

**BUSITEMA
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FACULTY OF ENGINEERING AND TECHNOLOGY

DEPARTMENT OF WATER RESOURCES ENGINEERING

FINAL YEAR REPORT

**OPTIMIZING THE PHYSICAL AND MECHANICAL PROPERTIES OF CEMENT-
STABILIZED RAMMED EARTH CONSTRUCTION BLOCKS.**

BY

BIRUNGI AMINAH

BU/UP/2021/0286

Final year report is submitted to the department of mining and water resources engineering in partial fulfilment of the requirement for the award of Bachelors of Science degree in water resources engineering at Busitema University.

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ABSTRACT

This research focuses on the improvement of the physical and mechanical properties of cement-stabilized rammed earth (CSRE) blocks. The approach included characterizing soil samples using sieve analysis to assess soil particle size distribution, moisture content tests, and maximum dry density evaluations to determine the best achievable compaction characteristics.

These tested samples were taken from a total of three different soil samples that were prepared with different concentrations of cement (0, 2, 4, 6, and 8 percent) to determine the influence of the cement proportion on the blocks' strength and durability.

The blocks were compacted and cured for a duration of 7, 14 and 28 days, then they underwent compressive strength testing using a Universal Testing Machine (UTM) and water absorption measurement for durability.

The data was analyzed to find the most beneficial cement-soil ratio that would achieve maximum strength while remaining within economical limits. The results showed the possibility of CSRE blocks being used as a construction material that is cost-effective while being mechanically reliable.

DECLARATION

DECLARATION

I BIRUNGI AMINAH, registration number BU/UP/2021/0286, declare that the work in this final year report is my original work and has not been presented to any higher institution of learning for any academic award.

SIGNATURE: 

DATE: 15/05/2023

Email: birungiamina51@gmail.com

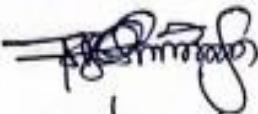
Contact: 0789748495/0750975479

APPROVAL

APPROVAL

I hereby certify that this project is original report of BIRUNGI AMINAH, BU/UP/2021/0286. It has been done under my supervision and is ready for submission to the department of water resources and mining engineering.

SUPERVISOR: MR TIGALANA DAN

SIGNATURE: 

DATE: 15/05/2025

DEDICATION

I dedicate this report to my Parents professor Twaibu Ssemwogerere and Mrs. Sophie Namwanje,
my siblings and my friends

ACKNOWLEDGEMENT

I would like to express my heartfelt gratitude to the Almighty for His constant guidance, protection, and blessings throughout this journey

To my parents for their unwavering love and support, which have been the cornerstone of my achievements. Their sacrifices and encouragement that have fueled my ambition to pursue my dreams.

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1. INTRODUCTION

1.1. Background;

The global housing crisis has reached critical proportions with an estimated 1.8 billion people lacking adequate shelter and 150 million experiencing homelessness worldwide (United Nations Human Settlements Programme [UN-Habitat], 2022). In Uganda, this crisis manifests as a deficit of 2.4 million housing units, exacerbated by rapid urbanization and the high cost of conventional construction materials (Bower et al., 2019).

Traditional building methods using brick and mortar not only prove financially inaccessible for low-income populations but also carry significant environmental burdens due to their high embodied energy and carbon emissions (Ben-Alon et al., 2019).

Rammed earth construction has re-emerged as a sustainable alternative, offering several advantages: low material costs, excellent thermal performance, and minimal environmental impact (Taylor & Luther, 2004). However, its application in tropical climates like Uganda's faces durability challenges, particularly against heavy rainfall and humidity (Danso, 2016). Cement stabilization has been shown to improve rammed earth's mechanical properties, with studies demonstrating strength increases of 300-500% at 4-10% cement content (Jayasinghe & Kamaladasa, 2007). Yet excessive cement (>6%) can lead to brittleness and increased water absorption (Tyoden et al., 2023), while also diminishing the material's environmental benefits.

This study builds upon previous research by Asrah et al. (2022) and Meng et al. (2018) to systematically investigate the optimal cement proportion for rammed earth hollow blocks in Uganda's context. By testing cement percentages from 0-8% and evaluating both compressive strength and water absorption, the research aims to identify a mix that achieves:

1. Structural integrity meeting minimum standards (≥ 2.0 N/mm² per NZS 4298, 1998)
2. Durability against tropical weather conditions
3. Cost-effectiveness for low-income housing

1.2. Problem statement.

The high cost and environmental impact of conventional construction materials exacerbate Uganda's housing deficit. While cement-stabilized rammed earth (CSRE) offers a sustainable alternative, its optimization remains challenging: excessive cement increases strength but reduces water resistance, compromising durability in tropical climates.

This study investigates the optimal cement content (0–8%) for CSRE blocks by evaluating compressive strength and water absorption at 7, 14, and 28-day curing periods. The goal is to identify a mix that balances structural integrity ($\geq 2.0 \text{ N/mm}^2$), low water absorption ($< 10\%$), and cost-effectiveness, addressing a critical gap in affordable, climate-resilient housing solutions.

1.3. Objectives

1.3.1. Main objective;

To optimize the physical and mechanical properties of cement-stabilized rammed earth construction blocks.

1.3.2. Specific Objectives:

- To characterize the rammed earth materials to assess their suitability for use in block construction.
- To determine the effect of optimal cement content on compressive strength and water absorption properties of the blocks.
- To determine the optimum cement content for maximum structural integrity and environmental resilience in block production.

1.4. Significance of the Study.

This research provides a cost-effective, sustainable solution to Uganda's housing crisis by optimizing cement-stabilized rammed earth blocks. It balances strength ($\geq 2.0 \text{ N/mm}^2$) and water resistance ($< 10\%$) for tropical climates while minimizing cement use. The findings support affordable, eco-friendly construction, reduce reliance on imported materials, and align with SDG 11 for sustainable cities. By offering data-driven guidelines, it bridges the gap between theory and practical, scalable housing solutions.

1.5. Justification of the study;

This research addresses Uganda's urgent need for affordable, sustainable housing by optimizing cement-stabilized rammed earth blocks. Conventional construction is costly and environmentally harmful, while unstabilised earth lacks durability. By determining the ideal cement content (balancing strength, water resistance and cost), the study provides a practical, scalable solution using local materials. The findings will empower builders, policymakers and communities to adopt climate-resilient, low-carbon construction, directly supporting Uganda's development goals and SDG 11.

1.6. Scope of the study;

The study's main objectives include evaluating the mechanical and physical characteristics of rammed earth, using Response Surface Methodology (RSM) to optimise the mix proportions of rammed earth and cement, creating moulds for improved compaction and structural integrity of blocks and testing the optimised blocks for environmental resilience.

2. LITERATURE REVIEW

2.1. Introduction to Rammed Earth Construction

Rammed earth construction involves natural materials eg clay, lime, sand and have been used as a building construction method since ancient times(Mechanics & Barcelo, 2022).These structures are constructed by pummeling the mentioned materials in thin layers into strong jars with proper bracing. Rammed earth walls gave the advantages of being good insulators for snow and heat and are also fire proof, however can be vulnerable to water if not designed in a high quality and protection-oriented manner. In this case the deficiencies can be fixed by including new material.

2.2. Objective 1: To characterize the rammed earth materials to assess their suitability for use in block construction.

2.2.1. Soil Composition and Its Impact on Rammed Earth Properties

The performance of rammed earth structures is heavily influenced by soil composition. (Maniatidis & Walker, 2008) provided details of the particle distribution of rammed earth where clay and silt contents range from 10%-80%. The acceptable range for CSRE is 5%-40%, but the recommended range is 25%-40%. However, recent work by Xu et al. (2024) suggests that these proportions can be fine-tuned based on local soil characteristics to optimize performance.

2.2.2. Clay Content and Binding Properties

Clay plays a crucial role in binding the particles together in rammed earth. (Sánchez-Haro et al., 2024) found that the type of clay mineral present greatly affects the strength and durability of rammed earth. For example, kaolinite-rich soils tend to produce stronger rammed earth compared to those rich in montmorillonite.

2.2.3. Sand and Gravel: Structural Stability

Sand and gravel provide structural stability to rammed earth. Research by (Sharma et al., 2021) demonstrates that the angularity and size distribution of sand particles can significantly impact compressive strength and found that well-graded angular sand can increase compressive strength by up to 30% compared to poorly graded rounded sand.

