AN INVESTIGATIVE STUDY OF RAMMED EARTH AS A SUSTAINABLE AND COST-CONSCIOUS MATERIAL FOR CONSTRUCTION

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MAT. NUMBER: ENV2103375

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A PROJECT RESEARCH WORK SUBMITTED TO THE DEPARTMENT OF ARCHITECTURE, FACULTY OF ENVIRONMENTAL SCIENCES, UNIVERSITY OF BENIN, BENIN CITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF BACHELOR OF SCIENCE (B.Sc.) DEGREE IN ARCHITECTURE

JANUARY, 2026.

DECLARATION

I hereby declare that this project titled "AN INVESTIGATIVE STUDY OF RAMMED EARTH AS A SUSTAINABLE AND COST-CONSCIOUS MATERIAL FOR CONSTRUCTION" has been carried out by me in the Department of Architecture, Faculty of Environmental Sciences, University of Benin, Edo State, Nigeria. The information derived from literature has been duly acknowledged in the text and a list of references provided. No part of this text was previously presented for another degree in this university or in any other institution.

All materials consulted in the course of this research are duly acknowledged in a list of references provided.

______________________ __________________

Oyiborode Christabel Akparobokoghene Date

(Student sign)

CERTIFICATION

This is to certify that this project work was carried out by **OYIBORODE CHRISTABEL AKPAROBOKOGHENE** with Matriculation Number **ENV2103375** of Department of Architecture, Faculty of Environmental Sciences, University of Benin, Edo State, Nigeria under the supervision and guidance of Arc. Kunle Oyewole in partial fulfilment of the requirement for the award of Bachelor of Science Degree in Architecture.

_______________________   _______________

Arc. Kunle Oyewole   Date

(Project Supervisor)

_______________________   _______________

Arc. Dr. Okafor U. Iwuchukwu   Date

(Head of Department, Architecture)

DEDICATION

This research is dedicated to myself for being strong and resilient through it all. It really wasn’t easy.

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ABSTRACT

This study investigates rammed earth as a sustainable and cost-effective alternative to conventional construction materials in Edo State, Nigeria. With rising cement costs, high carbon emissions from concrete production, and an increasing housing deficit, there is urgent need for affordable, eco-friendly building solutions. Rammed earth—a technique involving compaction of soil, sand, clay, and stabilizers into formwork—offers low embodied energy, excellent thermal mass, and utilization of locally available materials. A questionnaire-based research design was employed, targeting architects, quantity surveyors, civil engineers, and students within Benin City. Out of 75 questionnaires distributed, 60 responses were received, yielding an 80% response rate. Findings revealed that 60.75% of respondents were unfamiliar with rammed earth technology, indicating a significant awareness gap. However, 64.1% agreed that rammed earth contributes to sustainable building practices, with 69.25% recognizing its use of local materials and 52.8% acknowledging its energy efficiency. Key challenges identified included lack of skilled labor, limited public awareness, inadequate regulatory frameworks, and concerns about climate suitability. Despite these barriers, 46.1% of respondents expressed optimism about its future adoption in mainstream construction. The study concludes that rammed earth is a viable, durable, and sustainable material for residential construction in Edo State. Recommendations include increasing public and professional awareness, integrating rammed earth construction into academic curricula, developing standardized building codes, and encouraging its adoption through policy support and demonstration projects.

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CHAPTER ONE

1.0. INTRODUCTION

The rising cost of construction materials, coupled with growing environmental concerns, has intensified the search for sustainable and affordable building alternatives in Nigeria. In Edo State, where urbanization is steadily increasing, conventional materials such as concrete and sandcrete dominate the construction industry despite their high production costs, energy-intensive manufacturing processes, and significant carbon footprint. Rammed earth, an ancient construction technique that involves compacting a mixture of soil, water, and stabilizers into a formwork, has gained renewed interest globally as a viable, eco-friendly, and cost-effective substitute for modern masonry materials (Thompson, Augarde, & Osorio, 2025; Amede *et al.*, 2024). This method offers benefits such as low embodied energy, thermal efficiency, and the potential use of locally sourced materials, which could significantly reduce dependency on expensive imported cement-based products (Onyegiri *et al.*, 2024; Serrano *et al*., 2017).

Recent studies and pilot projects have demonstrated that, when properly engineered and stabilized, rammed earth structures can match or even exceed the performance standards of concrete and sandcrete in certain applications. Randeep, Srivastava, and Soamidas (2025) demonstrated through an experimental investigation that the incorporation of 10% Limestone Calcined Clay Cement (LC^3) as a stabilizer, combined with pine fiber reinforcement, significantly enhanced the mechanical performance of rammed earth blocks (REBs). Their findings revealed a compressive strength of 4.17 MPa and a flexural strength of 1.05 MPa, values that satisfy the IS and ARSO standards for low-rise or load-bearing masonry applications. This study provides empirical validation for the potential of engineered and fiber-reinforced rammed earth as a sustainable alternative to conventional masonry materials, offering both durability and structural adequacy (Randeep, Srivastava, & Soamidas, 2025).

In another research, Anysz, Rosicki, & Narloch, (2024) experimentally demonstrated that cement-stabilized rammed earth (CSRE) mixtures can achieve high structural performance when optimized for composition and curing duration. After 120 days of curing, certain mixes containing 5% cement and 20% clay reached compressive strengths of approximately 7.78 MPa. The researchers also observed negligible differences between laboratory cube specimens and in-situ core samples for several formulations, indicating that well-prepared rammed earth can maintain comparable mechanical integrity under real construction conditions. These findings reinforce the structural viability of CSRE as a sustainable alternative to conventional masonry materials (Anysz *et al.,* 2024).

Ma, J., Zhang, H., Shobeiri, V. *et al.* (2025) also conducted an experimental investigation demonstrating that the mechanical performance of rammed earth can be significantly enhanced through confinement with Carbon Fiber Reinforced Polymer (CFRP). Their findings revealed that CFRP-confined rammed earth specimens achieved remarkably high compressive strengths of 22.36 MPa, 64.38 MPa, and up to approximately 75.68 MPa, depending on the thickness of the applied confinement. These values far exceed the typical compressive strength of conventional concrete masonry units, illustrating that, with proper reinforcement and structural engineering, rammed earth can exhibit superior load-bearing capacity and durability under certain conditions (Ma *et al.*, 2025).

Despite these advantages, its adoption in Edo State remains limited due to factors such as lack of awareness, insufficient technical knowledge, and absence of standardized construction guidelines. This study seeks to investigate the viability of rammed earth as an alternative construction material in the state, examining its structural performance, economic benefits, and environmental impact in comparison to conventional materials. The findings aim to provide practical insights that could inform sustainable building practices, promote resource efficiency, and support affordable housing initiatives in the region.

1.1. BACKGROUND OF STUDY

Construction remains a critical driver of economic growth and infrastructure development in Nigeria, yet the sector faces persistent challenges related to cost, material availability, and environmental sustainability (Akanbi, 2024). In Edo State, concrete and sandcrete are the dominant materials for structural and non-structural applications due to their proven durability and wide acceptance within the industry. However, these materials require significant quantities of cement, which is energy-intensive to produce, contributes heavily to greenhouse gas emissions, and is subject to fluctuating market prices (Scott, 2025; Ekanem, 2024). The high cost of cement-based construction often makes housing unaffordable for low- and middle-income earners, thereby widening the housing deficit in the state.

Rammed earth construction, which involves compacting layers of moistened subsoil (often with stabilizers such as cement or lime) into formwork to create solid walls, offers a potentially sustainable alternative (Thompson, Augarde, & Osorio, 2025; Amede *et al.*, 2024). Historically, rammed earth has been used in various parts of the world for centuries, with notable examples of its durability found in both rural and urban contexts. Some examples are: The Watchtower Houses in Chongqing, China, Aït Benhaddou in Morocco which also serves as a UNESCO Heritage site and The Casa do Sítio Tatuapé, São Paulo, Brazil built between 1668 & 1698 and still stands to this day. (Shu & He, 2021; Wikipedia, 2025; Ramalho, 2016). In recent decades, advancements in soil testing, stabilization techniques, and moisture control have improved its structural integrity and resistance to weathering, making it a more viable option for modern construction. In the Nigerian context, the abundant availability of suitable soils presents a clear advantage for adopting rammed earth as a local building solution.

Globally, sustainable construction is gaining momentum as nations work toward reducing carbon emissions in line with climate change mitigation goals. In this regard, rammed earth aligns with the principles of low embodied energy, use of renewable resources, and minimal processing requirements (Onyegiri *et al.*, 2024; Serrano *et al.*, 2017). In Edo State, where both rural and peri-urban areas are expanding, adopting rammed earth could contribute to lowering construction costs, improving thermal comfort in buildings, and reducing environmental impact. However, despite these potential benefits, there is a lack of widespread implementation and standardized building codes for rammed earth in the region. This gap underscores the need for a comprehensive study that assesses its feasibility in comparison to established materials like concrete and sandcrete, with consideration of local soil types, climatic conditions, and construction practices.

