In addition to the structural performance, the cost of a building material is also an important parameter for making it competitive and popular (Jayasinghe & Mallawarachchi, 2016).

According to (Ciancio & Beckett, 2013), the general cost of a house is mainly determined by:

1) the cost of the construction materials and
2) the cost of the labour force working on the construction site.

Two more expenses must be added to the list in case the construction site is in a remote location that may neither have construction materials nor skilled labor readily available:

3) the transportation cost of the materials to the remote site and
4) the accommodation of the skilled labour force brought on site.

(Jayasinghe & Mallawarachchi, 2016) conducted a cost study on a 160mm thick stabilized unplastered Rammed Earth wall that comprised 10% cement. They evaluated the wall to cost Sri Lankan Rs.6840/= per $10m^2$ (approximately UGX.121,549). In addition, they went ahead to carry out cost studies on walls built with the conventional walling materials (based on the standard work norms and the Building Schedule of Rates for Sri Lanka). They reported that unplastered walls of 225mm and 113mm brickwork both with 1:5 c/s mortar cost about Rs.9600 (approximately UGX.170,594) and Rs. 5200/= (approximately UGX.92,405) respectively per $10m^2$ of each wall. Where one side of each of the walls was finished smooth with the standard cement, lime and sand plaster of mix ratio 1:1:5, the cost increased by Rs.4070/= (approximately UGX.72,325) per $10m^2$ of the wall. (Jayasinghe & Mallawarachchi, 2016) concluded that when plaster costs were considered alongside the costs of the conventional wall materials, all the conventional materials i.e., Burnt Clay Brickwork would be more expensive than the unplastered and painted cement stabilized Rammed Earth wall.

(Dabaieh & Sakr, 2014) also reported in their study that experimental low housing construction with Rammed Earth cost 30 to 40 Euros per square metre, which was less than 50% of conventional techniques like Burnt Clay Brickwork.

CHAPTER 3: RESEARCH METHODOLOGY

This section presents the materials and methods that were employed to compare the compressive strength and durability of both Burnt Clay Brick and CSRE wall panels.

3.1. Selection of Materials

3.1.1. Selection of the Burnt Clay Bricks

Purposive sampling was done to select twenty-four (24) bricks from a bricklaying in Mpererwe. This site seemed suitable for the sampling since it is a source of bricks for construction of residential houses in Mpererwe and the surrounding areas.

3.1.2. Selection of soils for Rammed Earth

Purposive sampling was done to select two (2) soil samples from two different locations within Makerere University that is the sample A was selected from the Tank hill area while sample B was selected from a location behind the old CEDAT building. These locations were selected for this study as they were previously used for use in previous earthen related studies at the University. Both soil samples that were used for the study were excavated from a depth of 0.8-1m below the top soil and then collected in sisal sacks.

3.2. Materials' Tests

3.2.1. Burnt Clay Bricks

A sample of five bricks was subjected to tests for hardness, soundness, structure and homogeneity for which three of the bricks passed all the tests. However, all the bricks did not conform to the standard size of the Burnt Clay Brick in BS 3921**.** This is because the sizes of the brick moulds vary from one brick laying site to another. The dimensions of the bricks in the sample are shown in ***Table 1*** below:

Brick	Length(mm)	Width(mm)	Height(mm)
1	215	110	100
2	230	112	100
3	226	115	109
4	218	110	104
5	216	109	105

Average	221	111	104

Table 1: Dimensions of brick sample

3.2.2. Soil

The following soil tests were carried out to determine the mechanical properties of the soil samples;

3.2.2.1. Particle Size Distribution

This experiment was done to understand the predominant soil components in each soil sample so as to ascertain whether the soils were suitable for both cement stabilization and ramming. The test was carried out in accordance with BS: 1377-part 2 (1990).

Calculations

For each sieve size:

Percentage passing (%) = 100 – Percentage retained (%)

$$= 100 - \left(\frac{M}{Ms} \times 100\right)$$

Cumulative percentage passing = 100 – Cumulative percentage retained

$$= 100 - \left(\frac{\text{Cumulative retained}}{\text{Dry mass}} \times 100\right)$$

$$= 100 - \left(\frac{M+Mb}{Ms} \times 100\right)$$

Where:

M and M_b - retained masses for current and previous sieves respectively

Ms – dry mass

The sieve sizes together with the partial and cumulative masses retained were recorded in ***Table 16*** and ***Table 17*** in appendix A.

Graphs for cumulative percentage passing against sieve sizes for each test sample were then plotted as shown in ***Figure 21*** in appendix A**.**

Figure 1: Wet Sieving and Dry Sieving

3.2.2.2. Soil Plasticity Index

This is a measure of a soil's ability to undergo irreversible deformation whilst withstanding an increase in loading. It is established by experimental tests to determine the Atterberg limits that is liquid and plastic limits of the soil.

Plasticity index = Liquid Limit – Plastic Limit

Liquid Limit

This refers to the soil's moisture content at which it transitions from the liquid state to the plastic state. For this study, it was used to estimate the compressibility of the soil, which generally increases with increase in the liquid limit. The experiment was carried out with reference to BS: 1377-part 2 (1990).

<u>Calculations</u>

The moisture content, w, of the soil sample on each container was calculated as:

$$w = \left(\frac{M1-M2}{M2-M3}\right) \times 100\ (\%)$$

where:

M1 = mass of wet soil + container

M2 = mass of dry soil + container

M3 = mass of container

Average moisture content was calculated as follows for each test:

$$w_{ave} = \left(\frac{w1+w2}{2}\right)\%$$

The readings of average cone penetration and average moisture content were recorded in *Table 18* and *Table 19* in appendix A.

The relationship of average cone penetration and average moisture content was then plotted to obtain a line of best fit as shown in *Figure 22*. The Liquid Limit was the average moisture content corresponding to 20mm average cone penetration.

Figure 2: Cone Penetration test for Liquid Limit

Plastic Limit
This refers to the moisture content of soil at which it becomes too dry and it begins to behave as a plastic material. The experiment was carried out with reference to the procedure in BS: 1377-part 2 (1990).

Calculations

The moisture content for the first, w1 and second portion, w2 was calculated as:

w = $\left(\frac{M1-M2}{M2-M3}\right) \times 100\ (\%)$

where:

M1 = mass of wet soil threads + container

M2 = mass of dry soil threads + container

M3 = mass of container

The plastic limit will be the average moisture content of both portions provided their difference does not exceed 0.5% as shown in *Table 18* and *Table 19*.

Plastic Limit = $\left(\frac{w1+w2}{2}\right)$ %

Figure 3: Soil threads for Plastic Limit test

Linear Shrinkage

This is a measure of the amount of shrinkage likely to be experienced by a wall if the drying process is prolonged beyond the plastic limit. This test is used to confirm the results from the Plasticity Index test. The experiment was done in accordance with the procedure in BS: 1377-part 2 (1990).

Calculations

Linear shrinkage (%) = $\left(1 - \frac{LD}{LO}\right) \times 100$

Where;

L_D = Oven-dried length of the soil bar

L_O = Initial length of the soil bar/mould

Figure 4: Initial soil bar in mould

Figure 5: Oven-dried soil bar in mould

3.2.2.3. Proctor Compaction test

This test was carried out to obtain relationships between compacted dry density and soil moisture content that is the Optimum Moisture Content at which each soil type will become the most dense and attain its Maximum Dry Density. It was used to provide a guide for specifications on field compaction. This experiment was carried out with reference to the procedure in BS 1377-Part 4 (1990).