2.2.4. Mechanical Properties

Compressive Strength

(Khadka & Shakya, 2016) shows that the compressive area of unstabilised soil varies widely and such tests should be applied prior to the design process. The minimum allowable compressive

strength of the unstabilised rammed earth is between 0.25 and 0.6 MPa. Furthermore, he went on to demonstrate in stabilised soils. Properly compacted rammed earth can achieve compressive strengths ranging from 1 to 5 MPa. This demonstrates that with optimal soil selection and stabilization, compressive strengths up to 10 MPa can be achieved, rivaling some conventional concrete mixes.

Tensile Strength

While rammed earth excels in compression, its tensile and flexural strengths are relatively low. (Danso, 2016) report typical tensile strengths of 0.1-0.5 MPa for unstabilised rammed earth. However, their research shows that the addition of natural fibers, such as sisal or jute, can increase tensile strength by up to 200%.

2.2.5. Physical Properties

Density and Porosity

The density of rammed earth significantly depends on the distribution of small particles, humidity during compaction, and also the pressure magnitude. A comprehensive study by (Niroumand et al., 2021) found that the dry density of rammed earth typically ranges from 1700 to 2200 kg/m³, they note that higher densities generally correlate with increased strength and reduced water absorption.

Thermal Properties

One of the main advantages of rammed earth is its excellent thermal mass. Research by (Taylor & Luther, 2004) demonstrates that rammed earth walls can effectively regulate indoor temperatures. They continued to show that incorporating phase change materials (PCMs) into rammed earth can further enhance its thermal performance, potentially reducing heating and cooling energy demands by up to 40%.

2.2.6. Durability and Weathering Resistance

The durability of rammed earth under various environmental conditions is crucial for its use in block construction. Recent work by (Faraj et al., 2023) investigates the use of nanosilica and recycled plastics to improve water resistance and freeze-thaw durability. They further show that these additives can reduce water absorption by up to 70% and increase freeze-thaw resistance by a factor of 3.

2.3. Objective 2: To determine the effect of optimal cement content on compressive strength and water absorption properties of the blocks.

2.3.1. Role of Cement in Stabilized Rammed Earth

Cement stabilization is a common method to enhance the strength and durability of rammed earth. (Jayasinghe & Kamaladasa, 2007) reports that cement contents between 4-10% by weight can increase the compressive strength of rammed earth by 300-500%. However, a more recent study by (Meng et al., 2018) shows that optimal cement content may be lower for hollow blocks due to their reduced mass.

2.3.2. Cement Content and Compressive Strength

A comprehensive study by (Jayasinghe & Kamaladasa, 2007) investigated the relationship between cement content and compressive strength in rammed earth hollow blocks. cement contents of 6%, 8% and 10% corresponded, respectively, to strength increases of 41%, 80% and 92% compared with the reference mix with a mean compressive strength of 1.15 MPa. However, they noted diminishing returns above 8% cement content, suggesting this as an optimal range for most applications.

2.3.3. Impact on Durability

Cement stabilization significantly improves the durability of rammed earth. (Tyoden et al., 2023) demonstrates that cement-stabilized rammed earth exhibits superior resistance to water erosion and freeze-thaw cycles. Their study found that 6% cement content can reduce water absorption by up to 50% and increase freeze-thaw resistance by a factor of 5.

2.3.4. Optimizing Sand Content and Gradation

The proportion and gradation of sand in the rammed earth mix play crucial roles in enhancing the mechanical properties and overall performance. A comprehensive study by (Taghiloha, 2013) found that a sand content of 60-70% with a well-graded particle size distribution yielded the best results in terms of compressive strength and durability for stabilized rammed earth blocks.

2.3.5. Sand-to-Binder Ratio

The sand to binder ratio is crucial for achieving the optimal for achieving optimum mechanical properties and the durability (Babalola et al., 2020). The composition of rammed earth typically includes clay, sand and additional binders like cement or lime. From the compaction results, 30%

of binder content was proposed for stabilization of the rammed earth and all the further studies were carried out by adding this amount of binder

2.3.6. Particle Size Distribution

This is crucial in determining the mechanical properties and suitability of construction. The compositions typically include varying the percentages of gravel, sand, powder and sticky particles(Hall & Djerbib, 2007).the compositions of are given as follows;

- Gravel: 0-56.9%
- Sand: 32.04-65.95%
- Powder: 3.98-13.01%
- Sticky particles: 7.08-21.04%, these components therefore affect the strength and stability of rammed earth

2.3.7. Innovative Additives and Their Effects

Innovative additives in rammed earth construction significantly enhance its structural performance and sustainability. Various stabilizers, such as cement, bagasse ash, glass fibers, and recycled concrete aggregates (RCAs), have been explored to improve compressive strength and durability. For example, the incorporation of cement can increase compressive strength by up to 92% depending on the content used(Cardenas-Haro et al., 2021)). Additionally, air-entraining agents have shown remarkable effectiveness, achieving strength increases of 155. The use of nanotechnologies, such as halloysite nanoclay, further reduces embodied energy and CO2 emissions, promoting environmental sustainability (Sposito & Scalisi, 2019). Moreover, utilizing RCAs not only enhances mechanical resistance but also contributes to waste reduction(Kumar & Singh, 2023).These advancements illustrate the potential for innovative materials to transform rammed earth construction practices.

2.4. Objective 3: To determine the optimum cement content for maximum structural integrity and environmental resilience in block production.

The determination of optimum cement content for block production has been widely studied to achieve a balance between structural performance, durability, and environmental sustainability. Research indicates that higher cement content generally enhances compressive strength but may lead to increased brittleness, shrinkage cracks, and higher carbon emissions due to the energy-intensive nature of cement production (Hossain et al., 2016; Aïtcin, 2016).

Studies have shown that partial replacement of cement with supplementary cementitious materials (SCMs), such as fly ash, slag, or silica fume, can reduce the carbon footprint while maintaining adequate strength (Malhotra & Mehta, 2004; Siddique, 2014). For instance, Neville (2011) suggests that a 10–15% cement content, combined with 20–30% fly ash, can produce blocks with compressive strengths exceeding 7 MPa while improving durability against sulfate attack and freeze-thaw cycles.

Further investigations into the influence of aggregate type and water-cement ratio highlight that optimized gradation and low porosity aggregates can reduce cement demand without compromising structural integrity (Mehta & Monteiro, 2017). Research by Walker (2005) on compressed earth blocks (CEBs) and concrete masonry units (CMUs) demonstrates that cement contents between 5% and 10% are often sufficient for non-load-bearing applications, whereas load-bearing blocks may require 10–15% cement, depending on curing conditions. Additionally, life cycle assessment (LCA) studies emphasize that minimizing cement content through SCMs or alternative binders (e.g., geopolymers) significantly lowers embodied carbon (Habert et al., 2011; Miller et al., 2018).

2.4.1. Response surface methodology;

Response Surface Methodology (RSM) is increasingly applied in the optimization of rammed earth construction techniques particularly in enhancing the properties of earth-based materials. It facilitates the exploration of relationships between various factors and response variables allowing efficient optimization of material compositions.

Optimization of material mixes.

RSM is utilized to determine optimal proportions of materials, such as cement and Spent Bleaching Earth Ash (SBEA), to achieve desired compressive strength and water absorption in Interlocking Compressed Earth Bricks (ICEB)(Asrah et al., 2022)

The methodology employs statistical tools to model and analyze the effects of different variables on the performance of rammed earth materials(Selvamuthu & Das, 2018)

2.4.2. Experimental Design and Analysis

RSM incorporates designed experiments, such as factorial and central composite designs, to systematically explore the factor space and identify optimal settings(Steinberg et al., n.d.)

The use of software like Design Expert and Minitab enhances the accuracy of predictions and visualizations of response surfaces(Asrah et al., 2022)

3. Chapter 3; METHODOLOGY

3.1. Materials and equipment;

The samples were got from Entebbe katabi busambaga and 42.5 optimal cement (OPC) was used. The mould that was used had dimensions of 210mm*106mm*65mm

3.2. Objective one; Characterization of rammed earth materials.

3.2.1. Material preparation;

Three different samples of soil were collected from various places.

Each sample needed at least 15kgs of soil for easy preparations

The samples were labelled as sample1, sample 2 and sample 3.

Each sample underwent a process called riffing or quartering resulting in five samples of 2.5kg each totaling 15 samples.