1.2. RESEARCH GAP

While the use of concrete and sandcrete blocks has long been established in the Nigerian construction industry, these materials present significant economic and environmental drawbacks, including high production costs, dependence on imported cement, and considerable carbon emissions during manufacture. In Edo State, these issues are compounded by rising cement prices and a growing housing deficit, which make affordable construction increasingly difficult to achieve. Alternative building materials, such as rammed earth, have been explored in other parts of the world for their low environmental footprint and cost efficiency. However, their application within the local context of Edo State remains minimal and under-researched.

Existing studies on rammed earth construction in Nigeria tend to focus on general material properties, historical use, or small-scale experimental projects without thoroughly comparing its performance to conventional materials under real-world construction conditions. Most available literature lacks in-depth assessment of locally sourced soils in Edo State, particularly in relation to their suitability for rammed earth stabilization, long-term durability, and compliance with modern structural safety standards. Furthermore, limited research has examined the thermal performance, maintenance requirements, and life-cycle cost advantages of rammed earth in this specific region.

Another critical gap lies in the absence of comprehensive policy or building code provisions that recognize rammed earth as a standardized construction material in Edo State. Without such regulatory backing, even proven technical viability may not translate into practical adoption by builders, architects, or policymakers. There is also a knowledge gap in public and professional awareness—many construction stakeholders in the state are unfamiliar with modern rammed earth techniques, perceiving them as outdated or unsuitable for urban projects.

This study aims to address these gaps by providing a comparative analysis of rammed earth, concrete, and sandcrete within the context of Edo State's environmental conditions, material availability, and socio-economic realities. It will investigate the technical feasibility, cost implications, and environmental advantages of rammed earth while identifying strategies to promote its acceptance and integration into mainstream construction practices.

1.3. RESEARCH PROBLEM

Despite the increasing global shift toward sustainable construction materials, the building industry in Edo State continues to rely heavily on concrete and sandcrete as primary construction materials. This dependence poses several challenges: the high cost of cement makes construction expensive, the production process contributes significantly to environmental degradation through carbon emissions, and the reliance on non-renewable raw materials threatens long-term resource availability. These factors exacerbate the housing affordability crisis and limit opportunities for environmentally responsible building practices in the state.

Rammed earth presents a potential alternative that could address these issues, yet its use in Edo State remains extremely limited. The lack of empirical studies evaluating its structural strength, durability, cost-effectiveness, and thermal efficiency in comparison to conventional materials within the local context leaves builders, policymakers, and the public uncertain about its viability. Furthermore, no standardized construction guidelines or regulatory frameworks exist to govern its application, creating additional barriers to adoption.

The real-time problems that arise from this situation can therefore be framed as follows:

1. Why has rammed earth not been widely adopted as a construction material in Edo State despite its potential economic and environmental benefits?

2. How does the structural performance and durability of rammed earth compare to concrete and sandcrete under local soil and climatic conditions in Edo State?

3. What are the cost implications of using rammed earth relative to conventional materials, particularly for low-cost housing projects?

4. To what extent does rammed earth improve environmental sustainability in construction within the state?

5. What policy, technical, or perceptual barriers hinder the adoption of rammed earth in the building industry of Edo State?

These unresolved issues highlight the need for a targeted study that will generate practical, evidence-based recommendations for integrating rammed earth into mainstream construction practices in the region.

1.4. RESEARCH QUESTIONS

To guide the direction and scope of this study, the following research questions have been formulated based on the identified problem areas and variables of interest:

1. What factors are responsible for the limited adoption of rammed earth as a construction material in Edo State?

2. How does the compressive strength, durability, and overall structural performance of rammed earth compare to concrete and sandcrete under the soil and climatic conditions of Edo State?

3. What are the cost differences between constructing with rammed earth and using conventional materials such as concrete and sandcrete, particularly in residential building projects?

4. How does rammed earth construction contribute to environmental sustainability in terms of energy use, carbon emissions, and material sourcing in Edo State?

5. What technical, regulatory, and societal measures are needed to encourage the acceptance and large-scale use of rammed earth in the state's construction industry?

These questions will form the foundation for data collection, analysis, and interpretation, ensuring that the study remains focused on evaluating both the technical and socio-economic viability of rammed earth in the context of Edo State.

1.5. RESEARCH OBJECTIVES

The primary objective of this study is to evaluate the viability of rammed earth as a sustainable and cost-effective substitute for concrete and sandcrete in the construction industry of Edo State, Nigeria. To achieve this, the study will pursue the following specific objectives:

1. To investigate the factors limiting the adoption of rammed earth construction in Edo State.

2. To compare the structural strength, durability, and overall performance of rammed earth with that of concrete and sandcrete under local environmental conditions.

3. To assess the cost implications of using rammed earth in comparison to conventional materials, particularly for low-income housing projects.

4. To evaluate the environmental impact of rammed earth construction in terms of energy consumption, carbon footprint, and use of local resources.

5. To propose policy, technical, and awareness strategies that can promote the acceptance and integration of rammed earth into mainstream construction practices in Edo State.

1.6. SIGNIFICANCE OF STUDY

This study is significant as it addresses the urgent need for affordable, sustainable, and locally adaptable building solutions in Edo State, Nigeria. By examining rammed earth as a viable substitute for concrete and sandcrete, the research has the potential to contribute to reducing construction costs, thereby making housing more accessible for low- and middle-income households. The use of locally sourced soil could minimize dependence on cement and other imported materials, fostering economic resilience and supporting local industries.

From an environmental perspective, the study aligns with global and national efforts to reduce carbon emissions and promote eco-friendly construction methods. Rammed earth's low embodied energy and potential for thermal efficiency make it a promising material for mitigating the environmental impact of building projects in the state. Additionally, the findings will provide valuable data for policymakers, architects, engineers, and builders, enabling evidence-based decision-making and encouraging the development of regulatory frameworks for alternative construction materials.

Ultimately, this research could serve as a reference point for similar studies in other regions of Nigeria, paving the way for wider adoption of sustainable construction practices nationwide. By bridging the gap between traditional building knowledge and modern engineering standards, it holds the potential to transform how construction is approached in resource-limited and environmentally conscious contexts.

1.7. DEFINITION OF TERMS

RAMMED EARTH

Rammed earth is a construction technique that involves compacting a mixture of natural soil, typically containing sand, silt, clay, gravel, and water—within temporary formwork to create solid, load-bearing walls (Petcu *et al.*, 2023). The compacted layers form a dense, durable mass with good thermal properties (Jiang *et al.,* 2023). When stabilizers such as cement or lime are added, the material is referred to as stabilized rammed earth (SRE), which improves strength, moisture resistance, and longevity (Ávila, Puertas, & Gallego, 2022).

COMPACTING (OR COMPACTION)

Compaction is the mechanical process of compressing soil particles to reduce air gaps and increase density (Schmitz *et al.*, 2024). In rammed earth construction, compaction is achieved by ramming layers of slightly moist soil inside formwork to produce a dense, solid wall (Vora *et al.*, 2014). Proper compaction enhances the wall's compressive strength, reduces permeability, and improves overall structural integrity (Narloch *et al.*, 2020).

COMPRESSIVE STRENGTH

Compressive strength refers to the ability of a material to resist deformation or failure under a compressive (pushing) load. In rammed earth, it measures how much pressure the wall can withstand before cracking or collapsing (Sahito *et al.*, 2025). Typical compressive strength values range from 2–4 MPa for unstabilized rammed earth and 5–8 MPa or higher for stabilized forms, depending on soil composition and compaction quality (Anysz, Rosicki, & Narloch, 2024; Amede *et al.*, 2024).

TENSILE STRENGTH

Tensile strength is the maximum amount of stress a material can withstand while being stretched or pulled before breaking. Rammed earth has low tensile strength because soil particles are held together mainly by friction and cohesion, not by tensile bonds (Sahito *et al.*, 2025; Araki *et al.*, 2016). For this reason, reinforcement materials—such as steel rods, bamboo, or geogrids—are sometimes incorporated to resist tension and prevent cracking (Thompson, Augarde, & Osorio, 2025).

STABILIZER

A stabilizer is an additive used to enhance the strength, water resistance, and durability of rammed earth (Thompson, Augarde, & Osorio, 2025). Common stabilizers include cement, lime, bitumen, fly ash, and natural polymers (Thompson, Augarde, & Osorio, 2025; Sesay *et al.*, 2025). These materials chemically react with soil particles to form stronger bonds, improving the structure's long-term stability and resistance to erosion (Thompson, Augarde, & Osorio, 2025).

THERMAL MASS

Thermal mass is the ability of a material to absorb, store, and gradually release heat energy (Tay *et al.*, 2022). Rammed earth walls possess high thermal mass, helping to regulate indoor temperatures by absorbing heat during the day and releasing it at night (Jiang *et al.,* 2023). This property contributes to energy efficiency and comfort in both hot and temperate climates.