<u>Calculations</u>

Bulk density, $\rho = \frac{m2-m1}{V} \times 1000$ (in kg/m^3)

Where:

M1 = mass of mould and baseplate (g)

M2 = mass of mould, baseplate and compacted soil (g)

V = volume of mould (in cm^3)

Dry Density, $\rho_d = \frac{100\rho}{100+w}$ where w is the moisture content of the soil (in %)

The readings of the dry densities and corresponding moisture contents were recorded in *Table 20* and *Table 21* in appendix A. A curve of best fit was then drawn on a plot of dry densities against corresponding moisture contents. The MDD and OMC for the soil types was determined from the point of maxima on the curve as shown in *Figure 23*

Figure 6: Compaction test

3.3. Construction of Wall Panels

3.3.1. Burnt Clay Brick Panels

Six panels comprising Burnt Clay Bricks were built. The bricks used to build the panel were selected at random from the sample of bricks used for the study. Each panel was built such that it had a two-brick length and a two-course width of half bricks. The mortar used comprised of a 1:3 mix of Tororo PPC cement and lake sand respectively.

Figure 7: One of the BCB wall panels

Panel No.	Length(mm)	Width(mm)	Height(mm)
1	445	108	242
2	465	109	240
3	460	120	241
4	461	112	238
5	460	115	241
6	468	110	240
Average	460	112	240

Table 2: Dimensions of BCB wall panels

3.3.2. CSRE Wall Panels

3.3.2.1. Preparation of wall mould

Steel plates were welded to form a mould with the average dimensions of the BCB panel such that the steel mould was 460mm × 112mm × 400mm. An allowance of 160mm was added to the height of the mould to leave space through which the rammer would move during compaction. 8mm iron bars were welded on opposite ends to increase its strength and also reduce the extent of expansion of the soil in the panel. The sides of the mould were welded with plates with holes for bolts. This was done to allow opening the mould after the soil had been compacted. The bottom of the mould was also screwed to a 1 and ½ inch wooden base plate onto which the soil was to be compacted.

Figure 8: Steel mould for making CSRE wall panels

3.3.2.2. Soil Drying and Sieving

Both soil samples to be used in the construction were air-dried on sacks for 8 hours. According to Norton (1997) and other Rammed Earth researchers, any material coarser than 5 – 10 mm was to be sieved out. The soils were thus sieved through a 10 mm sieve into different sisal sacks. This ensured that there was a considerable amount of gravel in the composition to improve the structural stability of the panels (Sabbà et al., 2021)

Figure 9: Soil being air- dried and sieved

3.3.2.3. Mix Design

The weight of both soil samples to be rammed in each panel were measured using a full rectangular basin flushed with soil. This was done because the quantities of lake sand and cement to be added to the soils were to be calculated by weight. Each of the actual quantities of soil to be rammed were then mixed with 10% of dry lake sand measured by weight. This was done to reduce any clay content available in the soil and also improve the resistance of the panels to atmospheric agents (Sabbà et al., 2021)

Figure 10: Basin used for measuring quantities

The above mixes were then mixed with Tororo PPC cement at different percentages of 6%, 8% and 10% by weight. This was done in accordance with an earlier study carried out by C. Jayasinghe & Kamaladasa (2005) in which the structural properties of CSRE from different soil samples were studied by varying the proportions of cement in the mix in the range of 6-10%. Similarly, prior to this research, C. Jayasinghe & Mallawarachchi (2006) had established that a minimum proportion of 6% cement in all types of laterite soils was sufficient to provide the required strength for CSRE walls in construction.

Small quantities of water were then continuously sprinkled to the soil-sand-cement mixture while mixing with a spade until the Optimum Moisture Content (OMC) of the overall mixture was achieved. This was tested by using the drop test in accordance with SADCSTAN (2014)

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Figure 11: Mixing the soil with cement and sand

Figure 12: Testing to check whether OMC of mixture has been attained

Mix Design Calculations

Prior to these calculations, a sample Unstabilised Rammed Earth wall was built from each soil sample to ascertain the approximate weight of each soil sample required to build a Rammed Earth wall panel of 460mm × 112 mm × 240 mm using the mould in *Figure 8*

MIX A

Soil A

1 rectangular basin = 20,000g of soil sample A

1 panel from sample A required two rectangular basins = 40,000g of soil

Sand

1 wall panel of sample A = 40,000g of soil

Weight of sand for each wall panel from sample A = 10% × 40,000g of soil

= 4000g of lake sand

Cement (% of weight of soil A)

Cement %	6%	8%	10%
Cement (g)	2400	3200	4000

Table 3: Cement compositions for mix A

MIX B

Soil A

1 rectangular basin = 14,610g of soil

1 panel from sample B required two rectangular basins = 29,220g of soil

Sand

1 wall panel of sample A = 29,220g of soil

Weight of sand for each wall panel from sample A = 10% × 29,220g of soil

= 2,922g of lake sand

Cement (% of weight of soil B)

Cement %	6%	8%	10%
Cement (g)	1753.2	2337.6	2922

Table 4: Cement compositions for mix B

Summary of mix design proportions for each panel from each soil sample

CSRE mix(g)	Soil	Sand (10%)	Cement		
			6%	8%	10%
Mix A	40000	4000	2400	3200	4000
Mix B	29220	2922	1753.2	2337.6	2922

Table 5: Mix design proportions for soil A and B

3.3.2.4. Ramming

Twenty-four CSRE wall panels were built from each of the two soil mixtures in *Table 5*. The soils were rammed such that the dimensions of the CSRE panels are similar to the average dimensions of the BCB panels in *Table 2*. This was done to allow for the cross-sectional areas of both types of walls to be similar or almost similar when subjected to a Uniformly Distributed Load in compression tests. A tolerance of ± 10 mm on all sides of the walls was allowed to cater for workmanship issues such as ramming less or excess soil in the layers.

Compaction of the soil in the steel mould was done in two layers, each approximately 12 cm, using a steel rammer of 5kg, moved through an average distance of 10 cm during the compaction. Each layer of soil A and soil B was compacted with an average of 63 and 80 blows respectively to reach full compaction. Prior to compaction, the inner surfaces of the steel mould were greased to ensure that the soil in the panels did not stick to the inner surfaces of the mould.

A 1 and ½ inch wooden plate was placed at the top of each layer during compaction in the mould to ensure that a uniform load was applied to each layer during compaction. Once the compaction was done, the wall was removed by unscrewing the bolts on the base plate and on the sides of the mould. The panels were then placed under a shade (free from rain and sunshine) and covered with sisal sacks. They were cured by sprinkling water on the tops and sides for 21 days.

Figure 13: Pouring soil mix into mould and ramming

Figure 14: Front and side views of one of the CSRE panels

Figure 15: Steel rammer used for ramming

Figure 16: CSRE panels covered with sisal sacks

3.4. Comparison of Compressive Strength

With reference to the procedure in BS EN 772-1 (2015), dry compressive strength tests were carried out on 3 BCB and 12 CSRE panels (6 CSRE panels for each soil sample) at 21 days using a UTM machine. Prior to loading, mild steel rectangular plates were placed at the top and bottom of the panels to allow for a UDL across the cross sections of the panels. The compressive strength of the BCB and CSRE panels will be determined from the following equation:

$$Fc = F/A$$

Where Fc is the dry compressive strength (N/mm^2), F is the UDL at which the BCB/CSRE panel fails (N), and A is the cross-sectional area of the BCB/CSRE panel at which the UDL was applied (mm^2).

Figure 17: BCB and CSRE panels under compression

3.5. Comparison of Durability

Durability of BCB and CSRE panels was compared using the wet to dry strength ratios of each panel. 3 BCB and 12 CSRE panels were fully immersed in a water tank for 24 hours. This was done at the end of the 21 days. The panels were removed and tested for the wet compressive strength in accordance to the same procedure used for the dry panels.

Wet to dry strength ratio = Wet compressive strength/Dry compressive strength

Figure 18: Some of the panels immersed in water for 24 hours

Figure 19: Appearance of one of the CSRE panels after 24hr water immersion

Figure 20: Failure of Wet BCB and CSRE panels under compression

3.6. Cost Variation between BCB and CSRE walls

The cost variations between the two types of walling were assessed by preparing separate material schedules for each walling in a typical residential 2-bedroom house model plan in Uganda. Both model plans had similar floor areas, similar wall face cross-sectional areas and similar dimensions for openings.