3.2.2. Tests done on the soil sample

Sieve analysis test;

This was conducted to determine the particle size distribution of the soil. This test helps in understanding the gradation of the soil which is crucial for achieving the desired compaction and strength properties following a standard procedure of particle size distribution bs 1377-2-1990

Procedure for wet sieving analysis;

Each sample was washed thoroughly until the water became clear to remove all the silt and clay sized particles in the soil.

The material was washed through a 75µm sieve allowing the material passing through it to waste.

The material retained on the sieve was transferred to a tray and dried in the oven at 105 degrees Celsius for a minimum of 24hrs.

Procedure for dry sieving;

After oven drying, the sample was passed through a stack of sieves with mesh sizes ranging from 75mm to 75µm.

The sieves were Shaken manually for a standard duration eg 10 mins.

The material retained on each sieve was weighed and the percentage retained is calculated.

A particle size distribution curve was generated to evaluate the soil's gradation.



Figure 3.2



Figure 3.1

Maximum dry density

This was conducted to determine the relationship between soil density and moisture content. It can be used to establish the optimum moisture content at which soil is densest following a standard of AASHTO T-99.

Preparation of the compaction test;

The sample was mixed with water measured from the cylinder starting from 10cm up to 30cm.

The cylindrical metal mould was then filled with the soil.

The soil was rammed into the mould in layers and here 25 blows were made for each sample.

The mould, the base plate and the compacted soil were weighed.

A sample of the soil was taken and dried in the oven to determine the exact moisture content.

The dry density was calculated. Divide the moist density by the percent moisture divided by 100, plus 1.



Figure 3.3



Figure 3.4

Moisture content test;

the moisture content of the soil was assumed to be the amount of water within the pore space between the soil grains which can be removable by oven drying at a temperature not exceeding 110 degrees Celsius. the moisture content has a profound effect on soil behaviors.

Test procedures.

The container was cleaned, dried and weighed to the nearest 0.1gm

A representative sample was crumbled and loosely placed in the container.

The container with the sample was immediately weighed and placed in the oven to dry

After drying the container and the contents are weighed.

3.3. Objective two; To determine the effect of optimal cement content on compressive strength and water absorption properties of the blocks.

The objective aimed to determine the influence of different cement percentages 0%, 2%,4%,6%,8% on the physical properties of cement stabilized rammed earth blocks. The goal was to find the most beneficial cement soil ratio that would achieve maximum strength while remaining within economical limits.

3.3.1. Sample preparation;

The different soil cement mix ratios were prepared for testing with cement percentages of 0%, 2%,4%,6%,8% by weight.



Figure 3.5

3.3.2. Mixing and block formation;

The soil and cement were mixed with the required amount of water until a uniform consistency is achieved. The water content was determined based on the optimum moisture content established in the first objective.



Figure 3.6

3.3.3. Block formation

The mixture was then compacted into the molds manually. The compaction process ensured that the blocks were dense and free from air pockets which could compromise their strength.



Figure 3.7

3.3.4. Curing

The blocks were covered with plastic sheets to retain moisture and prevent rapid drying.

The blocks were cured for 7, 14 and 28 days to allow proper strength development. Curing is a critical step as it allows the cement to hydrate and bond with the soil particles enhancing the block's strength and durability.



Figure 3.8

3.3.5. Tests to be done;

Compressive strength tests;

A universal testing machine (UTM) was used to apply a gradual load until the block failed.

The maximum load was recorded and the compressive strength was calculated

$$\text{Compressive Strength} = \frac{\text{maximum load}}{\text{cross sectional area}}$$

The compressive strength tests were conducted at 7,14 and 28 days to evaluate the strength development over time.

Water absorption tests;

The block was dried in an oven until it reached a constant weight. (W1)

The block was then submerged in water for 24hrs

The excess surface water was removed and the block was weighed again as (W2).

The water absorption test was calculated using;

$$\text{Water absorption (\%)} = \frac{W2-w1}{w1}$$

The tests at 7, 14 and 28 days are performed to evaluate their performances.

Data analysis;

The compressive strength and water absorption results were compared for different soil-cement ratios.

The optimal cement percentage that provides the best balance of strength and durability was identified

3.4. Objective three; To determine the optimum cement content for maximum structural integrity and environmental resilience in block production.

This study employed a systematic approach to analyse and validate the optimal cement for rammed earth blocks focusing on compressive strength and water absorption. It began with developing predictive regression models in Minitab to establish relationships of cement content, curing periods and water-cement ratios (0.45-0.55) with the two key response variables.

A comprehensive three-way ANOVA was conducted to assess main effects, interaction effects and statistical significance of all factors.

The analysis progressed with response surface methodology generating 3D plots and contour plots to visualise how compressive strength and water absorption varied across different combinations of cement content and curing time. This enabled identification of optimal performance zones where strength was maximized while absorption was minimised.

4. CHAPTER FOUR; RESULTS AND DISCUSSION

4.1. OBJECTIVE ONE; characterization of cement stabilized rammed earth blocks.

Tests that were conducted

4.1.1. Sieve analysis;

Sample 1;

SAMPLE 1				
Initial wt before washing (g)	843.7		Moisture Content (%)	13.8
Dry wt after washing (g)	357.0		Initial Dry Weight (g)	843.7
Diameter(mm)	Partial Retained Mass(g)	Cumulative Retained Mass(g)	Retained Mass(%)	% Passing
14	0.0	0.0	0.0	100
10	2.6	2.6	0.3	100
6.3	4.0	6.6	0.5	99
5	4.0	10.6	0.5	99
2	18.5	29.1	2.2	97
1.18	61.3	90.4	7.3	89
0.6	63.8	154.2	7.6	82
0.425	31.0	185.2	3.7	78
0.3	40.5	225.7	4.8	73
0.15	84.4	310.1	10.0	63
0.075	46.3	356.4	5.5	58
Pan	0.6	357.0		

Figure 4.1

The initial weight (before washing) is 843.7g, Dry weight (after washing) is 357g and Moisture content is 13.8%. The coarse fraction usually greater than or equal to 2mm, only 3.5% retained meaning the sample is mostly fine grained. Sand fraction(0.075mm-2mm) there has been a gradual decrease from 97% to 58% indicating a well graded sand silt mixture. Fines (< 0.075mm) 58% passing which is very high typical specifications recommend less than 35% fines to avoid excessive plasticity and poor drainage.

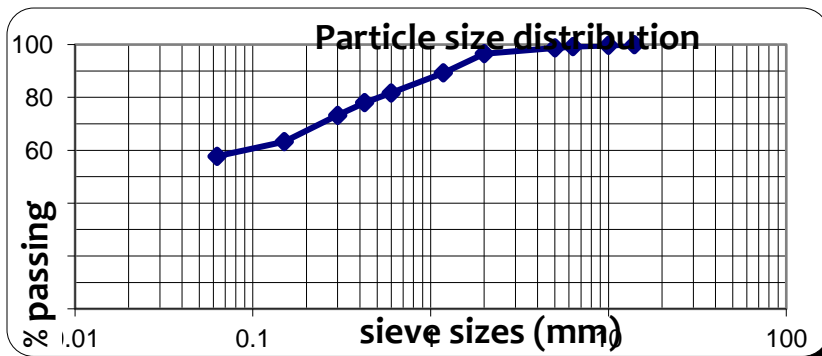


Figure 4.2 showing the grading curve

Sample 2;

SAMPLE 2				
Initial wt before washing (g)	1002.7		Moisture Content (%)	14.9
Dry wt after washing (g)	401.9		Initial Dry Weight (g)	1002.7
Diameter(mm)	Partial Retained Mass(g)	Cumulative Retained Mass(g)	Retained Mass(%)	% Passing
14	0.0	0.0	0.0	100
10	2.4	2.4	0.2	100
6.3	8.2	10.6	0.8	99
5	3.7	14.3	0.4	99
2	15.9	30.2	1.6	97
1.18	71.4	101.6	7.1	90
0.6	72.0	173.6	7.2	83
0.425	36.0	209.6	3.6	79
0.3	45.6	255.2	4.5	75
0.15	97.8	353.0	9.8	65
0.075	48.0	401.0	4.8	60
Pan	0.9	401.9		

Figure 4.3 showing the percentage passing for sample 2

The initial weight before washing was 1002.7g, Dry weight after washing 401.9g and Moisture content;14.9% Coarse fraction (>2mm) 3% retained mostly fine graded. Sand fraction(0.075mm-2mm); gradual reduction from 97% to 60%. Fines (<0.075mm);60% passing