SUSTAINABILITY

Sustainability in construction refers to using materials and methods that minimize environmental impact and resource depletion (Kiani Mavi *et al.*, 2021). Rammed earth is considered sustainable because it utilizes locally available soil, requires minimal processing, has low embodied energy, and produces little waste (Onyegiri *et al.*, 2024; Serrano *et al*., 2017). Its thermal performance also reduces dependence on artificial heating and cooling systems (Jiang *et al.,* 2023).

EMBODIED ENERGY

Embodied energy is the total amount of energy consumed throughout a material's lifecycle, including extraction, processing, transportation, and construction. Rammed earth has very low embodied energy compared to materials like concrete or fired bricks since it relies primarily on natural soil and mechanical compaction rather than energy-intensive manufacturing (Fernandes *et al.*, 2019).

FORMWORK

Formwork refers to the temporary molds or panels used to shape and support rammed earth walls during construction. It holds the soil mixture in place while it is being compacted, ensuring consistent wall thickness and smooth surfaces. Modern formwork is made from wood, metal, or composite panels and can be reused across multiple sections of a structure.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1. HISTORICAL BACKGROUND OF RAMMED EARTH CONSTRUCTION

2.1.1. ORIGIN AND TRADITIONAL USES

Rammed earth construction is one of the oldest known building techniques, with archaeological and historical evidence tracing its origins to several ancient civilizations across Asia, Africa, and Europe (Muguda-Viswanath, 2019; Global Times, 2025; Jaquin, 2012). The technique—known for using compacted natural soils to form strong structural walls—emerged independently in different regions due to the widespread availability of earth materials and the simplicity of the construction process (Jaquin, 2012). In China, rammed earth (referred to as *hangtu*) was extensively used as early as 5000 BCE during the Neolithic period, notably in defensive and residential structures (Steinhardt, 2022). One of the most prominent examples of early rammed earth application is found in the construction of the Great Wall of China, where compacted earth mixed with straw and other organic fibers served as the primary material in many sections before later restorations introduced brick and stone (Yang *et al.*, 2017).

In North Africa and the Middle East, particularly in regions like Morocco and Yemen, rammed earth (locally termed *pisé de terre* or *tabiya*) was a preferred material due to its excellent thermal performance in arid climates (Lechheb *et al.*, 2024). Settlements such as Aït Benhaddou, a UNESCO World Heritage Site in Morocco, and the Wadi Hadhramaut mudbrick and rammed earth towers of Yemen, demonstrate its use in both residential and defensive architecture (Wikipedia, 2025; Fahfouhi *et al.*, 2025; Baeissa, 2013). In Europe, especially in southern France and Spain, rammed earth gained prominence during the Roman and medieval periods. It was used in farmhouses, fortifications, and city walls because of its low cost, thermal regulation, and adaptability to local environmental conditions (Gil and Ignacio, 2013; Jaquin, 2012). These early applications reflect not only technical ingenuity but also environmental consciousness, as the material was readily available, recyclable, and provided excellent insulation in both hot and temperate climates.

Over centuries, traditional rammed earth construction evolved in response to changing architectural demands and advancements in material science. Early forms relied primarily on raw, unmodified soils compacted manually with simple tools. However, as structural and durability requirements increased, builders began experimenting with stabilization techniques, introducing natural additives such as lime, animal blood, or plant extracts to enhance cohesion and resistance to water erosion (Rocha *et al.*, 2024; Sesay *et al.*, 2025). The 20th century marked a pivotal transition with the incorporation of cement and lime stabilizers, leading to what is now termed stabilized rammed earth (SRE) (Liu *et al.*, 2022). These additives improved compressive strength, moisture resistance, and longevity, allowing rammed earth to compete with modern construction materials (Sahito *et al.*, 2025; Cruz *et al.*, 2024).

The evolution also included significant innovations in compaction methods. Manual tamping gave way to mechanical compactors and pneumatic rammers, ensuring higher density and uniformity within the walls (Gomaa *et al.*, 2023; Pei *et al.*, 2022). Technological advances in soil analysis, moisture control, and mix design further standardized the process, allowing engineers to predict and optimize structural performance (Suresh, 2023; Anysz & Narloch, 2019). The modern era of engineered rammed earth (ERE) integrates contemporary engineering principles, sustainability standards, and aesthetic design (Akbulut & Alibeyoglu, 2025). Reinforcement using steel or geogrid meshes, prefabricated formwork systems, and computer-aided design (CAD) tools have enabled architects to combine the traditional ecological appeal of rammed earth with modern precision and safety standards (Zhou, 2024; Adnan *et al.,* 2022).

2.1.2. EXAMPLES OF ANCIENT AND CONTEMPORARY STRUCTURES

Rammed earth's enduring relevance is evident in both its ancient legacies and modern reinterpretations. The Great Wall of China remains a defining example of the material's durability, with many sections still standing after millennia of exposure (Yang *et al.*, 2017).

In North Africa, Aït Benhaddou exemplifies the blend of cultural heritage and architectural resilience achieved through rammed earth (Fahfouhi *et al.*, 2025). Similarly, traditional earthen kasbahs in the Atlas Mountains and fortified villages in Spain and France highlight the regional adaptations of this building form (Gil and Ignacio, 2013; Jaquin, 2012).

In contemporary architecture, rammed earth has experienced a revival driven by the growing emphasis on sustainability and low-carbon construction. Notable modern examples include the Napa Valley House in California, which uses stabilized rammed earth for both structural and aesthetic purposes (Flint, 2025); the Great Wall House in Australia, designed by architect Luigi Rosselli (Rosselli, 2020); and the Earth House Project in the United Kingdom, which integrates rammed earth with renewable energy technologies.

Fig. 2.1. The Great wall of China

Fig. 2.2. Morocco's most famous ksar, The Ait Ben Haddou

Fig 2.3. The Great Wall House in Australia, designed by architect Luigi Rosselli (Rosselli, 2020)

Fig. 2.4. The rammed Napa Valley House in California

2.2. COMPOSITION AND PROPERTIES OF RAMMED EARTH

2.2.1. MATERIAL COMPOSITION

Rammed earth is primarily composed of natural soil, sand, silt, clay, gravel, water, and occasionally stabilizing agents such as lime, cement, or bitumen (Petcu *et al.*, 2023). The conventional method which relies solely on soil and water as its basic materials, where clay naturally serves as the binding component of the mixture gives what is referred to as unstabilized rammed earth (URE) (Ávila, Puertas, & Gallego, 2022). The introduction of stabilizers—such as cement, lime, fly ash, bitumen, and ground granulated blast-furnace slag (GGBS) leads to the production of Stabilized Rammed Earth (SRE) (Ávila, Puertas, & Gallego, 2022).

The quality and performance of rammed earth depend significantly on the proportions and characteristics of these components (Sahito *et al.,* 2025). Traditionally, the soil used in rammed earth construction was obtained locally, often from the site itself, which minimized transportation costs and environmental impact (Anysz & Narloch, 2019). The ideal mix comprises approximately 5–35% clay, 10–30% silt (acting as a binder) and 30–80% sand (acting as aggregates) (Petcu *et al.*, 2023). This balanced particle size distribution ensures adequate cohesion, compaction, and mechanical strength (Petcu *et al.*, 2023).

Each constituent performs a distinct role. Clay acts as a natural binder that holds the particles together once dried, while sand and gravel provide structural bulk, reducing shrinkage and cracking (Sabbà *et al.*, 2021; Koutous & Hilali, 2019). Water facilitates compaction and aids in achieving uniform density throughout the wall, though excessive water can weaken the mix (Bui *et al.*, 2011; Sabbà *et al.*, 2021). Stabilizers, such as lime or cement, chemically modify the soil structure to enhance cohesion, moisture resistance, and compressive strength (Sahito *et al.,* 2025). Lime reacts with clay minerals to form calcium silicate hydrates, improving durability and resistance to weathering (Mileto *et al.*, 2025). In modern construction, small percentages (typically 5–10%) of cement or lime are added to enhance long-term stability, especially in regions with high rainfall or variable humidity (Amede *et al.*, 2024).

2.2.2. PHYSICAL AND MECHANICAL PROPERTIES

The physical and mechanical behavior of rammed earth is governed by its composition, degree of compaction, and curing conditions (Sahito *et al.,* 2025). A well-compacted wall typically achieves a density range of 1,700–2,200 kg/m^3, depending on the soil type and stabilizer content (Petcu *et al.*, 2023). Compressive strength, which is a critical determinant of structural performance, generally ranges from 2 to 4 MPa for unstabilized mixes and 5 to 8 MPa for cement-stabilized variants (Anysz, Rosicki, & Narloch, 2024; Amede *et al.*, 2024). While these values are lower than those of conventional concrete, they are sufficient for low- to medium-rise structures when appropriately designed.