The wall thickness on the BCB model plan was assumed to be 102.5mm in accordance to BS 3921 while the wall thickness on the CSRE model plan was assumed to be 300mm (the minimum wall thickness recommended by (SADCSTAN, 2014).

The cost comparison study assumed that the walls were to be built for 7 days, at the same location and that the suitable soil was readily available on site. In addition, it was assumed that the CSRE wall project was a first-time project and that all equipment was either bought or hired.

CHAPTER 4: RESULTS, ANALYSIS AND DISCUSSION

This section presents the results obtained from various tests conducted during this study alongside their analysis and interpretations.

4.1. Soil tests

4.1.1. Particle Size Distribution

The graph below shows the results from the particle size analysis for both soil samples, A and B.

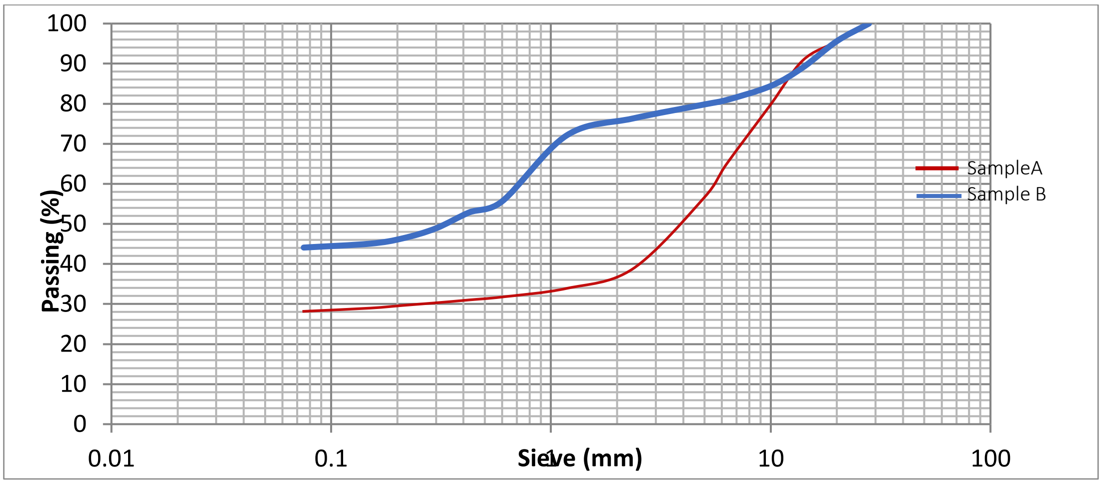

Figure 21: Particle Size Distribution of A and B

With reference to the UCSC (ASTM, 2000), soil A contained 28% fines, 11% sand and 61% gravel thus clayey gravel **while** soil B contained 44% fines, 32% sand and 24% gravel thus clayey sand. Therefore, both soil samples were suitable for both cement stabilization and Rammed Earth construction. This was because their grading was in line with research done by (Gooding, 1993; Maniatidis & Walker, 2003; Montgomery, 1998; United Nations, 1964) in which a soil suitable for cement stabilization was required to have a combined sand and gravel content, at least greater than 50% and preferably closer to 75% and a sufficient amount of fines (up to a maximum of 55%).

4.1.2. Atterberg Limits

The results for the Liquid Limit (LL), Plastic Limit (PL), Plasticity Index (PI) and Linear Shrinkage (LS) for both soil samples, A and B are presented in the table below:

Soil	Liquid limit (%)	Plastic limit (%)	Plasticity Index (%)	Linear shrinkage (%)
A	30.8	18.2	12.6	8.57
B	44.8	19.5	25.3	10.71

Table 6: Atterberg limits for both soil samples

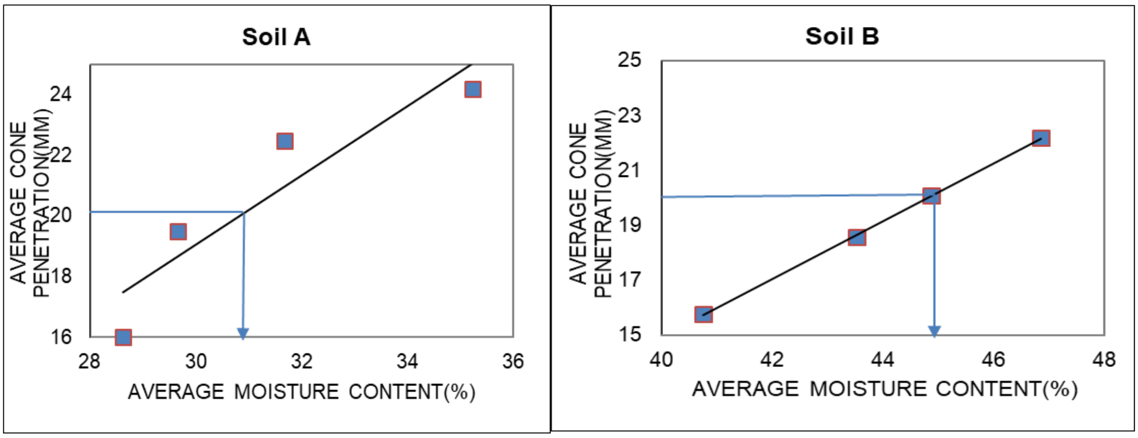

Figure 22: Liquid limits of the soils

The liquid and plastic limits for both soils were within the range stated by (Houben & Guillaud, 1994) in which the liquid limit for un-stabilized soils was recommended to be between 25% and 50% (30%-35% preferred) and the plastic limit between 10% and 25% (12%-22% preferred).

Soil B had a higher plasticity index and linear shrinkage than soil A as shown in table __ indicating that it comprised a higher percentage of fines. It was noted that the plasticity indices of both soils shown in *Table 6* were well within the nomogram plasticity index chart in *Figure 28* developed by (Delgado & Guerrero, 2007). This chart showed that soils with a plasticity index of 16% to 28% and liquid limit of 32% to 46% were suitable for cement stabilization and Rammed Earth construction. Similarly, the values also satisfied the range established by (Standards Australia, 2002) in which a Plasticity Index range of 15-30% was sufficient for Rammed Earth construction.

4.1.3. Proctor Compaction

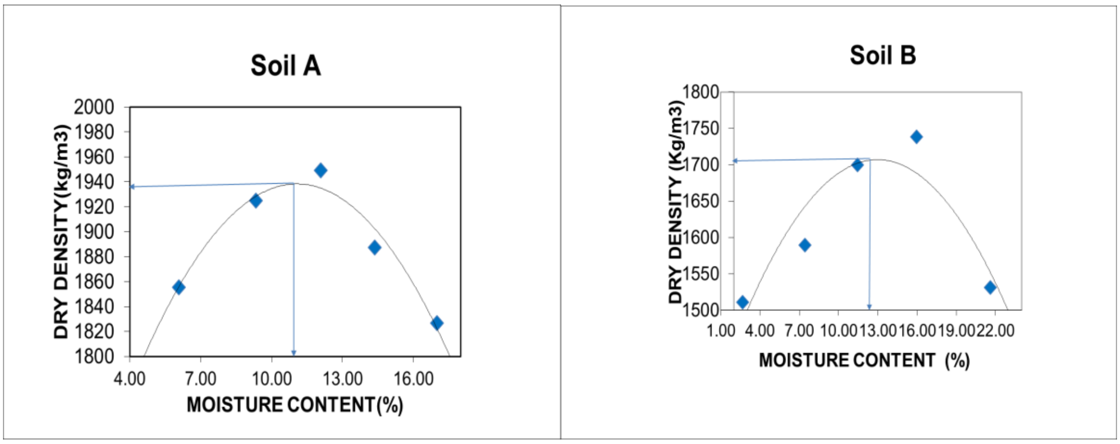

Figure 23: Compaction curves for the soils

Soil A had an MDD of 1938 kg/m3 at 11.1% OMC while soil B had a MDD of 1705 kg/m3 at 12.8% OMC. Both MDD values were within the range of 1700 - 2200 kg/m3 stated in earlier studies by (Maniatidis & Walker, 2003; Q. B. Bui et al., 2014) for Rammed Earth construction. Hence both soils were suitable for CSRE construction.