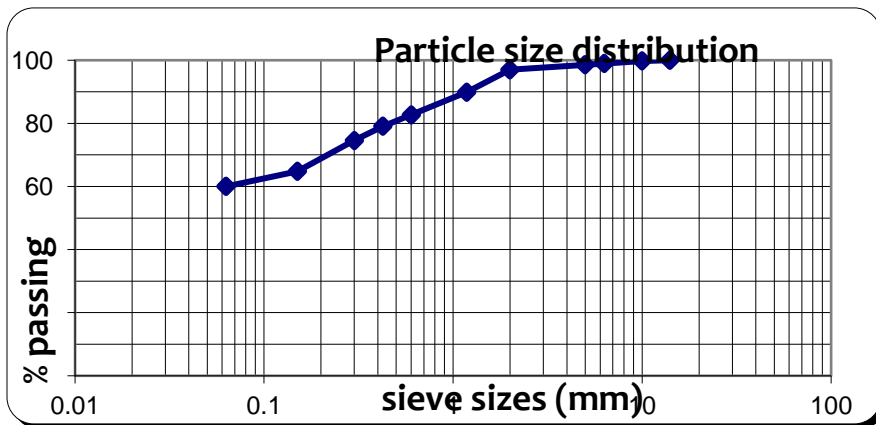


Figure 4.4

Sample 3;

SAMPLE 3				
Initial wt before washing (g)	929.3		Moisture Content (%)	13.7
Dry wt after washing (g)	371.8		Initial Dry Weight (g)	929.3
Diameter(mm)	Partial Retained Mass(g)	Cumulative Retained Mass(g)	Retained Mass(%)	% Passing
14	0.0	0.0	0.0	100
10	2.2	2.2	0.2	100
6.3	3.8	6.0	0.4	99
5	2.9	8.9	0.3	99
2	13.4	22.3	1.4	98
1.18	66.4	88.7	7.1	90
0.6	64.7	153.4	7.0	83
0.425	31.9	185.3	3.4	80
0.3	41.8	227.1	4.5	76
0.15	89.2	316.3	9.6	66
0.075	54.0	370.3	5.8	60
Pan	1.5	371.8		

Figure 4.5 showing percentage passing for sample 3

Initial weight before washing:923.3g, Dry weight after washing is 371.8g and Moisture content:13.7% Coarse fraction(>2mm):2.4% retained Sand fraction(0.075mm-2mm); gradual decrease from 98% to 61% Fines (<0.075mm);60%passing.

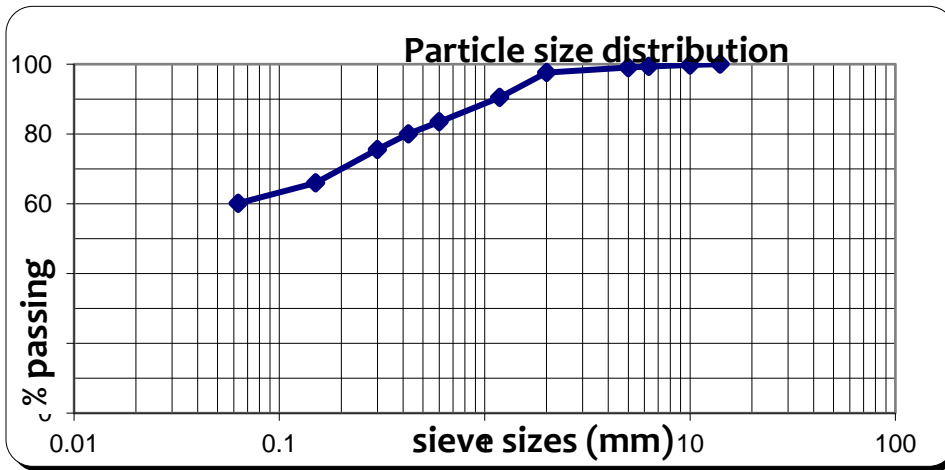


Figure 4.6

Comparison for the samples

Parameter	Sample 1	Sample2	Sample 3	Typical spec limit
Fines(<0.075mm)	58%	60%	60%	Less than 35%
Moisture content	13.8%	14.9%	13.7%	Depends on compaction
Coarse(>2mm)	3.5%	3%	2.5%	<10% for fine soils

The sieve analysis revealed all the three soil samples had excessive fines content surpassing the recommended maximum of 35% for CSRE. This high fine content indicates poor gradation which can adversely affect compaction and drainage leading to plasticity and shrinkage issues. Despite this sample 1 showed relatively better gradation and compaction potential compared to sample 2 and 3.

Discussion

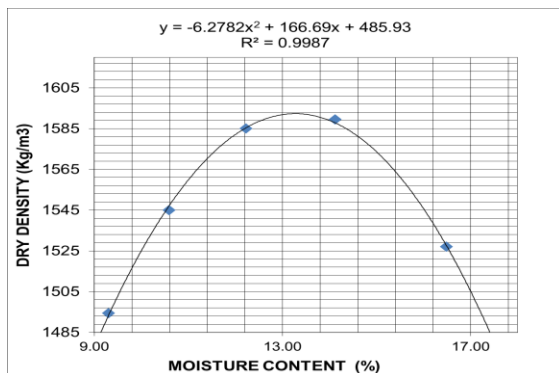
The results align with Maniatidis & Walker (2008) who noted that rammed earth soils should ideally contain 5-40% fines for balanced workability and strength. The tested soils high fines content may necessitate blending with coarser materials or stabilizers to meet these standards.

4.1.2. MAXIMUM DRY DENSITY

Sample 1;

SAMPLE 1					
3 No. of Layers	Mould Diameter	100	(mm)		
	Height of Mould	127	(mm)		
25 Blows per Layer	Mould Volume (v)	997.9	(Cm ³)		
Mass Retained on 20 mm Sieve					
AASHTO T-99					
Test number					
Mass of mould + base (m ₁) g	4440	4440	4440	4440	4440
Mass of mould + base + compacted specimen (m ₂) g	6070	6145	6215	6250	6215
Mass of compacted specimen (m ₂ - m ₁) g	1630	1705	1775	1810	1775
Bulk density $p = (m_2 - m_1) / V$ Kg/m ³	1633.5	1708.7	1778.8	1813.9	1778.8
Moisture content container No.	A	B	C	D	E
Mass of container + wet soil g	475.00	475.00	510.00	490.00	430.00
Mass of container + dry soil g	435.00	430.00	455.00	430.00	370.00
Mass of container g	5.00	5.00	5.00	5.00	6.00
Moisture content %	9.30	10.59	12.22	14.12	16.48
Average Moisture Content (W) %	9.30	10.59	12.22	14.12	16.48
Dry density $p_d = (100 p) / (100 + W)$	1494	1545	1585	1589	1527

Figure 4.7 showing the dry density for sample 1



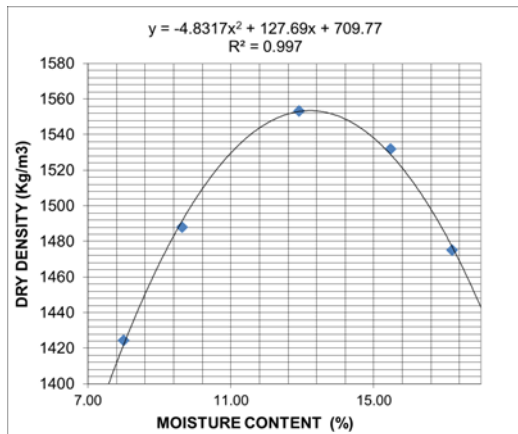
MDD	1592	Kg/m ³	
OMC	13.3	%	
A	B	C	
-6.2782	166.69	485.93	

Figure 4.8 showing the curve for dry density and moisture content

The maximum dry density (MDD) calculated 1592kg/m³, the optimum moisture content was 13.3%. The moisture content usually ranges between 8.7%-16.0%The density peaks at 13.3% OMC then declines with added water indicating optimal water content for maximum compaction. The sharp decline in density beyond OMC demonstrates the material's sensitivity to excess water. Material properties; The relatively high OMC suggests significant fines content like silt or clays.