Rammed earth exhibits high thermal mass, allowing it to absorb, store, and gradually release heat—thereby maintaining stable indoor temperatures (Jiang *et al.*, 2023). This property contributes to passive energy efficiency, especially in arid or temperate climates (Carrobé *et al.*, 2021). However, the material has low tensile strength (typically less than 0.2 MPa), making it unsuitable for spanning large openings without reinforcement (Araki *et al.*, 2016). Its porosity and permeability depend on clay content and compaction; excessive porosity can lead to moisture ingress and erosion, particularly in unstabilized walls exposed to rain (Narloch *et al.*, 2021). To mitigate this, stabilized rammed earth incorporates hydrophobic additives or protective finishes, which reduce water absorption and surface degradation (Sesay *et al.*, 2025). Proper soil grading and controlled compaction are therefore essential for achieving uniform strength and durability across the wall structure.

2.2.3. ENVIRONMENTAL PROPERTIES

Rammed earth is recognized as one of the most environmentally sustainable building materials due to its minimal processing, local sourcing, and low embodied energy (Onyegiri *et al.*, 2024; Serrano *et al.*, 2017). Unlike fired bricks or concrete, which require high-temperature production processes, rammed earth construction relies on mechanical compaction and natural drying, resulting in a significantly lower carbon footprint (Dulal & Giri, 2023; Akbarnezhad & Xiao, 2017). The use of locally available soils reduces transportation emissions and fosters material circularity, as the walls can be easily dismantled and the earth reused or returned to the ground without environmental harm (Pritchard, 2024; Dai *et al.,* 2024).

Additionally, rammed earth structures exhibit excellent life-cycle performance (Jiang *et al.,* 2023). Their thermal mass reduces reliance on artificial heating and cooling systems, contributing to energy conservation (Jiang *et al.,* 2023). When stabilizers like lime are used instead of cement, the environmental impact is further minimized since lime production emits less CO_2 (Akbarnezhad & Xiao, 2017). Furthermore, rammed earth is non-toxic, naturally regulates humidity, and provides a healthy indoor environment, aligning with modern green building standards and sustainable design principles (Gao *et al.*, 2022).

2.2.4. INFLUENCE OF MODERN STABILIZATION TECHNIQUES

Advancements in material science and engineering have refined traditional rammed earth construction into a more reliable and standardized system. The introduction of stabilizers—such as cement, lime, fly ash, bitumen, and ground granulated blast-furnace slag (GGBS) leads to the production of Stabilized Rammed Earth (SRE) (Ávila, Puertas, & Gallego, 2022). This improves both structural integrity and environmental resilience (Ávila, Puertas, & Gallego, 2022). These additives enhance binding capacity, reduce permeability, and increase compressive strength, making rammed earth suitable for use in urban and high-precipitation environments .

Modern stabilization techniques are complemented by innovations in soil testing and mechanical compaction. Laboratory analysis now allows for precise determination of particle size distribution, Atterberg limits, and optimum moisture content, ensuring that soil mixes meet structural and durability requirements. Pneumatic and hydraulic rammers have replaced manual tamping, achieving consistent compaction and higher density throughout the wall. In addition, admixtures such as natural polymers, nanoclays, and silica fumes are increasingly used to improve performance and extend lifespan without compromising sustainability.

CHAPTER THREE

3.0. RESEARCH METHODOLOGY

This chapter outlines the procedures used to gather data and the strategies applied throughout the research process. The methodology explains the practical steps that were followed in the research to obtain the primary or raw data needed for analysis.

3.1. RESEARCH DESIGN

This study adopted a questionnaire-based research design. A questionnaire is a data collection instrument consisting of a series of structured questions designed to gather information from participants. It can be viewed as a written form of an interview.

The questionnaires were distributed through various channels, including face-to-face delivery, online platforms, and postal services. This approach provided a fast, convenient, and efficient means of obtaining substantial data from a large group of respondents.

3.2. POPULATION AND SAMPLING TECHNIQUES

The target population for the study comprised respondents within Benin City. In line with the research topic, *"An Investigative Study Of Rammed Earth As A Sustainable And Cost-Conscious Material For Construction"*, the primary participants were Architects and Quantity Surveyors, who represented key professionals in the construction and built environment sectors.

Their inclusion was justified because they possessed expert knowledge of building materials, low-carbon construction methods, and the sustainability of residential structures. They also had a solid understanding of construction processes and the cost implications associated with the use of rammed earth. For these reasons, architects, quantity surveyors, and students in these fields formed the respondents for the questionnaire.

3.3. SAMPLE SIZE

In administering the questionnaires, a total of 75 individuals were contacted, and 60 completed responses were obtained. This resulted in a response rate of 80%.

3.4. METHODS OF DATA COLLECTION

To describe the participants involved in the study and to present the overall patterns observed across the various variables examined, frequency counts of the responses were generated. Tables and percentages were applied during the analysis to condense the large amount of information and enhance the clarity of the report.

Descriptive statistics—including pie charts, tables, and percentage distributions—were used to organize, code, and interpret the data.

3.5. DATA COLLECTION ETHICS

The rights of respondents were taken into account during data collection to prevent ethical concerns and to ensure that the process remained as unbiased as possible. This approach helped to guarantee that the study did not cause any harm to participants and that their privacy was adequately protected.

The ethical principles applied during the data collection process included:

- Obtaining informed consent from participants
- Protecting the privacy and confidentiality of individuals
- Ensuring transparency in how data were collected
- Maintaining fairness and avoiding bias in the data collection process

- Using the collected data solely for the purposes of the research

3.6. RESPONSE RATE

Table 3.1. below shows that out of a total of 75 questionnaires sent out to the public, 60 responses were received thereby obtaining a response rate of 80%

Sent Questionnaire	Received Questionnaire	Response Rate
75	60	80%

Table 3.1 shows the response rate from the questionnaires sent out

CHAPTER FOUR

4.0. DATA PRESENTATION AND ANALYSIS

4.1. INTRODUCTION

This chapter focuses on the presentation and interpretation of the findings obtained from the study. Data for the research were collected using a Google Form questionnaire administered to more than 80 stakeholders and members of the target audience within the study area. The survey was conducted in two different phases, yielding 54 and 45 responses respectively. The percentage outcomes from both phases were combined and averaged to produce a single consolidated result.

4.2. SURVEY QUESTIONS AND RESULTS

QUESTION 1

What is your current occupation or field of expertise related to construction or sustainable building materials?

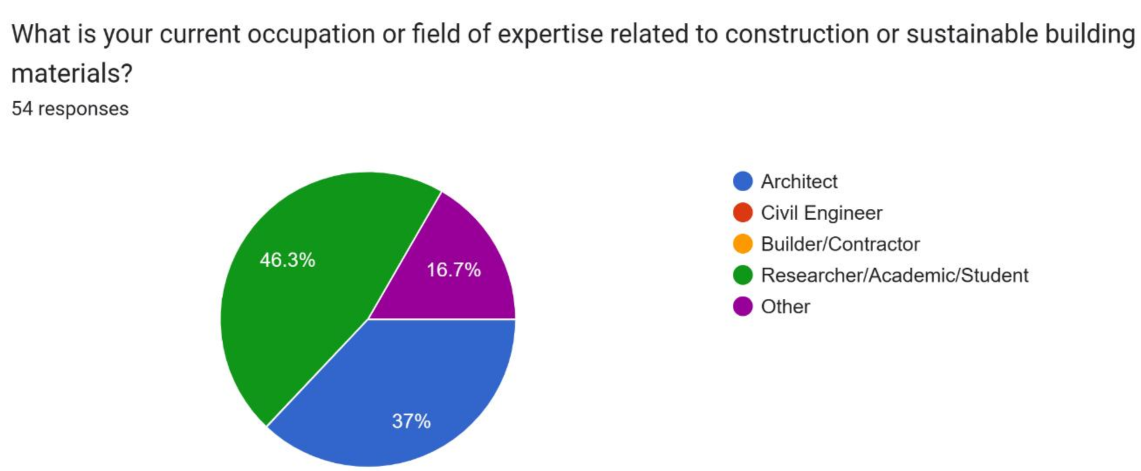

Fig. 4.1: First pie chart showing the distribution of respondents by occupation in construction and sustainable building materials

Source: Researchers' Fieldwork

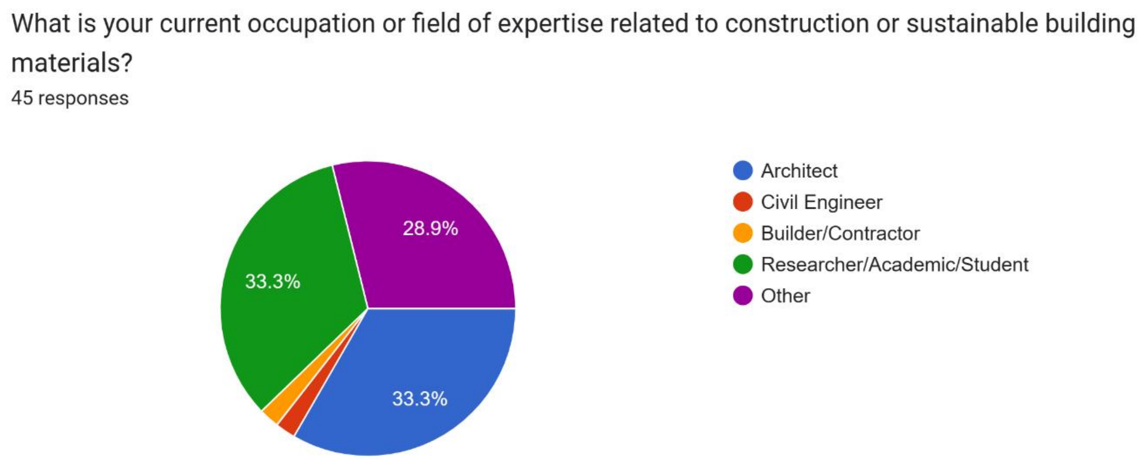

Fig. 4.2: Second pie chart showing the distribution of respondents by occupation in construction and sustainable building materials

Source: Researchers' Fieldwork

The questionnaire was targeted at Architects, Civil Engineers, Builders/Contractors, Researchers/Students, and other related professionals.

