TECHNICAL CONSIDERATIONS FOR EARTHEN CONSTRUCTION: A COMPREHENSIVE STUDY OF STANDARDS, PRACTICES AND PERFORMANCE CRITERIA

By

Abraham U. AFAHA,

Michael C. Oguike Ph.D.,

And

Arc. Utibe E. Akah Ph.D.
Department of Architecture,
Faulty of Environmental studies
University of Uyo, Akwa Ibom State

ABSTRACT

This study assessed technical considerations for earthen construction as a comprehensive review of standards, practices, and performance criteria. Three specific research objectives and corresponding research questions were developed, and a content analysis method was adopted in which relevant and related studies were examined to draw logical inferences. Evidence from the reviewed studies confirmed that the global landscape of technical standards for earthen construction is characterized by fragmentation, inconsistency, and incompleteness, while also affirming that the application of clearly defined technical requirements leads to measurable improvements in the safety, durability, and overall performance of earthen structures. Furthermore, findings from the third research question indicated that the development of a harmonized and unified set of technical specifications has strong potential to enhance the adoption and standardization of earthen construction practices worldwide. The study concluded that earthen construction, when executed in accordance with clearly defined technical requirements for material selection, structural design, moisture management, and quality control, can produce buildings that are safe, durable, and fit for purpose. Based on these findings, it was recommended that national and international standards organizations priorities the development of comprehensive and integrated technical standards covering all major earthen building systems—adobe, compressed earth blocks (CEB), rammed earth, cob, and cast earth—within a coherent framework, with clear guidance materials, design, quality control, and maintenance; that governments, especially in regions where earthen construction is prevalent such as Sub-Saharan Africa, South Asia, and Latin America, establish or adopt building codes that formally recognize these systems and provide clear regulatory pathways alongside minimum performance standards aligned with international best practices; and that procurement and funding frameworks, particularly in public and affordable housing sectors, be adapted to support earthen construction by recognizing its economic, environmental, and social sustainability benefits.

KEYWORDS: Technical Data, Earth Building Material, Earthen Construction, Standards, Codes, Compressed Earth Blocks, Rammed Earth, Adobe

INTRODUCTION

In recent times, innovation and research on earthen building materials and construction have increased throughout Europe and North America by agencies and institutions in France, Germany, Spain, Canada, the USA and Latin America. This innovation enables architects, engineers and artisans to use and specify earthen building materials without undue risk (Reddy and Reddy, 2022).

However, many design professionals, contractors, institutions, and governments remain highly skeptical of building with earth, especially when the earth is load-bearing and not just a facade. Among skeptics, concerns center on the performance of the material, especially how it can be standardized for mass production, and what is its ability to meet norms and codes. Convincing a wider audience requires well-documented study, particularly those that demonstrate an optimal balance between local labour and technical innovation. Hence, the ability to test, prove and document technical data on consistent earthen material properties and construction is central to increasing the use of earth in contemporary building practices (Valverde-Palacios et al., 2022).

Earth is a versatile and sustainable material used for construction for thousands of years. It can be employed in various forms, such as road bed material, unfired building blocks, compressed earth blocks (CEBs), rammed earth, adobe masonry, and cob. Around one-third of the world's population lives in earthen structures (Valverde-Palacios et al., 2022). More so, earth is a 100%eco-friendly building material that is neither manufactured nor transported long distances. For instance, a wall made from raw earth serves as a natural ai conditioner, being warm in winter and cool in summer. When demolished, the earth returns to the soil and can be recycled indefinitely.

Nevertheless, technical data available on earthen materials and construction differ considerably in terms of terminology, testing procedures and production methods. The lack of clear codes and standardization contributes to inconsistent construction practices for earthen structures and substandard quality, posing risks to the safety, durability and underutilization of earthen materials (Bowen, 2017; Danso, 2018). Based on the foregoing, this paper examines the technical considerations for earthen construction, focusing on a comprehensive overview of the standards, practices, and performance criteria.

Statement of the Problem

Earthen construction represents one of humanity's oldest building traditions, providing shelter to an estimated one-third of the global population. As the construction industry is facing serious pressures to reduce embodied carbon and adopt regenerative building practices, earthen materials (e.g. adobe, rammed earth, compressed earth blocks, and cob), earthen construction have emerged as technically and environmentally compelling alternatives to energy-intensive conventional materials. The increasing relevance of earthen construction is therefore not merely historical but is increasingly affirmed by contemporary sustainability imperatives that demand a rigorous, science-backed re-engagement with earth as a primary structural medium.