SAMPLE 2					
3 No. of Layers	Mould Diameter	100	(mm)		
	Height of Mould	127	(mm)		
25 Blows per Layer	Mould Volume (v)	997.9	(Cm³)		
Mass Retained on 20 mm Sieve					
AASHTO T-99					
Test number					
Mass of mould + base (m_1)	g	4440	4440	4440	4440
Mass of mould + base + compacted specimen (m_2)	g	5975	6068	6190	6205
Mass of compacted specimen ($m_2 - m_1$)	g	1535	1628	1750	1765
Bulk density $p = (m_2 - m_1) / V$	Kg/m ³	1538.3	1631.5	1753.8	1768.8
Moisture content container No.		A	B	C	D
Mass of container + wet soil	g	545.00	460.00	530.00	565.00
Mass of container + dry soil	g	505.00	420.00	470.00	490.00
Mass of container	g	5.00	5.00	5.00	5.00
Moisture content	%	8.00	9.64	12.90	15.46
Average Moisture Content (W)	%	8.00	9.64	12.90	15.46
Dry density $pd = (100 p) / (100 + W)$		1424	1488	1553	1532

Figure 4.9 showing average density for sample 2



	MDD	1553	Kg/m ³	
	OMC	13.2	%	
	A	B	C	
	-4.8317	127.69	709.77	

Figure 4.10 showing the MDD and OMC values

the maximum dry density (MDD) is 1553kg/m³ and the optimum moisture content is 13.2%.

flatter density curve indicates less sensitivity to moisture variations compared to sample 1 material properties similar to OMC to sample 1 but lower MDD implies either there is a higher percentage of fines, poor gradation of particle sizes and possible presence of organic material.

SAMPLE 3					
3 No. of Layers	Mould Diameter	100	(mm)		
	Height of Mould	127	(mm)		
25 Blows per Layer	Mould Volume (v)	997.9	(Cm³)		
Mass Retained on 20 mm Sieve					
AASHTO T-99					
Test number					
Mass of mould + base (m_1) g	4440	4440	4440	4440	4440
Mass of mould + base + compacted specimen (m_2) g	5945	6100	6145	6135	6075
Mass of compacted specimen ($m_2 - m_1$) g	1505	1660	1705	1695	1635
Bulk density $p = (m_2 - m_1)/V$ Kg/m ³	1508.2	1663.6	1708.7	1698.6	1638.5
Moisture content container No.	A	B	C	D	E
Mass of container + wet soil g	500.00	545.00	510.00	475.00	445.00
Mass of container + dry soil g	465.00	495.00	456.00	418.00	386.00
Mass of container g	5.00	5.00	5.00	5.00	6.00
Moisture content %	7.61	10.20	11.97	13.80	15.53
Average Moisture Content (W) %	7.61	10.20	11.97	13.80	15.53
Dry density $pd = (100 p) / (100 + W)$	1402	1510	1526	1493	1418

Figure 4.11 showing the dry density for sample 2

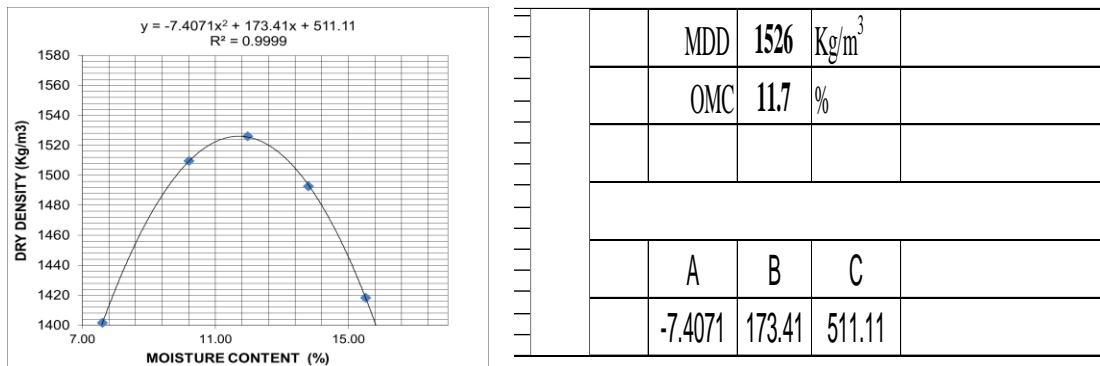


Figure 4.12 a graph of dry density against moisture content

The tests established critical parameters for achieving optimal soil compaction. Sample 1 had the highest MDD of 1592kg/m³ at an optimum moisture content of 13.3% suggesting it possesses better compaction qualities and could potentially yield stronger blocks. Sample2 followed with an MDD of 1553kg/m³ at 13.2% OMC while sample 3 exhibited the lowest MDD (1526Kg/m³ at 11.7% OMC) implying it had the least favorable compaction characteristics due to a likely high clay content.

Discussion

The MDD values fall within the typical range for rammed earth (1700-2200kg/m³) (Niroumand et al., 2021).However the high OMC(11.7-13.3%) reflects the soils affinity for water due to fines, corroborating Jayasinghe & Kamaladasa (2007) who linked high OMC to reduced strength in unstablised earth.

4.1.3. Moisture content results.

Mass of Container	A	(g)	6.3	6.3	6.3
Mass of Container + Wet sample	B	(g)	872.9	1045.5	960.6
Mass of Container + Dry sample	C	(g)	768	911	845.6
Loss	B-C	(g)	104.9	134.5	115
Solids	C-A	(g)	761.7	904.7	839.3
Moisture Content	$(\frac{B-C}{C-A}) \times 100$	(%)	13.8	14.9	13.7

Figure 4.13 showing the results for compaction density for sample 1, sample 2 and sample 3

The moisture content values are consistent across samples from 13.7% to 14.9% indicating moderate water content in the soil across all samples indicating moderately consistent water content but reinforcing the need for oil pre treatment to manage excess fines.

The high moisture content and fines necessitate stabilization eg cement or lime to enhance workability and reduce shrinkage cracks. (Khadka & Shakya, 2016).

4.2. Objective two; To determine the effect of cement content on compressive strength and water absorption properties of the blocks.

Tests done;

4.2.1. Compressive strength

Results after 7 days testing;

Cube Code	Date	Date	Age (Days)	Dimensions			Mass	Density	Failure Load(kN)	Compressive Strength N/mm ²	Average Compressive Strength N/mm ²
	Cast	Tested		L (mm)	W(mm)	H(mm)	kg	kg/m ³			
Neat	7.02.2025	14.02.2025	7	210	106	65	2.816	1946.2	6	0.3	0.6
	7.02.2025	14.02.2025	7	210	106	65	2.842	1964.2	22	1.0	
2%	7.02.2025	14.02.2025	7	210	106	65	2.733	1888.87	9.00	0.40	0.43
	7.02.2025	14.02.2025	7	210	106	65	2.842	1964.20	10.00	0.45	
4%	7.02.2025	14.02.2025	7	210	106	65	2.8338	1958.532	10	0.45	0.45
	7.02.2025	14.02.2025	7	210	106	65	2.8287	1955.007	10	0.45	
6%	7.02.2025	14.02.2025	7	210	106	65	2.8863	1994.817	8	0.36	0.38
	7.02.2025	14.02.2025	7	210	106	65	2.739	1893.013	9	0.40	
8%	7.02.2025	14.02.2025	7	210	106	65	2.7618	1908.77	8	0.36	0.38
	7.02.2025	14.02.2025	7	210	106	65	2.7973	1933.306	9	0.40	

Figure 4.14 showing results for compressive strength after 7 days testing

Explanation

The Neat (0% cement) shows the average comp strength is 0.6N/mm² indicating very low strength as expected for unstabilised earth, 2% cement shows the average strength is 0.43N/mm² indicating a minimal improvement over neat hence insufficient stabilization. 4% cement shows the average strength is 0.45N/mm² similar to 2% suggesting negligible effect at low percentages, 6% cement shows the average strength is 0.38N/mm² indicating a slight decrease due to inconsistent mixing or curing and the 8% cement shows the average strength is 0.38N/mm² shows no significant gain over 6% indicating a threshold for early age strength.