4.1.4. Summary of the properties of soils used in the study

Property	Soil A	Soil B
Particle Size Distribution (%)		
Gravels	61	24
Sand	11	32
Fines	28	44
Atterberg limits (%)		
Liquid limit	30.8	44.8
Plastic limit	18.2	19.5
Plasticity Index	12.6	25.3
Linear Shrinkage	8.57	10.71
Compaction		
MDD (kg/m3)	1938	1705
OMC (%)	11.1	12.8
Soil Type	Clayey Gravel	Clayey Sand

Table 7: Properties of soils used in the study

4.2. Compressive Strengths

The results from the compressive strength tests for both the BCB and CSRE panels at 21 days are summarized in the tables below. The tables showing the detailed results from the compressive strength tests are attached in APPENDIX A.

4.2.1. BCB Wall Panels

BCB panel	Dimensions			Failure load (kN)	Dry compressive strength (N/mm2)
	L (mm)	W(mm)	H(mm)		
1	455	108	242	120	2.44
2	465	109	240	96	1.89
3	460	110	241	87	1.72
Average	460	109	241	101	2.02

Table 8: Dry Compressive Strengths for BCB panels

The compressive strengths for the Burnt Clay Brick panels varied between 1.72 N/mm2 and 2.44 N/mm2 with a standard deviation of 0.08 and an average strength of 2.02 N/mm2. The difference in strengths among the brick panels was likely caused by the use of uneven bricks along with the uneven filling of mortar into the vertical joints during the construction of the panels.

4.2.2. CSRE Wall Panels

Soil sample	Cement (%)	Dimensions			Average failure load(kN)	Average compressive strength (N/mm2)
		L (mm)	W(mm)	H(mm)		
A	6	460	112.5	242	60	1.16
	8	460	112.5	241	62	1.17
	10	460	114.5	241	79	1.54
B	6	457.5	113	240	32	0.64
	8	457.5	111	240	50	0.95
	10	459	109	242	63	1.20

Table 9: Average Dry Compressive Strengths for CSRE panels at 21 days

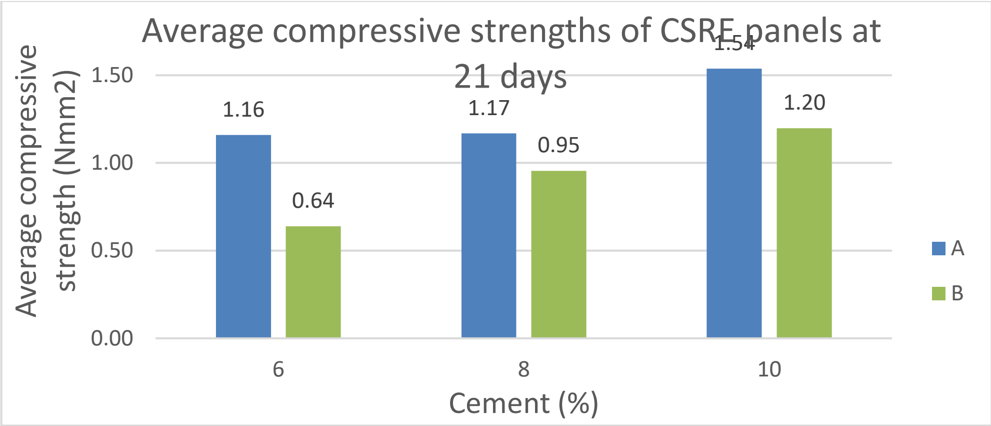

Figure 24: Variations in average dry compressive strengths of CSRE panels at 21 days

The average compressive strengths of the CSRE panels increased gradually across 6-10% cement stabilization. However, the average compressive strength of CSRE panels from soil A were higher than those of soil B. According to Kouakou & Morel, 2009; Ciancio & Beckett, 2013), the resistance to compression of Rammed Earth is proportional to its dry density. Soil A gave a higher MDD than soil B hence had higher compressive strength values. In addition, soil A had more gravel particles than soil B thus attained greater compressive strength.

Furthermore, the differences in the average compressive strength between CSRE panels of soils A and B were 0.52, 0.22 and 0.34 N/mm2 at 6%, 8% and 10% cement stabilization. This showed that sufficient strengths of walls with both soils could be achieved with 8% (optimal) cement stabilization at 21 days.

Overall, all the CSRE wall panels showed sufficient strength at 21 days curing, which was above the safe compressive stress recommended by (Middleton, 1992) of 0.25 N/mm2 for stabilized Rammed Earth. The strength values were also above the ranges established by (Standards Australia, 2002) and (NZS 4297, 1998) therefore making the stabilized soils suitable for wall construction.

4.2.3. Comparison of Average Compressive Strengths of BCB and CSRE Panels

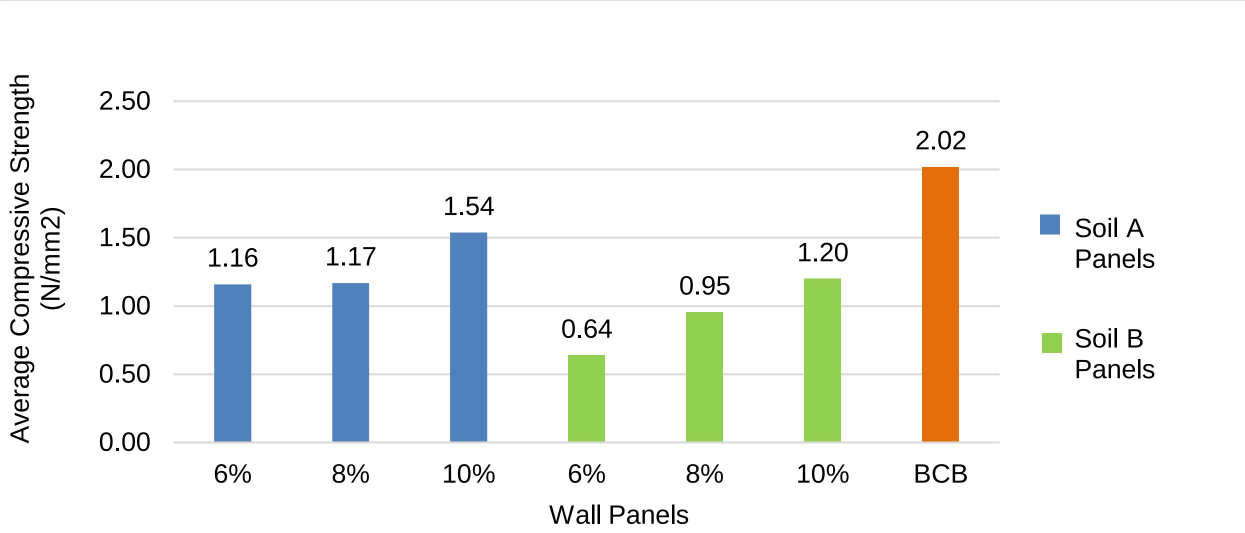

Figure 25: Compressive strength of BCB versus average compressive strength of CSRE panels at 21 days

The average compressive strength of BCB panels (2.02 N/mm2) was higher than the average strengths of all the panels stabilized across a range of 6-10 % cement. This difference could be attributed to the mineralogical composition of the bricks and the cement-sand bond strengths within the joints of the BCB panels. CSRE panels have no joints and therefore the cement sand mortar bonds with the soils have to be enforced through proper mixing at the optimum moisture content.

4.3. Durability test

The summary of results from the wet compressive tests for both the Burnt Clay Brick and CSRE panels are shown in the tables below. The tables showing the detailed results from the wet compressive strength tests are attached in APPENDIX A.