Analysis of the two pie charts generated from separate Google Form surveys indicates that Researchers/Students accounted for the highest average response rate at 39.8%, followed by Architects at 35.15%, and respondents from other related professions at 22.8%. Civil Engineers and Builders recorded the lowest participation, each representing 2.2% of the total responses.

These findings suggest that the data obtained are reliable, as the majority of respondents possess adequate literacy and professional knowledge relevant to rammed earth building materials.

QUESTION 2

Are you familiar with the concept of rammed earth as a construction material?

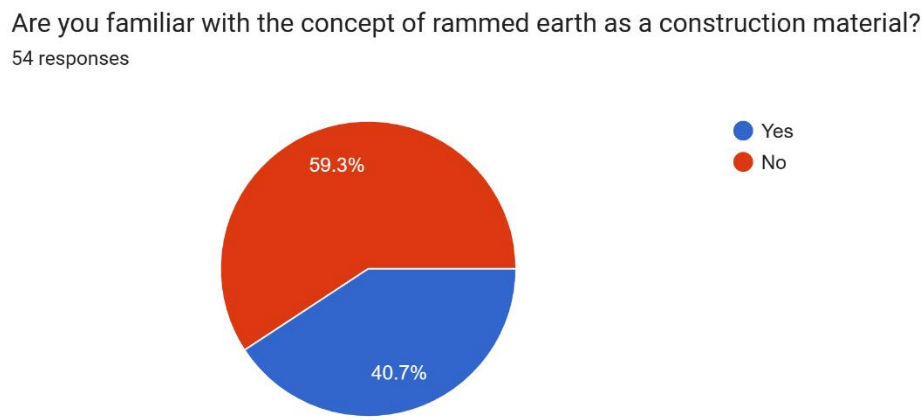

Fig. 4.3: First pie chart showing the distribution of respondents' level of awareness of rammed earth technology

Source: Researchers' Fieldwork

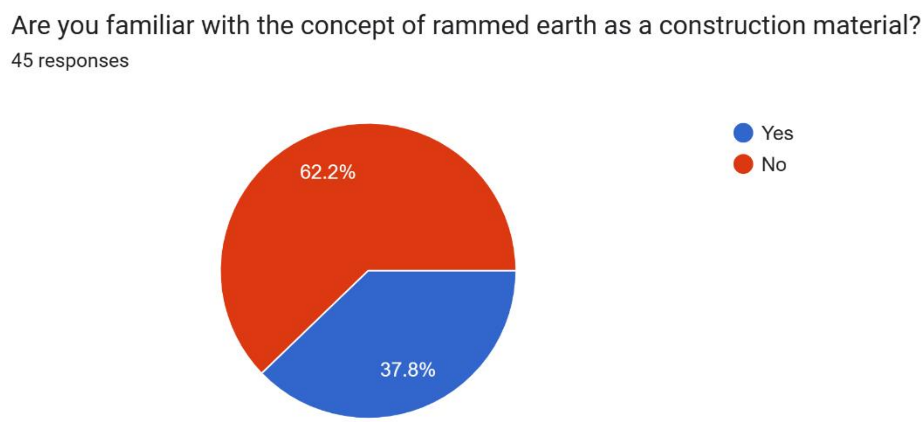

Fig. 4.4: Second pie chart showing the distribution of respondents' level of awareness of rammed earth technology

Source: Researchers' Fieldwork

The results indicate that a majority of the respondents (60.75%) are unfamiliar with the concept of rammed earth as a building material, whereas 39.25% reported that they have some level of knowledge or awareness of it.

QUESTION 3

If yes, please briefly describe your knowledge or experience with rammed earth.

In this subsection, a total of 44 participants provided responses to the question. Out of this number, 10 respondents indicated that they had no prior experience with rammed earth construction. The remaining 34 respondents shared their individual experiences and understanding of rammed earth as a building material.

Presented below is one of the responses provided by a participant (**georaakun@gmail.com**):
"The concept of rammed earth in construction basically entails the use of well compacted earth or laterite fills to create wall massing components in building construction. Rammed earth is an alternative to the prevalent and commonly used concrete construction of sandcrete walls et all. Rammed earth is durable, thermally efficient and cheaper if utilised and explored."

Another response was given by (**benedictonathaniel2002@gmail.com**):
"Rammed earth is a sustainable building material due to its use of abundant, local resources, low embodied energy, thermal mass properties, longevity, low maintenance, non-toxic nature, recyclability, and potential for local job creation. It offers eco-friendly construction while maintaining an aesthetically pleasing, natural appearance."

QUESTION 4

In your opinion, what are the key environmental benefits of using rammed earth as a building material? (select all that apply)

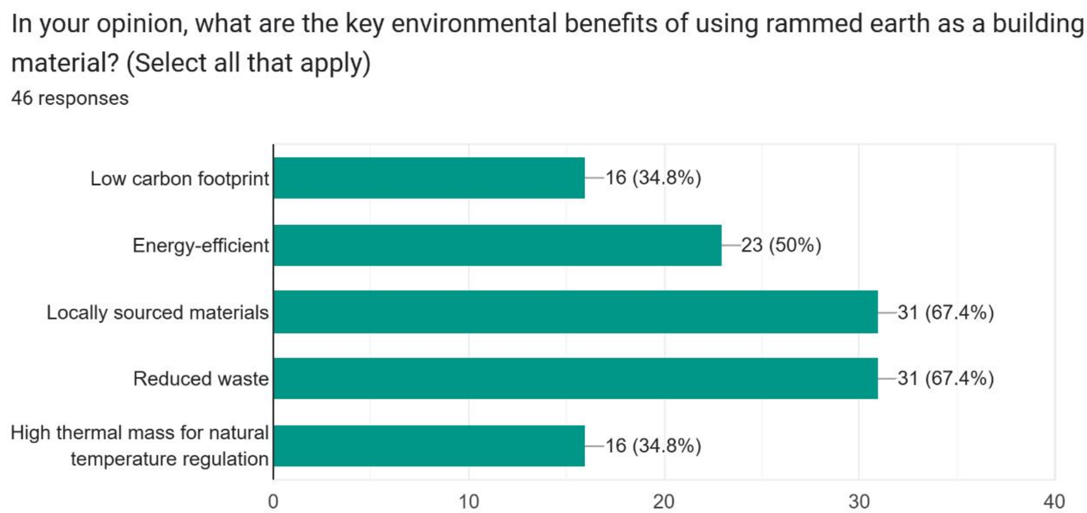

Fig. 4.5: First bar chart showing respondents' perceptions of the environmental benefits of rammed earth as a building material

Source: Researchers' Fieldwork

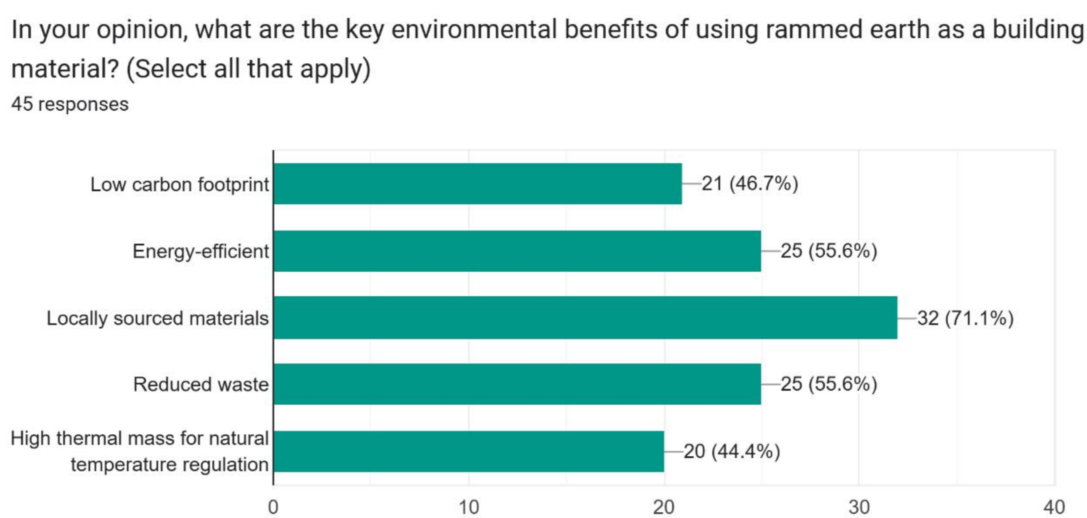

Fig. 4.6: Second bar chart showing respondents' perceptions of the environmental benefits of rammed earth as a building material

Source: Researchers' Fieldwork

In this section, respondents were invited to express their views on the major environmental advantages associated with the use of rammed earth as a construction material. The response options provided included low carbon footprint, energy efficiency, use of locally sourced materials, waste reduction, and high thermal mass for passive temperature control.