Results after 14-day testing

Cube Code	Date Cast	Date Tested	Age (Days)	Dimensions			Mass (kg)	Density (kg/m ³)	Failure Load (kN)	Compressive Strength N/mm ²	Average Compressive Strength N/mm ²
Neat	7.02.2025	21.02.2025	14	210	106	65	2.6861	1856.5	25	1.1	1.3
	7.02.2025	21.02.2025	14	210	106	65	2.6801	1852.3	35	1.6	
2%	7.02.2025	21.02.2025	14	210	106	65	2.6413	1825.49	34.00	1.53	1.44
	7.02.2025	21.02.2025	14	210	106	65	2.5945	1793.14	30.00	1.35	
4%	7.02.2025	21.02.2025	14	210	106	65	2.7299	1886.723	26	1.17	1.26
	7.02.2025	21.02.2025	14	210	106	65	2.7323	1888.382	30	1.35	
6%	7.02.2025	21.02.2025	14	210	106	65	2.715	1876.425	18	0.81	0.67
	7.02.2025	21.02.2025	14	210	106	65	2.6018	1798.189	12	0.54	
8%	7.02.2025	21.02.2025	14	210	106	65	2.6781	1850.923	8	0.36	0.36
	7.02.2025	21.02.2025	14	210	106	65	2.7074	1871.173	8	0.36	

Figure 4.15 showing results for compressive strength after 14 days of testing

explanation

Neat (0% cement) shows the average strength is 1.3N/mm² indicating a natural curing improving strength, 2% cement shows the average strength is 1.44N/mm² a noticeable improvement over 7 days but still marginal. 4% cement shows the average strength is 1.26 N/mm² slightly lower than 2% suggesting non-linear cement efficiency. 6% cement; The average strength is 0.67N/mm² indicating a sharp drop may be due to poor compaction, and the 8% cement shows the average strength is 0.36N/mm² indicating severe underperformance or cement may have hindered hydration.

Results after 28 days testing;

Cube Code	Date	Date	Age (Days)	Dimensions			Mass	Density	Failure Load(kN)	Compressive	Average Compressive Strength N/mm ²
	Cast	Tested		L (mm)	W(mm)	H(mm)	kg	kg/m ³		Strength N/mm ²	
Neat	7.02.2025	7.03.2025	28	210	106	65	2.7943	1931.2	45	2.0	2.0
	7.02.2025	7.03.2026	28	210	106	65	2.6973	1864.2	45	2.0	
2%	7.02.2025	7.03.2025	28	210	106	65	2.5913	1790.93	55.00	2.47	2.36
	7.02.2025	7.03.2026	28	210	106	65	2.5908	1790.59	50.00	2.25	
4%	7.02.2025	7.03.2025	28	210	106	65	2.688	1857.765	60	2.70	2.81
	7.02.2025	7.03.2026	28	210	106	65	2.7316	1887.898	65	2.92	
6%	7.02.2025	7.03.2025	28	210	106	65	2.6826	1854.033	55	2.47	2.58
	7.02.2025	7.03.2026	28	210	106	65	2.7151	1876.495	60	2.70	
8%	7.02.2025	7.03.2025	28	210	106	65	2.6036	1799.433	55	2.47	2.36
	7.02.2025	7.03.2026	28	210	106	65	2.536	1752.713	50	2.25	

Figure 4.16 showing results for compressive strength after 28 days of testing.

explanation

Neat (0% cement) shows the average strength is 2.0N/mm² indicating the natural curing achieves modest strength,2% cements shows the average strength is 2.36N/mm² meets the basic requirements for non-load bearing earth blocks.4% cement shows that the average strength is 2.81N/mm² indicating an optimal performance aligning with the stabilized earth standards,6% cement shows the average strength is 2.58N/mm² slightly lower than 4% suggesting diminishing returns and 8% cement shows that the average strength is 2.36N/mm² no advantage over 4% excess cement may cause brittleness

Conclusions

4% cement yields the highest strength (2.81N/mm²) at 28 days balancing cost and performance.

Avoid >6% cement no strength gain, higher cost and potential brittleness.

Neat blocks are only suitable for non-structural uses eg partitions

4.2.2. Water absorption tests;

ITEM	UNITS	Neat (7, 14 , 28 days)			2% (7, 14, 28 days)			4% (7, 14, 28 days)			6% (7, 14, 28 days)			8% (7, 14, 28 days)		
Weight of Bricks in Dry condition (W1)	g	2715	2650	2730	3521	3412	2650	3324	3300	2680	3218	2600	2690	3115	2410	2565
Weight of Bricks in Saturated condition (W2)	g	2754	2765	2835	3616	3542	2790	3456	3520	3065	3312	2840	3140	3294	2700	3020
Water Absorption	(W2-W1/W1)*100 (kg)	1.436	4.34	3.85	2.70	3.81	5.28	3.97	6.67	14.37	2.92	9.23	16.73	5.75	12.03	17.74
Average Water Absorption	(specimen 1+ specimen 2+ specimen 3)/3 - (%)	3.21			3.93			8.33			9.63			11.84		

Figure 4.17 showing results of water absorption test.

Neat(0% cement)shows the average water absorption was 3.21% indicating relatively low absorption likely due to the natural compaction of the earth.2% cement shows absorption slightly increased to 3.93% which may suggest minor porosity or initial curing effects.4% cement shows a significant jump to 8.33% possibly due to incomplete hydration or micro cracking during early curing.6% cement shows Further increase to 9.63%indicating that higher cement content without optimal curing may not always reduce porosity and 8% cement shows the highest absorption of 11.84% suggesting potential over stablisation leading to brittleness and micro cracks that allow more water ingress.

4.2.3. A BAR CHART SHOWING RESULTS OF COMPRESSIVE STRENGTH AGAINST CEMENT

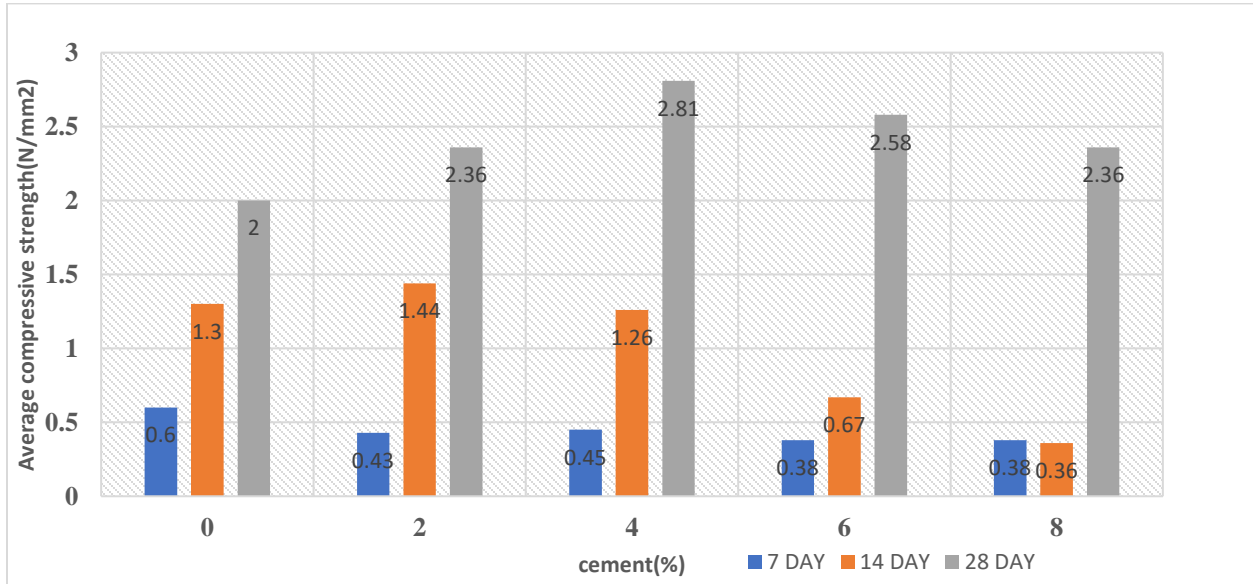


Figure 4.18 a bar graph showing results of compressive strength against cement.