4.3.1. BCB Wall Panels

BCB panel	Dimensions			Failure load (kN)	Wet compressive strength (N/mm2)
	L (mm)	W(mm)	H(mm)		
1	465	108	241	74	1.47
2	456	111	241	80	1.58
3	460	110	242	82	1.62
Average	460	110	241	79	1.56

Table 10: Wet Compressive Strengths for BCB panels

The compressive strength of the BCB panels decreased in general when they were immersed in a water tank for 24 hours. This is because these previously air cured BCB panels absorbed water into the mortar and the bricks. At 24 hours, this moisture content had increased the strength of the mortar but had consequently weakened the strength of the bricks thus weakening the entire wall panel.

4.3.2. CSRE Wall Panels

Soil sample	Cement (%)	Dimensions			Average failure load(kN)	Average wet compressive strength (N/mm2)
		L (mm)	W(mm)	H(mm)		
A	6	459	109.0	238.0	15	0.30
	8	458	112.5	239.3	28	0.54
	10	459	115.0	222.0	47	0.88
B	6	458	109.5	232.5	27	0.54
	8	458	109.5	239.0	43	0.86
	10	455	110.5	238.0	57	1.13

Table 11: Average Wet Compressive Strengths for CSRE panels at 21 days

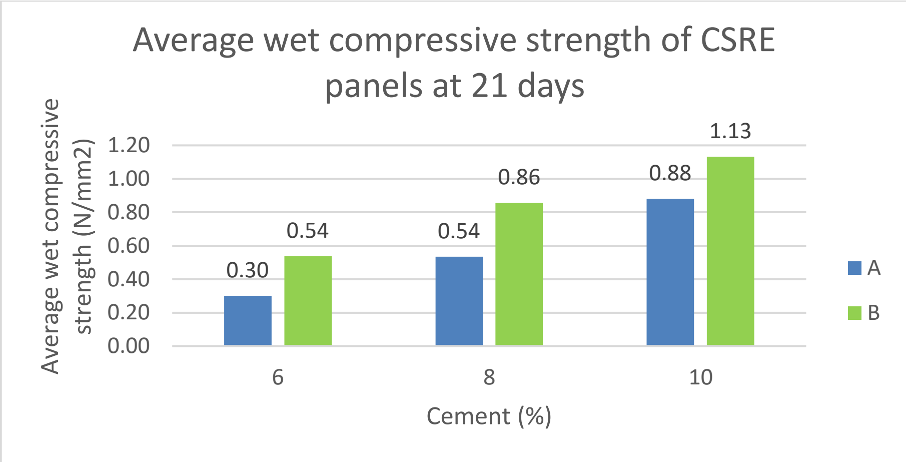

Figure 26: Variations of wet compressive strengths of CSRE panels across 6-10% cement at 21 days

From the table above, the average wet strength of panels from soil B was greater than that in panels of soil A.

The average wet compressive strength of CSRE panels of both soils A and B increased gradually across 6-10% cement stabilization. However, CSRE panels of soil B showed greater wet compressive strengths than those of soil A across 6% to 10% cement content. This was assumed to be caused by the presence of finer particles in soil B than in soil A as shown in the particle size distribution curves in *Figure 21*. Therefore, particles in soil B along with cement sand particles formed greater bonds with water than the gravel particles in soil A. This increased the strengths of the wet panels of soil B at the time of testing.

4.3.3. Comparison of Durability

The durability of both the BCB and CSRE panels were compared using their respective wet to dry strength ratios as shown in the tables below.

Average dry compressive strength(N/mm2)	Average wet compressive strength(N/mm2)	wet/dry strength ratio
2.02	1.56	0.77

Table 12: Average Wet to Dry Strength Ratio for BCB panels

Soil sample	Cement (%)	Average dry compressive strength (N/mm2)	Average wet compressive strength (N/mm2)	wet/dry strength ratio
A	6	1.16	0.30	0.26
	8	1.17	0.54	0.46
	10	1.54	0.88	0.57
B	6	0.64	0.54	0.84
	8	0.95	0.86	0.90
	10	1.20	1.13	0.95

Table 13: Average Wet to Dry Strength Ratio for CSRE panels at 21 days

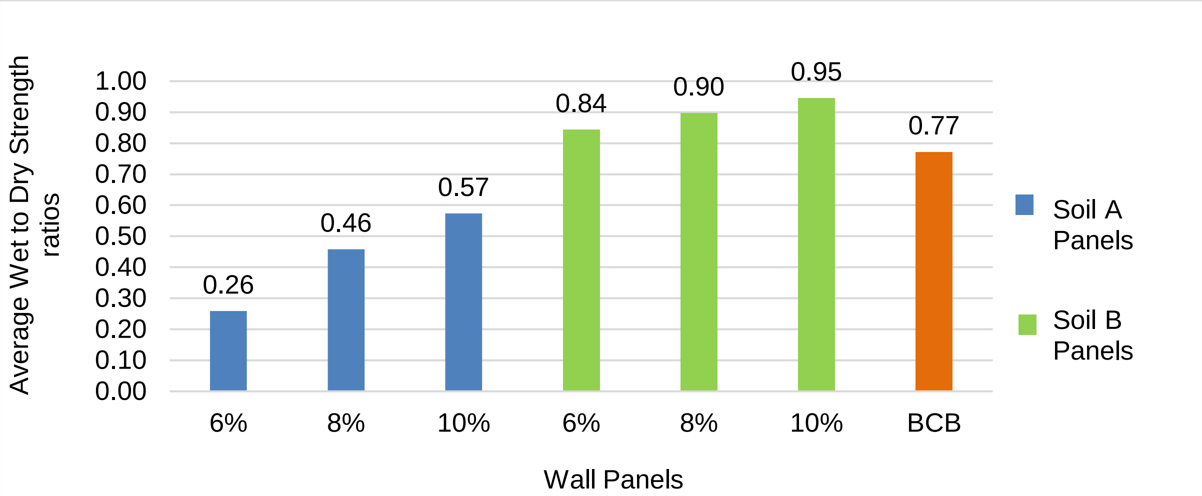

Figure 27: Comparison of Durability of BCB and CSRE panels at 21 days

The wet/ dry strength ratios for all the CSRE panels were in the range of 0.26-0.95. This showed a positive correlation with wet/dry strength ratio ranges of 0.46-0.69 earlier determined by (Guettala et al., 2006; C. Jayasinghe & Kamaladasa, 2005) for Rammed Earth walls at 28 days. This was an indicator that both soils when stabilized with cement at 6, 8 and 10% were suitable for CSRE walls under adverse conditions.

4.4. Cost Variations

The tables below show a summarized materials schedule for walling construction of a two-bedroom residential house model using both Burnt Clay Bricks and CSRE (with 6% cement). More detailed cost analyses of both walling materials are shown in *Table 26* and *Table 27* in APPENDIX A.