Analysis of the responses revealed that 40.75% of participants identified low carbon footprint as a key benefit, 52.8% selected energy efficiency, and 69.25% highlighted the use of locally available materials. Additionally, 61.5% of respondents acknowledged reduced waste generation, while 39.6% recognized the high thermal mass of rammed earth for natural indoor temperature regulation.

QUESTION 5

Do you believe that rammed earth construction can contribute to sustainable and eco-friendly building practices?

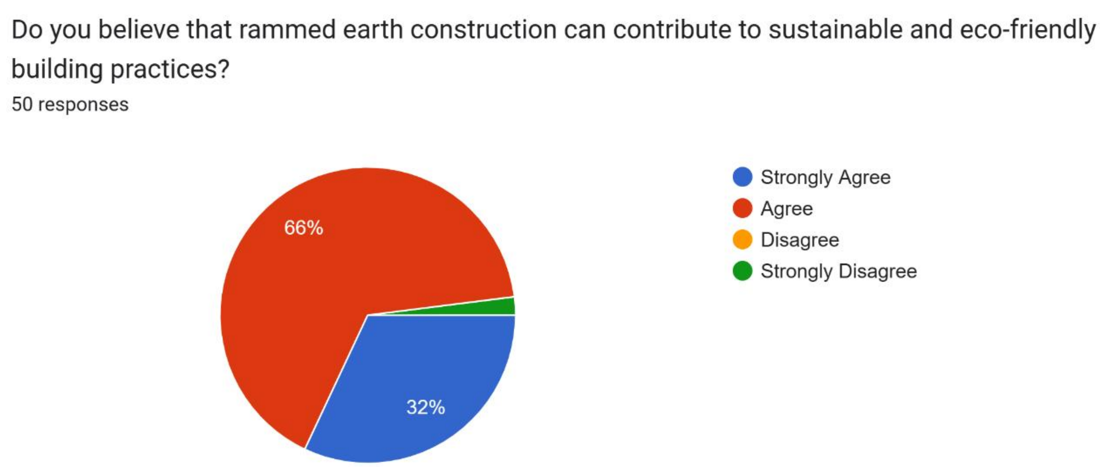

Fig. 4.7: First pie chart showing respondents' views on the contribution of rammed earth construction to sustainable and eco-friendly building practices

Source: Researchers' Fieldwork

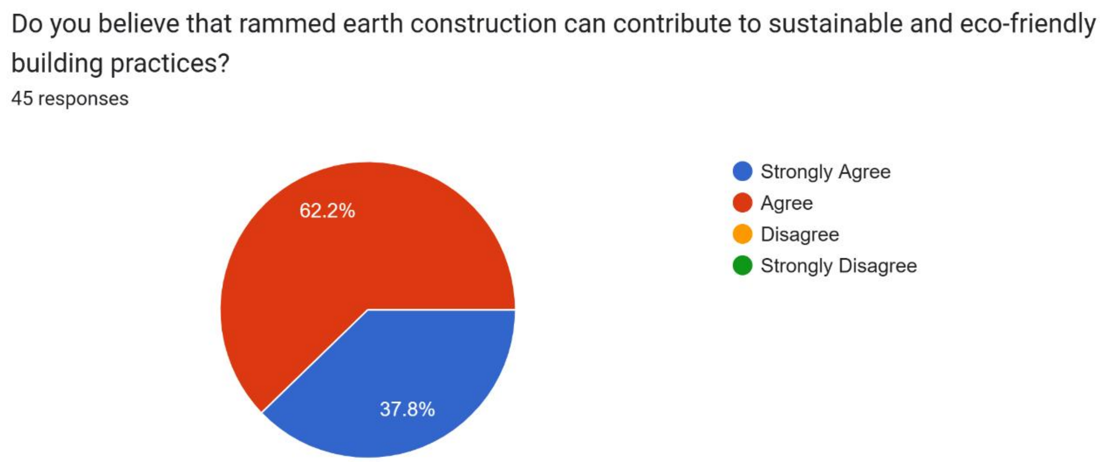

Fig. 4.8: Second pie chart showing respondents' views on the contribution of rammed earth construction to sustainable and eco-friendly building practices

Source: Researchers' Fieldwork

In this section, respondents were asked to indicate their level of agreement with the view that rammed earth construction can support sustainable and environmentally friendly building practices.

The results show that 64.1% of participants agreed with the statement, 34.9% strongly agreed, while a small proportion of respondents (1%) strongly disagreed.

QUESTION 6

What do you see as the main challenges or limitations of using rammed earth in modern construction?

In this section, a total of 70 respondents provided answers to the question, with the majority highlighting what they perceive as the major obstacles to the adoption of rammed earth in contemporary construction. Several of the challenges identified by respondents are presented below:

"I would say climate change. The only way rammed earth can be used in a designated environment or site is if the climate of that region is favourable."
(**benedictonathaniel2002@gmail.com**)

"It requires specialized skills and equipment, making it more expensive and time consuming to build with, than other building materials."
(**calebosayande4@gmail.com**)

Cost of material sourcing, market acceptance, and ready availability of builders skilled at rammed earth construction.
(**unique.akhigbe@gmail.com**)

They need roof overhangs to protect them from the rain and erosion, they're terrible insulators in colder climates, depending on the circumstances and the need for experienced labourers it isn't exactly cheap.
(**mercyalele2001@gmail.com**)

Exposure to this building material, many people don't realise the diverse building material and techniques they only see cement as the only source of building.
(**ehifomaovie@gmail.com**)

Lack of proper knowledge on its use and utilization. Lack of skilled expertise. Acceptance challenges end users as a result of improper understanding.
(**georaakun@gmail.com**)

Labour and time. It is a labour-intensive endeavour and it's also a time-consuming process
(**efosa.emonbeifo@eng.uniben.edu**)

QUESTION 7

Have you been involved in any construction projects that incorporated rammed earth as a building material? if yes, please provide details (project type, location, size, etc).

In this section, responses were received from 82 participants, the majority of whom indicated that they had not participated in any construction project involving rammed earth in contemporary building practice. Only one respondent reported prior involvement in such a project, as reflected in the response presented below:

"I was part of a design that involved rammed Earth but the construction has not been done yet."
(**ededjoernest@gmail.com**)

Based on these findings, it can be inferred that there is a significant need to improve public awareness and understanding of rammed earth as a viable building material.

QUESTION 8

Do you believe that rammed earth construction will become more prevalent in mainstream construction practices in the coming years?

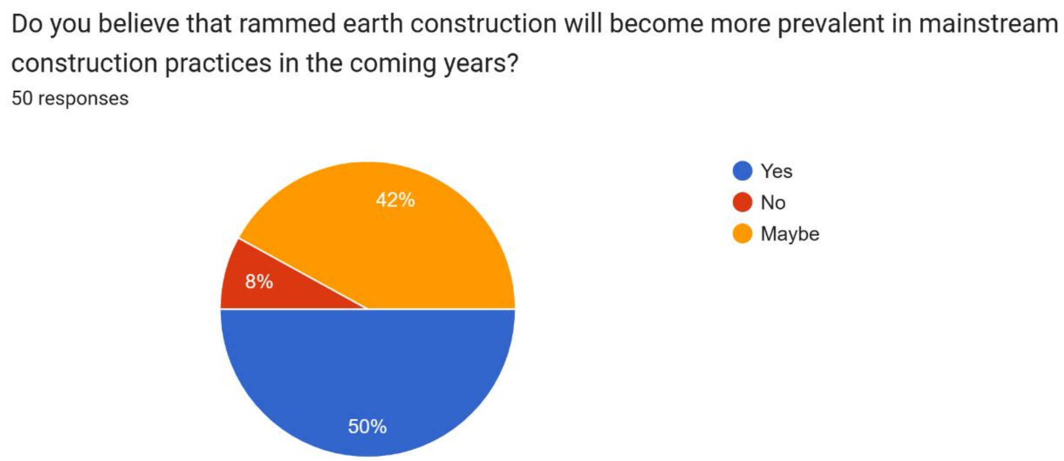

Fig. 4.9: First pie chart showing respondents' perceptions of the future adoption of rammed earth construction in mainstream building practices
Source: Researchers' Fieldwork

Fig. 4.10: Second pie chart showing respondents' perceptions of the future adoption of rammed earth construction in mainstream building practices
Source: Researchers' Fieldwork

In this section, respondents were asked to indicate whether they believe rammed earth construction is likely to gain wider acceptance in mainstream building practices in the future.