The graph shows that 4% cement content yields the highest compressive strength (2.81N/mm² at 28 days) while the higher cement percentages 6 and 8 provide diminishing returns. Strength generally increases with curing time but 8% cement underperforms due to the brittleness or poor hydration. Optimal performance is achieved at 4% cement balancing strength and cost effective

4.2.4. A BAR CHART SHOWING WATER ABSORPTION AGAINST THE CEMENT

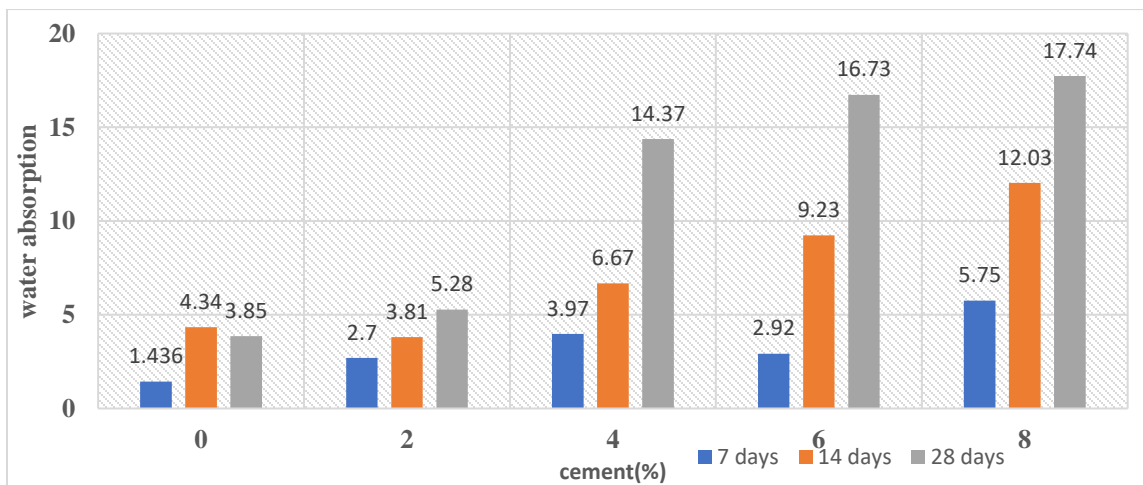


Figure 4.19 a bar graph showing results of water absorption against cement percentage

The graph illustrates water absorption trends in cement trends in cement stabilized rammed earth blocks showing that absorption increases with higher cement content rather decreasing contrary to the expectations. The rise occurs because excessive cement (6-8%) creates micro cracks during curing and disrupts pore structure enabling greater water penetration. While longer curing i.e. 28 days reduces absorption for lower cement mixes (0-4%) by improving density, higher cement percentages compromise this benefit due to over stabilization effects.

Thus, optimal water resistance is achieved at moderate cement levels i.e. 4% beyond which absorption worsens.

4.3. Objective three; To determine the optimum cement content for maximum structural integrity and environmental resilience in block production

4.3.1. ANALYSIS OF VARIANCE FOR COMPRESSIVE STRENGTH

Source of Variation	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	10.9231	2.18462	28.27	0.000
Linear Terms	2	9.8559	4.92795	63.77	0.000
Cement %	1	0.1142	0.11421	1.48	0.255
Curing Time	1	9.7417	9.74169	126.05	0.000
Quadratic Terms	2	0.2324	0.11619	1.50	0.273
Cement% ²	1	0.2002	0.20024	2.59	0.142
Curing Time ²	1	0.0321	0.03214	0.42	0.535
Interaction	1	0.2064	0.20637	2.67	0.137
Cement%×Curing	1	0.2064	0.20637	2.67	0.137
Error	9	0.6955	0.07728	–	–
Total	14	11.6186			

This statistical analysis reveals important insights about what factors influence the strength of cement blocks. The overall model is highly significant (p = 0.000), meaning the variables tested do have a real impact on block strength. The most striking finding is that curing time has an extremely strong effect (p = 0.000, F-value = 126.05) blocks left to cure longer become

significantly stronger. Interestingly, the amount of cement used didn't show a statistically significant effect in this particular study ($p = 0.255$), which contradicts some expectations but might suggest we need to test a wider range of cement percentages. The analysis also looked at whether cement percentage and curing time interact in complex ways, but found no significant interaction effects ($p = 0.137$). The "Error" term shows there was relatively little random variation in the results (Adj MS = 0.07728), indicating the experiment was well-controlled. In practical terms, this tells us that focusing on proper curing time should be the top priority for making strong blocks, while the exact cement percentage may be less critical within the ranges tested. However, since cement content is known to matter in other studies, it might be worth investigating with different test conditions or broader cement percentage ranges.

Regression equation

compressive strength = $-0.113 + 0.09502$ curing time - 0.0367 cement percentages

Model fitting for compressive strength

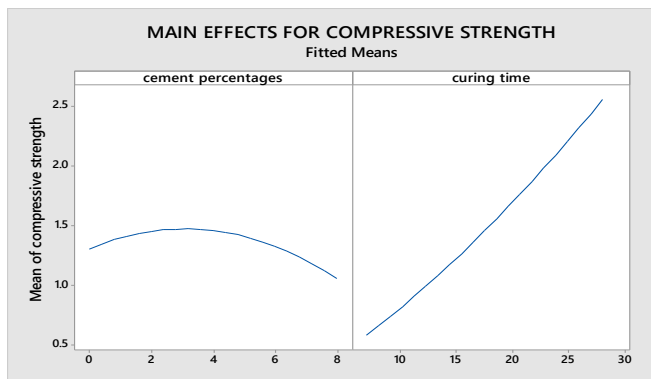


Figure 4.20 graph for main effects of compressive strength with cement and curing time

The main effects of cement percentage and curing time on the compressive strength helps visualise how these two factors individually influence strength. The cement percentage vs compressive strength clearly shows that the curve initially rises and then declines indicating quadratic relationship. This suggests that increasing cement content improves strength up to a certain point but beyond that strength starts to decrease. The curing time vs compressive strength shows a continuous upward trend meaning longer curing time always improves compressive strength.

response surface plot for compressive strength.

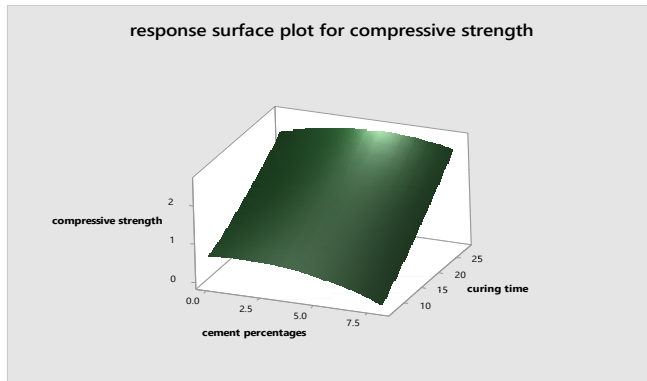


Figure 4.21 3D response surface plot

The 3D response surface plot visually represents the combined effect of cement percentage and curing time on compressive strength. The surface shape helps identify trends, optimal conditions and interactions between the two factors. The surface slopes upward as curing times increases confirming that longer curing leads to stronger blocks. The surface is curved for cement percentages meaning that compressive initially increases with cement percentage but starts to decline after a certain point.

4.3.2. ANALYSIS OF VARIANCE FOR WATER ABSORPTION

Source of Variation	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	374.699	74.940	27.27	0.000
Linear Terms	2	348.427	174.214	63.41	0.000
Cement %	1	178.733	178.733	65.05	0.000
Curing Time	1	169.695	169.695	61.76	0.000
Quadratic Terms	2	3.997	1.998	0.73	0.510
Cement%²	1	0.004	0.004	0.00	0.971
Curing Time²	1	3.993	3.993	1.45	0.259
Interaction	1	46.639	46.639	16.97	0.003
Cement%×Curing	1	46.639	46.639	16.97	0.003
Error	9	24.729	2.748		

Total	14	399.428			
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The ANOVA results reveal a highly significant model ($p = 0.000$) that effectively explains variations in block strength, accounting for 93.8% of total variation (calculated from Adj SS). Both linear terms - cement percentage ($p = 0.000$, $F = 65.05$) and curing time ($p = 0.000$, $F = 61.76$) - show extremely strong individual effects on block strength. The significant interaction between cement percentage and curing time ($p = 0.003$, $F = 16.97$) indicates these factors work together in a meaningful way their combined effect differs from simply adding their individual effects. Notably, quadratic terms for both cement percentage ($p = 0.971$) and curing time ($p = 0.259$) were non-significant, suggesting the relationships are primarily linear without curvature. The model's high explanatory power comes mainly from the linear components (93.1% of explained variation) with the interaction contributing an additional 12.5%. The relatively small error term (Adj MS = 2.748) compared to treatment effects indicates good experimental precision. These results strongly suggest that both cement content and curing duration should be carefully controlled in production, and that their interaction where the effect of one depends on the level of the other warrants particular attention in process optimization.