4.4.1. BCB House Walls

NO	DESCRIPTION	UNIT	QUANTITY	RATE(UGX)	AMOUNT(UGX)
1	**Bricks**	NO.	5703	500	2,851,500
2	**Tororo PPC**	BAGS	44	28,000	1,232,000
3	**Sand incl. transport**	TRIPS	3	170,000	489,600
4	**Labour (skilled and unskilled) for 7 days**	NO.	16	65,000	1,960,000
5	**Equipment (buying)**	ITEM	PS		249,000
6	**Hiring expenses**	ITEM	PS		980,000
7	**Transport**				
	Bricks	TRIPS	11	40,000	456,240
	Cement	TRIPS	2	40,000	88,000
	Equipment	TRIPS	1	40,000	40,000
	TOTAL				**8,346,340**

Table 14: Material Schedule for BCB walling

4.4.2. CSRE House Walls

NO	DESCRIPTION	UNIT	QUANTITY	RATE(UGX)	AMOUNT(UGX)
1	**Raw materials**				
	Soil excavation	CM	29	80,000	2,326,320
	Tororo PPC	BAGS	64	28,000	1,779,705
2	**Labour**	NO.	13	126,538	1,645,000
4	**Equipment**				
	Buying	ITEM	PS		2,294,950
	Hiring	ITEM	PS		665,000
5	**Transport for materials**				
	Cement	TRIPS	3.17804391	40,000	127,122
	Other equipment	TRIPS	2	40,000	80,000
	TOTAL				**8,918,096**

Table 15: Materials Schedule for CSRE walling

From the tables above, it is shown that the CSRE walling (6% cement) of a model of a standard two-bedroom residential house model in Uganda was estimated to be approximately 6% more expensive than the BCB walling. This can be attributed to the one-time costs such as the costs of formwork and the rammers under the section of equipment for purchase.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

From the experiments done in this study, the average compressive strength of BCB panels (2.02 N/mm2) was greater than that of the panels from both soil samples (1.29 N/mm2 and 0.98N/mm2). However, as far as earthen construction is concerned, both soils showed that they were capable of providing walls with sufficient strength at 21 days. This is because they had attained average compressive strength values of 1.29 N/mm2 and 0.98 N/mm2 above the recommended value of 0.5 N/mm2 at 28 days (NZS 4297, 1998).

In addition, the durability of BCB panels compared well with the CSRE panels at 21 days. BCB panels showed a higher wet to dry strength ratio (0.77) than the CSRE panels built from soil A (0.43). However, CSRE panels built from soil B had a higher average wet to dry strength ratio than the BCB and CSRE panels from soil A. This showed that CSRE Walls built from soil B had greater resistance to water than BCB and CSRE panels of soil A.

By comparison, the compressive strengths (dry and wet) of the CSRE were above the safe working ultimate limit state compressive stress of 0.25 N/mm2 recommended by (Middleton, 1992).

The cost analysis of both types of walls in housing construction showed that CSRE construction was about 6% more expensive than the BCB construction for a two-bedroom bungalow house. The cost savings from CSRE are expected to be realized only in cases of future projects where materials such as scaffolding are reused on the projects.

Though Rammed Earth construction offers structural and cost properties favorable for a bungalow house construction in Uganda, its awareness among the general population and some construction professionals is still in its early stages. Its integration into the formal construction sector should be a gradual process backed by formal and applied research. Despite the fact that it may never replace Burnt Clay Brick construction, it should be availed to the general public as an option for wall construction. This will enable Ugandans at different income levels to have a wide array of options to choose from when building their houses hence helping to tackle the housing crisis in Uganda.

5.2. Recommendations

Similar research should be carried out with half-scale and full-scale BCB and CSRE walls to investigate the effect of wall slenderness on compressive strengths and durability characteristics.

A comparative analysis of strengths and durability of both walling materials should be done but with thicker CSRE panels.

Similar investigations should be carried out with other stabilizing agents such as lime.

An actual cost study on site comparing the two walls should be carried out in the future.

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APPENDIX A

Sample A

Initial dry weight = 801.8 g

Sieve (mm)	Partial Retained Mass(g)	Cumulative Retained Mass (g)	Cumulative Retained (%)	% Passing (%)
28	0.0	0.0	0.0	100
20	35.90	35.9	4.5	96
14.0	37.80	73.7	9	91
10.0	88.20	161.9	20	80
6.3	119.10	281.0	35	65
5.00	66.50	347.5	43	57
2.360	143.30	490.8	61	39
1.180	39.20	530.0	66	34
0.600	17.20	547.2	68	32
0.425	5.90	553.1	69	31
0.300	5.80	558.9	70	30
0.212	5.20	564.1	70	30
0.150	5.40	569.5	71	29
0.075	6.40	575.9	72	28
Grading Modulus	1.60			

Table 16: Results from dry sieving soil sample A

Sample B

Initial dry weight = 713.1 g

Sieve (mm)	Partial Retained Mass(g)	Cumulative Retained Mass (g)	Cumulative Retained (%)	% Passing (%)
28	0.0	0.0	0.0	100
20	31.30	31.3	4.4	96
14.0	46.90	78.2	11	89
10.0	32.90	111.1	16	84
6.3	24.90	136.0	19	81
5.00	7.90	143.9	20	80
2.360	25.00	168.9	24	76
1.180	30.10	199.0	28	72
0.600	117.30	316.3	44	56
0.425	19.80	336.1	47	53
0.300	28.30	364.4	51	49
0.212	17.80	382.2	54	46
0.150	9.60	391.8	55	45
0.075	6.90	398.7	56	44
Grading Modulus	1.00			

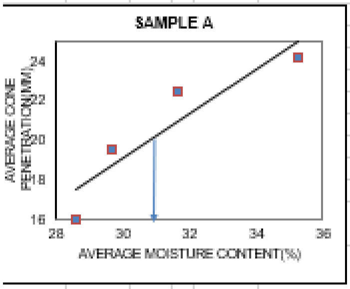
Table 17: Results from dry sieving soil sample B

SAMPLE A PLASTIC LIMIT

Container no.	1	2
Mass of wet soil + container(g)	10.90	10.90
Mass of dry soil + container(g)	9.50	9.53
Mass of container(g)	1.90	1.90
Mass of moisture(g)	1.40	1.37
Mass of dry soil(g)	7.60	7.63
Moisture content(%)	18.42	17.96

SAMPLE A LIQUID LIMIT

Test no.	1		2		3		4	
Average cone penetration(mm)	16.0		19.50		22.50		24.20	
Container no.	C1	C2	C3	C4	C5	C6	C7	C8
Mass of wet soil + container(g)	21.20	19.00	23.30	19.80	22.70	24.60	25.20	19.80
Mass of dry soil + container(g)	16.70	15.00	18.20	15.50	17.50	18.90	18.90	14.90
Mass of container(g)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mass of moisture(g)	4.50	4.00	5.10	4.30	5.20	5.70	6.30	4.90
Mass of dry soil(g)	15.70	14.00	17.20	14.50	16.50	17.90	17.90	13.90
Moisture content(%)	28.7	28.6	29.7	29.7	31.5	31.8	35.2	35.3
Average Moisture content(%)	28.6		29.7		31.7		35.2	



LIQUID LIMIT(%)	30.8
PLASTIC LIMIT(%)	18.2
PLASTICITY INDEX(%)	12.6

Initial length,Lo	140
length, Ld (mm)	128
Linear shrinkage, LS	8.57

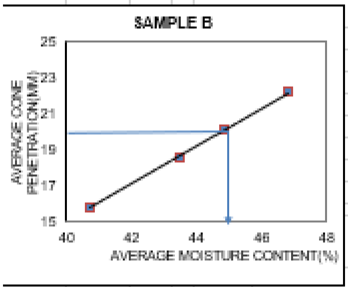
Table 18: Results from Atterberg limits' tests on soil A

SAMPLE B PLASTIC LIMIT

Container no.	1	2
Mass of wet soil + container(g)	20.00	20.00
Mass of dry soil + container(g)	16.90	16.96
Mass of container(g)	1.20	1.20
Mass of moisture(g)	3.10	3.04
Mass of dry soil(g)	15.70	15.76
Moisture content(%)	19.75	19.29

SAMPLE B LIQUID LIMIT

Test no.	1		2		3		4	
Average cone penetration(mm)	15.80		18.60		20.10		22.20	
Container no.	B1	B2	B3	B4	B5	B6	B7	B8
Mass of wet soil + container(g)	17.20	21.00	17.30	21.60	26.20	36.50	27.50	41.50
Mass of dry soil + container(g)	12.60	15.10	12.40	15.30	18.40	25.50	19.10	28.50
Mass of container(g)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Mass of moisture(g)	4.60	5.90	4.90	6.30	7.80	11.00	8.40	13.00
Mass of dry soil(g0	11.60	14.10	11.40	14.30	17.40	24.50	18.10	27.50
Moisture content(%)	39.7	41.8	43.0	44.1	44.8	44.9	46.4	47.3
Average Moisture content(%)	40.7		43.5		44.9		46.8	