The findings show that 46.1% of respondents selected *Yes*, indicating optimism about its increased adoption, while 43.2% chose *Maybe*, reflecting uncertainty. A smaller proportion of respondents, representing 10.65%, selected *No*, suggesting skepticism regarding its future prevalence.

CHAPTER FIVE

5.0. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

This chapter presents the overall summary of the study, draws conclusions based on the findings, and provides recommendations derived from the research outcomes.

5.2 SUMMARY

Chapter One introduced the fundamental concepts relevant to the research topic and provided the background of the study. This background established a foundation for Chapter Two, which focused on the review of related literature by examining both past and recent studies. These studies highlighted contributions from architects, researchers, and scholars who have explored the subject matter.

Chapter Three detailed the research methodology adopted for the study, outlining the research design, applied strategies, and methods used for data collection. Chapter Four presented the analysis of data obtained through questionnaires, accompanied by detailed explanations at each stage of analysis.

Findings presented in Chapter Five revealed that rammed earth construction involves the compaction of a mixture consisting of gravel, sand, clay, and soil using mechanical tampers to form strong wall systems. This method produces durable and sustainable structures suitable for residential building construction.

According to Architect Rakun, *"Rammed earth as a construction material needs more publicity and awareness so clients, architects, engineers and contractors can make good use of for construction project."* This highlights the need for increased awareness among professionals and stakeholders.

The study also emphasizes the importance of integrating rammed earth construction techniques into university and tertiary institution curricula, particularly within disciplines such as architecture and civil engineering, to equip students with the necessary knowledge and practical skills.

Engineer Efosa noted that *“It is a labour-intensive endeavour and it's also a time-consuming process,”* indicating that rammed earth construction requires skilled and experienced personnel. In addition, Engineer Benedict stated that *“Rammed earth is a sustainable building material due to its use of abundant, local resources, low embodied energy, thermal mass properties, longevity, low maintenance, non-toxic nature, recyclability, and potential for local job creation. It offers eco-friendly construction while maintaining an aesthetically pleasing, natural appearance.”*

5.3 CONCLUSION

In conclusion, the findings of this study demonstrate that rammed earth is a sustainable and durable construction material suitable for modern residential and other building applications. This conclusion is supported by data obtained and analysed through the questionnaire administered during the research.

5.4 RECOMMENDATIONS

Based on the study’s findings and conclusions, the following recommendations are proposed:

- Increased public awareness and sensitisation should be carried out to educate the general public on the sustainability, durability, and efficiency of rammed earth as a building material.
- Professionals such as architects, civil engineers, structural engineers, and quantity surveyors should assess project conditions—including climate, foundation requirements, and architectural design—and recommend rammed earth construction where appropriate.

- Academic programmes in architecture, civil engineering, structural engineering, and quantity surveying should incorporate detailed instruction on rammed earth construction techniques to enhance professional competence and adoption.

REFERENCES

Adnan, B., Omar, M., & Abdallah, S. (2022). Computer-aided design of reinforced earth walls. *Information Technology Journal*, 1(2), 142–148. https://doi.org/10.3923/itj.2002.142.148

Akanbi, F. (2025). Soaring material costs threaten Nigeria's construction boom. *ThisDay Live*. https://www.thisdaylive.com/2024/12/08/soaring-material-costs-threaten-nigerias-construction-boom/

Akbarnezhad, A., & Xiao, J. (2017). Estimation and minimization of embodied carbon of buildings: A review. *Buildings, 7*(1), 5. https://doi.org/10.3390/buildings7010005

Akbulut, D. E., & Alibeyoglu, R. N. (2025). Rammed earth construction: From tradition to a sustainable future. In *Modern masonry construction - The fusion of tradition, technology, and sustainability*. https://doi.org/10.5772/intechopen.1010217

Amede, E. A., Aklilu, G. G., Kidane, H. W., & Dalbiso, A. D. (2024). Examining the viability and benefits of cement-stabilized rammed earth as an affordable and durable walling material in Addis Ababa, Ethiopia. *Cogent Engineering, 11*(1), 2318249. https://doi.org/10.1080/23311916.2024.2318249

Anysz, H., & Narloch, P. (2019). Designing the composition of cement stabilized rammed earth using artificial neural networks. *Materials, 12*(9), 1396. https://doi.org/10.3390/ma12091396

Anysz, H., Rosicki, Ł., & Narloch, P. (2024). Compressive strengths of cube vs. cored specimens of cement stabilized rammed earth compared with ANOVA. *Applied Sciences, 14*(13), 5746. https://doi.org/10.3390/app14135746

Araki, H., Koseki, J., & Sato, T. (2016). Tensile strength of compacted rammed earth materials. *Soils and Foundations, 56*(2), 301–313. https://doi.org/10.1016/j.sandf.2016.02.003

Ávila, F., Puertas, E., & Gallego, R. (2022). Characterization of the mechanical and physical properties of stabilized rammed earth: A review. *Construction and Building Materials, 350*, 126693. https://doi.org/10.1016/j.conbuildmat.2022.126693

Baeissa, A. (2013). Mud brick houses in Hadhramout Valley, Yemen: Learning from the past experiences for sustainable development. 10, 145–156.

Bui, Q.-B., Hans, S., Morel, J.-C., & Mollion, V. (2011). Influence of water on the mechanical characteristics of rammed-earth material. *WIT Transactions on The Built Environment, 118*, 565–576. https://doi.org/10.2495/STR110471

Carrobé, A., Rincón, L., & Martorell, I. (2021). Thermal monitoring and simulation of earthen buildings: A review. *Energies, 14*(8), 2080. https://doi.org/10.3390/en14082080

Cruz, R., Bogas, J. A., Balboa, A., & Faria, P. (2024). Water resistance of compressed earth blocks stabilised with thermoactivated recycled cement. *Materials, 17*(22), 5617. https://doi.org/10.3390/ma17225617

Dai, S., Bai, W., & Xiao, J. (2024). Balancing environmental impact and practicality: A case study on the cement-stabilized rammed earth construction in Southeast rural China. *Sustainability, 16*(20), 8731. https://doi.org/10.3390/su16208731

Dulal, P., & Giri, R. R. (2023). Carbon emissions due to construction of buildings using cement-stabilized compressed earth bricks and comparison with conventional fired earth bricks. *Kathford Journal of Engineering and Management, 3*(1), 172–184. https://doi.org/10.3126/kjem.v3i1.62890

Ekanem, S. (2024). Price of cement jumps by 100% to hit ₦7,000 per bag in 3 years. *Pulse Nigeria.*https://www.pulse.ng/articles/business/domestic/price-of-cement-jumps-by-100-to-hit-naira7000-per-bag-in-3-years-2024072700132280841

Fahfouhi, K., Leal, A., Ferrández, D., & Cobo, A. (2025). Exploring material synergies: Earth-based materials and steel applications in modern construction. In *Proceedings of the XVIII Congreso Iberoamericano de Patología de la Construcción, XX Congreso de Control de Calidad en la Construcción.* https://doi.org/10.21041/CONPAT2025/V1CC128

Fernandes, J., Peixoto, M., Mateus, R., & Gervásio, H. (2019). Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks. *Journal of Cleaner Production, 241*, 118286. https://doi.org/10.1016/j.jclepro.2019.118286

Flint, J. (2025). House of the week: A rammed earth home in Napa Valley. *The Wall Street Journal.*https://www.wsj.com/real-estate/luxury-homes/rammed-earth-home-napa-california-4c29547f

Gao, Q., Wu, T., Liu, L., Yao, Y., & Jiang, B. (2022). Prediction of wall and indoor hygrothermal properties of rammed earth folk house in Northwest Sichuan. *Energies*, 15(5), 1936. https://doi.org/10.3390/en15051936

Gil C., Ignacio J. (2013). Rammed earth walls in the late middle age castles in the actual province of Soria, Spain. In "Vernacular heritage and earthen architecture: Contributions for sustainable development" (pp. 365–370). *Taylor & Francis*. ISBN 978-1-138-00083-4

Global Times. (2025). *New discovery in Zhengzhou pushes back rammed-earth construction origins by 5,000 years to mid-Yangshao culture.* Global Times https://www.globaltimes.cn/page/202502/1328990.shtml