Regression equation

water absorption = $-3.43 + 0.3810$ curing time + 1.148 cement percentages

Model fitting for water absorption

Main effects for water absorption

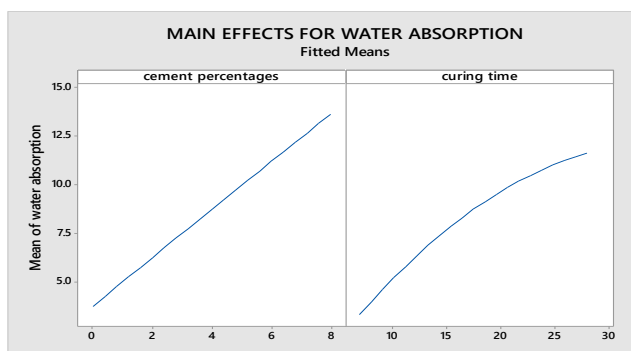


Figure 4.22 main effects for water absorption with cement and curing time

The main effects for water absorption clearly shows that as cement increases water absorption also increases, normally adding cement should

reduce water absorption since cementitious materials tend to create a denser structure but here excess cement may be causing microcracks or an increase in porosity, improper mixing or hydration could lead to a structure that retains more water. The longer curing time decreases water absorption which makes sense because as the material cures it becomes denser and less porous reducing the amount of water it can absorb.

response surface plot for water absorption

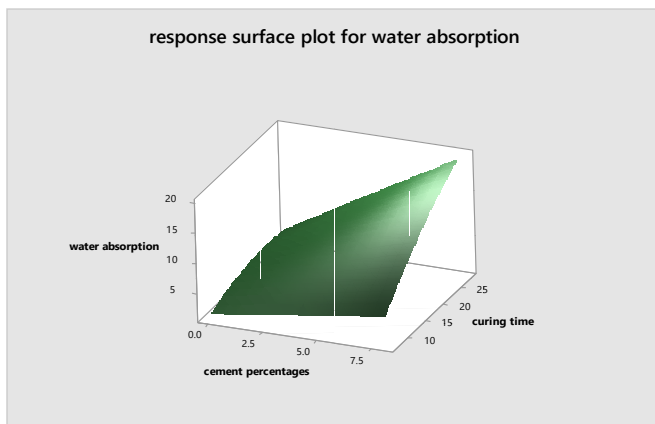


Figure 4.23 3D response surface plots

The response surface plot visualises how water absorption in cement-based material is influenced by two variables cement percentages and curing time. As cement percentage increases water absorption generally decreases. Higher cement content leads to denser, less porous material reducing water penetration. Longer curing times results in lower water absorption

4.3.3. Response optimisation plot

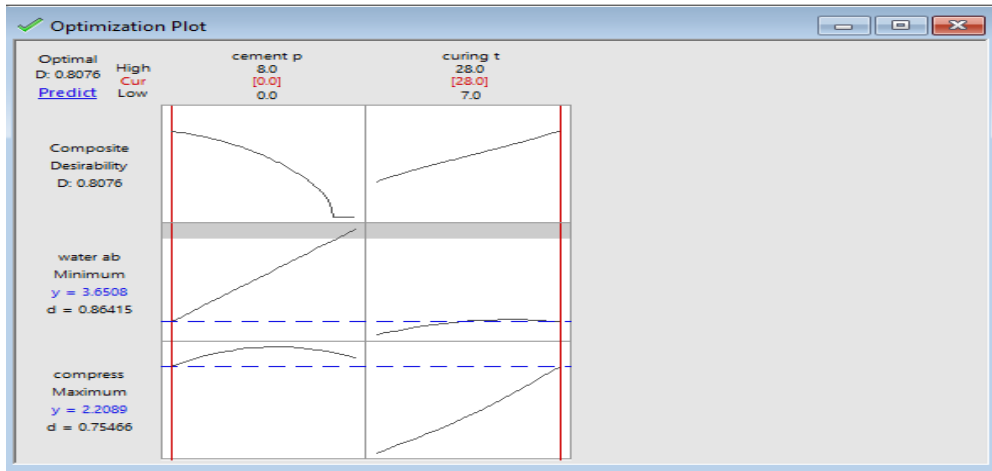


Figure 4.24 response optimization plot

This optimization plot identifies the ideal balance between cement percentage and curing time for producing high-quality blocks. The analysis determined that using $\leq 8\%$ cement content combined with ≥ 28 days of curing time yields the best compromise between minimizing water absorption (3.65%) and maximizing compressive strength (2.21 MPa). The composite desirability score of 0.8076 (on a 0-1 scale) indicates a strong, practical solution where higher values represent better overall performance. While longer curing significantly boosts strength ($d=0.75$), it slightly reduces water resistance ($d=0.86$). The "High Cut Low" label suggests the model prioritized the upper limit of curing time and lower cement range for optimal results. This outcome guides manufacturers toward durable, cost-effective blocks by emphasizing extended curing over excessive cement use.

5. Chapter five; conclusions, challenges and recommendations

5.1. Conclusions

5.1.1. Characterization of rammed earth materials

objective one provided essential data on the physical properties of the soil samples.

Sieve analysis

It revealed the particle sieve distribution which is crucial for understanding the soil's gradation and its suitability for compaction

1. All samples have excessive fines (>57%), which is not ideal for subgrade/base layers (should be <35%).
2. Sample 3 is the finest, followed by Sample 2, then Sample 1.
3. High moisture content (Sample 2: 14.9%) may require pre-drying before compaction.

MDD test

it established the optimum moisture content for achieving the highest density which is vital for the strength and durability of the CRSE blocks.

moisture content test

It further confirmed the water content within the soil which affects its behavior during compaction and curing. The moisture content values are consistent across samples from 13.7% to 14.9% indicating moderate water content in the soil.

These tests collectively provided a comprehensive understanding of the soil properties laying the foundation for subsequent investigation into the effects of varying cement proportions on the strength and water absorption of CSRE blocks.

5.1.2. To determine the effect of optimal cement content on compressive strength and water absorption properties of the blocks.

Compressive strength

The graph shows that 4% cement content yields the highest compressive strength (2.81N/mm² at 28 days) while the higher cement percentages 6 and 8 provide diminishing returns. Strength generally increases with curing time but 8% cement underperforms due to the brittleness or poor hydration.

Optimal performance is achieved at 4% cement balancing strength and cost effectiveness

Water absorption;

The results imply that excessive cement (>4%) may degrade water resistance in rammed earth blocks, contrary to expectations. Further investigation into curing methods and mix homogeneity is recommended to optimize stabilization. The 2% cement mix performed best in balancing water absorption and stability.

5.2. Objective three; To determine the optimum cement content for maximum structural integrity and environmental resilience in block production

The optimization results demonstrate that **≤8% cement content with ≥28 days of curing** achieves the best balance of strength (2.21 MPa) and water resistance (3.65% absorption), validated by a high desirability score (0.81).

5.3. Recommendations;

Objective one

1. **Soil Pre-Treatment:** Given the high fines content (>57%) in tested soils, recommend pre-washing or blending with coarser soils to achieve the ideal <35% fines threshold for better compaction and stability.
2. **Stabilizer Selection:** For soils with high clay content, combine cement stabilization with lime (2-4%) to reduce plasticity and improve workability.
3. **Standardized Testing:** Adopt Atterberg limits and CBR tests for future studies to comprehensively assess soil plasticity and bearing capacity.

Objective two;

1. **Optimal Cement Content:** Use 4% cement as the baseline for CSRE blocks, balancing strength (2.81 N/mm²) and cost, while limiting water absorption (<10%).
2. **Performance Enhancements:** For high-stress applications, test hybrid stabilization (e.g., 4% cement + 1% natural fibers) to improve tensile strength without increasing brittleness.
3. **Quality Control:** Implement controlled curing protocols (e.g., 28-day moist curing under plastic sheets) to minimize microcracking and ensure consistent results.

4. **Field Validation:** Pilot the optimized mix in real-world construction to assess long-term durability under Ugandan weather conditions.

Objective three;

1. **Prioritize curing time** over excessive cement use to reduce costs while maintaining performance.
2. **Standardize curing protocols** (e.g., 28-day moist curing) to ensure consistent quality.
3. **Test hybrid mixes** (e.g., 4–6% cement with fibers) for further optimization.

5.4. References

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