LIQUID LIMIT(%)	44.8
PLASTIC LIMIT(%)	19.5
PLASTICITY INDEX(%)	25.3

Initial length,Lo (mm)	140
Oven-dried length, Ld (mm)	125
Linear shrinkage, LS = 100 (1-Ld/Lo)	10.71

Table 19: Results from Atterberg limits' tests on soil B

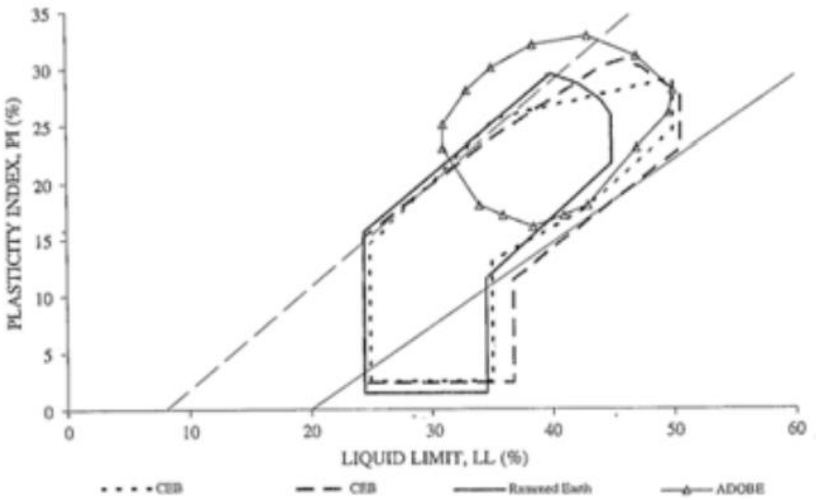


Figure 28: Plasticity nomogram Source: (Delgado & Guerrero, 2007)

Test number	0	1	2	3	4
Mass of mould + base (m_1) g	4430	4430	4430	4430	4430
Mass of mould + base + compacted specimen (m_2) g	6394	6530	6610	6584	6563
Mass of compacted specimen (m_2 - m_1) g	1964	2100	2180	2154	2133
Bulk density $p = (m_2 - m_1)/V$ Kg/m3	1968.2	2104.5	2184.7	2158.6	2137.6
Moisture content container No.	SK2	DP	SK2	KM	KM
Mass of container + wet soil g	426.00	522.00	378.00	572.00	626.00
Mass of container + dry soil g	402.00	478.00	338.00	501.00	536.00
Mass of container g	6.70	6.70	6.70	6.70	6.70
Moisture content %	6.07	9.34	12.07	14.36	17.00
Average Moisture Content (*W*) %	6.07	9.34	12.07	14.36	17.00
Dry density pd =(100 p) / (100 + W)	1856	1925	1949	1888	1827

Table 20: Results from compaction test on soil A

Test number	0	1	2	3	4
Mass of mould + base (m_1) g	4448	4448	4448	4448	4448
Mass of mould + base + compacted specimen (m_2) g	5996	6152	6338	6460	6306
Mass of compacted specimen (m_2 - m_1) g	1548	1704	1890	2012	1858
Bulk density $p = (m_2 - m_1)/V$ Kg/m3	1551.3	1707.7	1894.1	2016.3	1862.0
Moisture content container No.	SK2	DP	SK2	KM	KM
Mass of container + wet soil g	430.00	470.00	572.00	486.00	570.00
Mass of container + dry soil g	419.00	438.00	514.00	420.00	470.00
Mass of container g	6.70	6.70	6.70	6.70	6.70
Moisture content %	2.67	7.42	11.43	15.97	21.58
Average Moisture Content (*W*) %	2.67	7.42	11.43	15.97	21.58
Dry density pd =(100 p) / (100 + W)	1511	1590	1700	1739	1531

Table 21: Results from compaction test on soil B

BCB panel	Dimensions			Failure load (kN)	Dry compressive strength (N/mm2)
	L (mm)	W(mm)	H(mm)		
1	455	108	242	120	2.44
2	465	109	240	96	1.89
3	460	110	241	87	1.72
Average	460	109	241	101	2.02

Table 22: Dry Compressive Strength results of BCB panels

BCB panel	Dimensions			Failure load (kN)	Wet compressive strength (N/mm2)
	L (mm)	W(mm)	H(mm)		
1	465	108	241	74	1.47
2	456	111	241	80	1.58
3	460	110	242	82	1.62
Average	460	110	241	79	1.56

Table 23: Wet Compressive Strength results of BCB panels

Soil mix	Cement percentage (%)	Date Cast	Date Tested	Age (Days)	Dimensions L (mm)	W(mm)	H(mm)	Failure load (kN)	Dry compressive strength (N/mm2)
A	6	21-Dec-21	11-Jan-22	21	460	115	242	61	1.15
	6	21-Dec-21	11-Jan-22	21	460	110	240	59	1.17
	8	21-Dec-21	11-Jan-22	21	460	115	235	60	1.13
	8	21-Dec-21	11-Jan-22	21	460	114	236	63	1.20
	10	21-Dec-21	11-Jan-22	21	460	112	240	80	1.55
	10	21-Dec-21	11-Jan-22	21	460	110	238	77	1.52
B	6	21-Dec-21	11-Jan-22	21	455	108	242	30	0.61
	6	21-Dec-21	11-Jan-22	21	460	111	240	34	0.67
	8	21-Dec-21	11-Jan-22	21	460	114	241	48	0.92
	8	21-Dec-21	11-Jan-22	21	455	115	240	52	0.99
	10	21-Dec-21	11-Jan-22	21	459	110	235	66	1.31
	10	21-Dec-21	11-Jan-22	21	459	120	240	60	1.09

Table 24: Dry Compressive Strength results for CSRE panels

Soil mix	Cement percentage (%)	Date built	Date tested	Age	Dimensions L (mm)	W(mm)	H(mm)	Failure load (kN)	Wet compressive strength (N/mm2)
A	6	22-Dec-21	12-Jan-22	21	460	110	240	16	0.32
	6	22-Dec-21	12-Jan-22	21	457	108	236	14	0.28
	8	22-Dec-21	12-Jan-22	21	460	110	240	29	0.57
	8	22-Dec-21	12-Jan-22	21	455	115	238.5	26	0.50
	10	22-Dec-21	12-Jan-22	21	458	110	224	45	0.89
	10	22-Dec-21	12-Jan-22	21	460	120	220	48	0.87
B	6	22-Dec-21	12-Jan-22	21	455	109	230	24	0.48
	6	22-Dec-21	12-Jan-22	21	460	110	235	30	0.59
	8	22-Dec-21	12-Jan-22	21	456	108	238	40	0.81
	8	22-Dec-21	12-Jan-22	21	460	111	240	46	0.90
	10	22-Dec-21	12-Jan-22	21	460	111	236	60	1.18
	10	22-Dec-21	12-Jan-22	21	450	110	240	54	1.09