Gomaa, M., Schade, S., Bao, D. W., & Xie, Y. M. (2023). Automation in rammed earth construction for Industry 4.0: Precedent work, current progress and future prospect. *Journal of Cleaner Production, 398*, 136569. https://doi.org/10.1016/j.jclepro.2023.136569

Jaquin, P. (2012). Influence of Arabic and Chinese rammed earth techniques in the Himalayan region*.* *Sustainability, 4*(10), 2650–2660. https://doi.org/10.3390/su4102650

Jiang, M., Jiang, B., Lu, R., Chun, L., Xu, H., & Yi, G. (2023). Thermal and humidity performance test of rammed-earth dwellings in Northwest Sichuan during summer and winter. *Materials (Basel), 16*(18), 6283. https://doi.org/10.3390/ma16186283

Kiani Mavi, R., Gengatharen, D., Kiani Mavi, N., Hughes, R., Campbell, A., & Yates, R. (2021). Sustainability in construction projects: A systematic literature review. *Sustainability, 13*(4), 1932. https://doi.org/10.3390/su13041932

Koutous, A., & Hilali, E. M. (2019). A proposed experimental method for the preparation of rammed earth material: Application of the method to a case study. *International Journal of Engineering Research & Technology (IJERT), 8*(7), Article IJERTV8IS070140. http://www.ijert.org

Lechheb, M., Chrachmy, M., Achraf, H., & Ouallal, H. (2024). Physical and thermal properties of raw earthen bricks from Ksar Ait Benhaddou. In *Mediterranean Architectural Heritage, RIPAM10* (pp. 186–197). *Materials Research Proceedings.* https://doi.org/10.21741/9781644903117-20

Liu, K., Walske, M., Zhou, M., & Zhang, X. (2022). The dynamic material properties of stabilised rammed earth materials using cement and calcium carbonate residue. *International Journal of Protective Structures, 14*(4), 509–526. https://doi.org/10.1177/20414196221119239

Ma, J., Zhang, H., Shobeiri, V., Zhong, Y., Zhang, J., Bai, Y., Robert, D., & Xie, Y. M. (2025). CFRP-confined rammed earth towards high-performance earth construction. *Composite Structures, 371*, Article 119512. https://doi.org/10.1016/j.compstruct.2025.119512

Mileto, C., Vegas, F., Hueto-Escobar, A., & Manzano-Férnández, S. (2025). Towards the recovery of traditional hot-mixed lime techniques: Influence on the construction process and structural behaviour in rammed earth with lime. *Journal of Sustainability Research, 7*(2), e250021. https://doi.org/10.20900/jsr20250021

Muguda-Viswanath, S. (2019). *Biopolymer stabilised earthen construction materials* [Doctoral thesis, Durham University]. Durham E-Theses Online. http://etheses.dur.ac.uk/13444/

Narloch, P., Piątkiewicz, W., & Pietruszka, B. (2021). The effect of cement addition on water vapour resistance factor of rammed earth. *Materials, 14*(9), 2249. https://doi.org/10.3390/ma14092249

Narloch, P., Woyciechowski, P., Kotowski, J., Gawriuczenkow, I., & Wójcik, E. (2020). The effect of soil mineral composition on the compressive strength of cement stabilized rammed earth. *Materials, 13*(2), 324. https://doi.org/10.3390/ma13020324

Onyegiri, I., Okafor, M. U., & Iwuagwu, B. U. (2024). Cost-effective and energy-efficient building using the rammed earth technique in South East Nigeria: Challenges and prospects. *International Journal of Science and Research Archive, 13*(1), 2136–2139. https://doi.org/10.30574/ijsra.2024.13.1.1894

Pei, Q., Liu, X., Hou, Z., & Zhao, G. (2022). Ramming mechanical characteristics of rammed earthen sites. *Research Square*. https://doi.org/10.21203/rs.3.rs-1698786/v1

Petcu, C., Dobrescu, C. F., Dragomir, C. S., Ciobanu, A. A., Lăzărescu, A. V., & Hegyi, A. (2023). Thermophysical characteristics of clay for efficient rammed earth wall construction. *Materials (Basel), 16*(17), 6015. https://doi.org/10.3390/ma16176015

Pritchard, J. (2024). Why is rammed earth construction material sustainable? *Building Renewable*. https://buildingrenewable.com

Ramalho, N. A. (2016). *Museu da Cidade de São Paulo* [In Brazilian Portuguese]. Archived from the original on January 21, 2016. Retrieved April 23, 2017.

Randeep, Srivastava, S., & Soamidas, V. (2025). Mechanical and durability performance of pine fiber and limestone calcined clay cement stabilized rammed earth blocks. *Discover Civil Engineering, 2*, 176. https://doi.org/10.1007/s44290-025-00340-7

Rocha, M., Faria, P., & Gago, A. S. (2024). Conservation of defensive military structures built with rammed earth. *Buildings, 14*(1), 238. https://doi.org/10.3390/buildings14010238

Rosselli, L. (2020). The Great Wall of WA. *ArchDaily*. https://www.archdaily.com/771780/the-great-wall-of-wa-luigi-rosselli

Sabbà, M. F., Tesoro, M., Falcicchio, C., & Foti, D. (2021). Rammed earth with straw fibers and earth mortar: Mix design and mechanical characteristics determination. *Fibers, 9*(5), 30. https://doi.org/10.3390/fib9050030

Sahito, A. M., Memon, R. A., Kumar, A., & Bhanbhro, R. (2025). Evaluation of strength characteristics of cement-stabilized rammed-earth material. *Civil Engineering Journal, 11*(7), 2782–2810. https://doi.org/10.28991/CEJ-2025-011-07-09

Schmitz, L. P., Gosslar, J., Dorresteijn, E., Lowke, D., & Kloft, H. (2024). Experimental investigations on the compaction energy for a robotic rammed earth process. *Frontiers in Built Environment*, 10. https://doi.org/10.3389/fbuil.2024.1363804

Scott, M. (2025). Cement: Building a green path in a hard industry. *Reuters*. https://www.reuters.com/sustainability/decarbonizing-industries/cement-hard-industry-crack-down-emissions-2025-06-11/

Serrano, S., Rincón, L., González, B., Navarro, A., Bosch, M., & Cabeza, L. F. (2017). Rammed earth walls in Mediterranean climate: Material characterization and thermal behaviour. *International Journal of Low-Carbon Technologies, 12*(3), 281–288. https://doi.org/10.1093/ijlct/ctw022

Sesay, T., Xie, Y., Chen, Y., & Xue, J. (2025). Bio-based stabilization of natural soil for rammed earth construction: A review on mechanical and water durability performance. *Polymers, 17*(9), 1170. https://doi.org/10.3390/polym17091170

Sesay, T., Xie, Y., Chen, Y., & Xue, J. (2025). Bio-based stabilization of natural soil for rammed earth construction: A review on mechanical and water durability performance. *Polymers, 17*(9), 1170. https://doi.org/10.3390/polym17091170

Shu, Y., & He, Y. (2021). Research on the historical and cultural value of and protection strategy for rammed earth watchtower houses in Chongqing, China. *Built Heritage, 5*, 23. https://doi.org/10.1186/s43238-021-00042-w

Steinhardt, N. S. (2022). *The borders of Chinese architecture* (p. 30). Harvard University Press. https://doi.org/10.4159/978067424101

Suresh, A. (2023). A study on soil sample to evaluate the suitability for rammed earth construction. In *Proceedings of the 2nd International Conference on Modern Trends in Engineering Technology and Management* (ICMEM 2023). AIJR Proceedings. https://doi.org/10.21467/proceedings.160.2

Tay, L. T., Lee, Y. Y., Lee, Y. H., & Kueh, A. B. H. (2022). A review on the behaviour, properties and favourable characteristics for thermally insulated concrete for tropical climate. *Journal of Engineering Science and Technology*, 17(3), 1608–1643.

Thompson, D., Augarde, C., & Osorio, J. P. (2025). A review of chemical stabilisation and fibre reinforcement techniques used to enhance the mechanical properties of rammed earth. *Discover Civil Engineering, 2*, 27. https://doi.org/10.1007/s44290-025-00184-1

Vora, M., Patel, A., & Shaikh, M. S. (2014). *Stabilization of rammed earth.* Shankersinh Vaghela Bapu Institute of Technology.

Wikipedia, (2025.). *Aït Benhaddou*. In *Wikipedia, The Free Encyclopedia*. Retrieved [October 13, 2025], from https://en.wikipedia.org/wiki/A%C3%AFt_Benhaddou (en.wikipedia.org)

Yang, J., Tan, F. H., & Tan, A. H. (2017). The ancient construction materials and methods: The Great Wall of China in Jinshanling as a case study. *Journal of Construction Engineering and Project Management, 7*(1), 37–49. https://doi.org/10.6106/JCEPM.2017.3.30.037

Zhou, Q. (2024). Research on traditional reinforcement techniques for rammed earth walls in China. *International Journal of Architectural Heritage, 19*(5), 1–19. https://doi.org/10.1080/15583058.2024.2305190