Table 25: Wet Compressive Strength results for CSRE panels

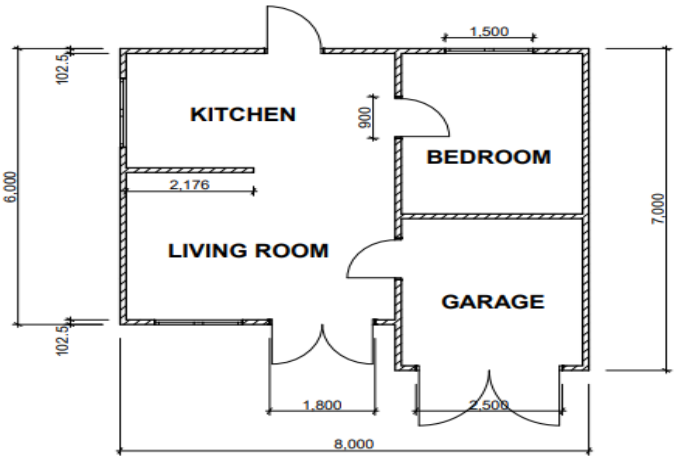


Figure 29: Floor plan used for the cost study of BCB Walls

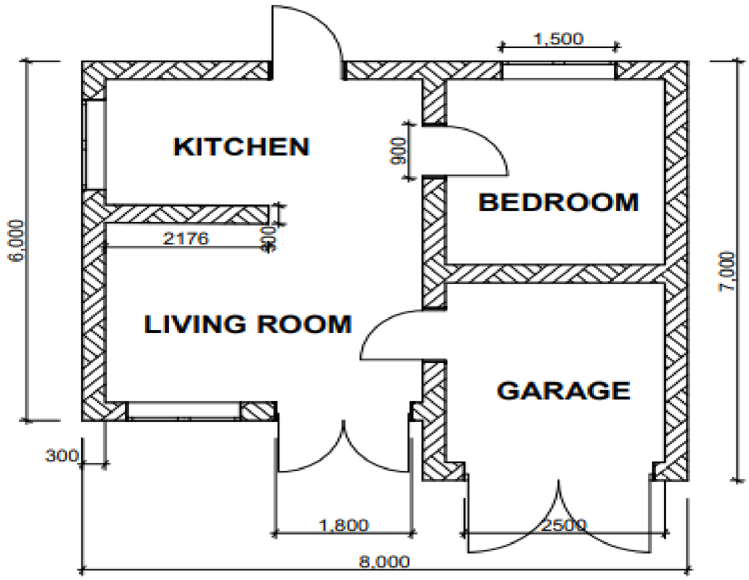


Figure 30: Floor plan used for the cost study of CSRE Walls

NO	DESCRIPTION	UNIT	QUANTITY	RATE(UGX)	AMOUNT(UGX)
1	**Bricks**	ITEM	5703	500	2,851,500
2	**Mortar (c/s = 1:3)**				
	Tororo PPC	BAGS	20	28,000	560,000
	Lake sand + transport	TRIPS	1.32	170,000	224,400
3	**Plaster (c/s mix = 1:3)**				
	Tororo PPC	BAGS	16	28,000	448,000
	Lake sand + transport	TRIPS	1	170,000	170,000
4	**Render (c/s mix = 1:3)**				
	Tororo PPC	BAGS	8	28,000	224,000
	Lake sand + transport	TRIPS	0.56	170,000	95,200
5	**Labour (7 days)**				
	Skilled	NO	1	30,000	210,000
	Unskilled				
	Mason	NO	5	20,000	700,000
	Porter	NO	10	15,000	1,050,000
6	**Equipment**				
	Trowel	ITEM	5	10,000	50,000
	Spirit level	ITEM	5	15,000	75,000
	Plumb bob	ITEM	5	7,000	35,000
	Tape measure	ITEM	5	10,000	50,000
	Spade(hire)	ITEM	5	20,000	700,000
	Jerrycans	ITEM	5	5,000	25,000
	Buckets	ITEM	2	7,000	14,000
	Wheelbarrow(hire) 2No.	DAYS	7	20,000	280,000
7	**Transport**				
	Bricks (Elf truck)	TRIPS	11.406	40,000	456,240
	Cement	TRIPS	2.2	40,000	88,000
	Equipment	TRIPS	1	40,000	40,000
	TOTAL				**8,346,340**

Table 26: Detailed Materials Schedule for BCB Walling

NO	DESCRIPTION	UNIT	QUANTITY	RATE(UGX)	AMOUNT(UGX)
1	**Raw materials**				
	Soil excavation	CM	29.079	80,000	2,326,320
	Tororo PPC (6% of soil weight)	BAGS	64	28,000	1,779,705
2	**Labour (7 days)**				
	Skilled	NO.	1	30,000	210,000
	Unskilled	NO.			-
	Mixers	NO.	2	15000	210,000
	Porters	NO.	5	15000	525,000
	Rammers	NO.	5	20000	700,000
3	**Equipment**				-
	Hoe(hire)	NO.	2	5,000	70,000
	Pick axe(hire)	NO.	1	5,000	35,000
	Wheelbarrow(hire)	NO.	2	20,000	280,000
	Spade(hire)	NO.	2	20,000	280,000
	Wooden formwork	SM	96.93	15,000	1,453,950
	Jerrycans	NO.	2	5,000	10,000
	Buckets	NO.	2	7,000	14,000
	Tape measure	NO.	2	10,000	20,000
	Wooden rammer	NO.	8	50,000	400,000
	Nails	kg	25kg		137,000
	Hammer	NO.	5	25000	125,000
	Iron rods (8 mm ribbed)	NO.	5	23000	115,000
	Grease (Jerrycan)	NO.	1	20000	20,000
4	**Transport**				-
	Equipment	TRIPS	1	40,000	40,000
	Wooden formwork	TRIPS	1	40,000	40,000
	Cement	TRIPS	3.17804391	40,000	127,122
	TOTAL				**8,918,096**

Table 27: Detailed Materials Schedule for CSRE Walling

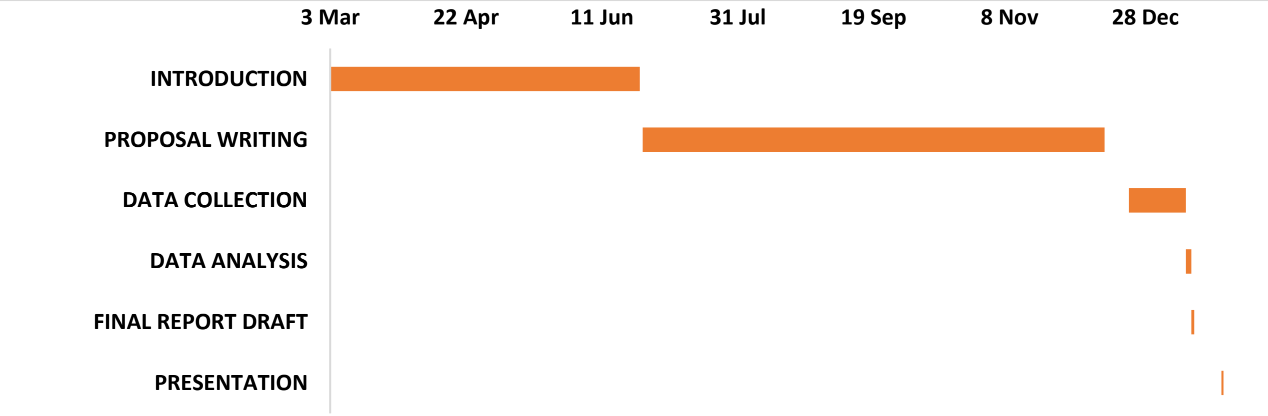
APPENDIX B

An itemized budget for the project is included below showing the expenditures during the data collection.

ITEM	QUANTITY	UNIT RATE	AMOUNT (UGX)
BRICKS	24	500	12,000
CEMENT	1	28,000	28,000
SOIL EXCAVATION @ SITE	2	15,000	30,000
STEEL MOULD	1	80,000	80,000
NOTE BOOK	1	2,000	2,000
PLUMB BOB	1	7,000	7,000
TRANSPORT (BRICKS)			10,000
TRANSPORT (SOIL)			10,000
PRINTING & BINDING			60,000
TOTAL			**239,000**

Table 28: Project Budget

The Gannt chart below shows the schedule for the project.



	PRESENTATION	FINAL REPORT DRAFT	DATA ANALYSIS	DATA COLLECTION	PROPOSAL WRITING	INTRODUCTIO N
Date of initiation	25/01/2022	14/01/2022	12/01/2022	22/12/2021	26/06/2021	03/03/2021
Duration of Activity(in days)	1	1	2	21	170	114

Figure 31: Project Schedule