Regardless of its significance, earthen construction continues to face profound technical challenges that constrain its wide acceptance and usage within the construction industry. Chief among these is the existing standards, which are geographically fragmented and methodologically inconsistent; the German DIN 18945-18948 series, New Zealand's NZS 4297-4299, Peru's NTE E.080, and equivalent national codes differ fundamentally in their soil classification criteria, testing protocols, admissible stress values, and seismic design provisions, making cross-jurisdictional practice structurally and legally precarious. More so, performance criteria for durability under cyclic wetting and drying, long-term erosion resistance, hydrothermal behavior, and seismic response remain inadequately codified, while construction practices lack the procedural uniformity necessary to guarantee reproducible structural outcomes. These compounding deficiencies collectively undermine the confidence of professionals in the construction industry in earthen construction as a technically defensible building system.

Extant literature in this direction reveals that while scholarly contributions to earthen construction have grown considerably over the past three decades, significant knowledge gaps persist. Studies such as Minke (2006), Houben and Guillaud (1994), and Walker et al.(2005)are material-specific and geographically isolated, focusing narrowly on the compressive strength of compressed earth blocks or the seismic vulnerability of adobe structures in particular regional contexts, without translating findings into generalized design principles or universally applicable performance benchmarks. Furthermore, comparative analyses of international standards remain sparse, qualitative in orientation, and insufficiently attentive to the practical needs of practitioners operating across diverse regulatory environments. Thus, no comprehensive study has yet synthesized technical considerations across the full spectrum of earthen construction methods, performance domains, and standard-setting bodies within a single, structured analytical framework.

There is therefore a compelling and urgent need for this study. By systematically examining the technical considerations governing earthen construction encompassing material characterization, structural performance criteria, construction practices, and the comparative analysis of international standards, this research aims to produce an integrated body of knowledge that bridges the gap between traditional practice and modern construction demands.

Research Objectives

The following research objectives guided this study:

i. To identify and evaluate the existing technical standards and codes governing earthen construction and determine their adequacy in addressing the full spectrum of earthen building systems, including adobe, rammed earth, and compressed earth blocks (CEBs).

ii. To examine the material, structural, and environmental performance requirements that constitute appropriate technical considerations for safe and sustainable earthen construction, with particular focus on soil properties, wall systems, moisture control, and structural design criteria.

iii. To propose a unified set of technical specifications for earthen construction that harmonizes discrepancies across existing international standards and provides a reliable, evidence-based framework applicable to diverse geographic and climatic contexts.

Research Questions

The study was guided by the following research questions:

i. What are the existing technical standards and codes available for earthen construction, and to what extent do they address the full range of earthen building systems and material properties?

ii. What specific material properties, structural design criteria, and quality control methods constitute appropriate technical considerations for safe, durable, and sustainable earthen construction?

iii. What unified technical specifications can be derived from a comparative review of international earthen building standards to guide consistent, safe, and efficient earthen construction practice globally?

LITERATURE REVIEW

Conceptual Framework

Technical consideration defines the technical requirements and performance standards for the design and construction of structures, and provides guidance on how these can be achieved. As a core basis of technical consideration, technical adequacy is highly considered for earthen construction in the construction industry. It refers to the extent to which existing codes, standards, and guidelines sufficiently address the design, material, structural, and quality requirements of earthen building systems. Technical adequacy recognizes that technical standardization is not an end in itself, but a means to achieving the broader goals of safety, sustainability, and economic viability in earthen construction. As Minke (2000) pointed out, the scalability of earth as a building material depends on the existence of reliable technical data that enable architects, engineers, and builders to make informed decisions at every stage of the construction process. The absence of such data creates a barrier to the mainstream adoption of earthen materials, regardless of their inherent environmental and economic advantages.

The concept of technical adequacy further brings to bear the concept of technology transfer, whereby innovations in earthen building developed in research laboratories and flagship projects in Europe and North America can be systematically codified and disseminated for application in diverse global contexts (Bowen, 2017). The conceptual framework thus positions this study as contributing to the evidence base needed to bridge the gap between earthen construction's traditional roots and its potential as a modern, standardised building technology.

Overview of the Earthen Building System

Earthen building systems include a diverse range of techniques, each with distinct material requirements, construction methods, and performance characteristics. In the course of this study, the principal systems reviewed in the literature are adobe or sun-dried mud brick masonry, compressed earth blocks (CEBs), rammed earth or pies. According to ASTM E2392 (2010), these techniques can be used as structural and non-structural wall systems, and their technical requirements are categorized under design criteria, structural systems, and structural components.

Adobe is the oldest and most widely used earthen building technique globally. It involves the hand molding or casting of earth-water mixtures into blocks, which are then sun-dried before use in masonry construction. The strength of adobe construction depends on the quality of the soil mix, the moisture content during molding, and the adequacy of the mortar joints between blocks. Fissure development is a key risk in adobe construction, which can be mitigated by the addition of straw or coarse sand to the mix and by ensuring adequate moisture in the contact area between layers.

Compressed earth blocks (CEBs) represent technological evolution of the adobe block, employing mechanical compaction to produce blocks of uniform dimensions and higher compressive strength. As documented by Bowen (2017) in the HUD Best Practices Manual, CEBs are typically formed by combining angular sand aggregate (40-70%), clay soil (15-60%),,and water (8-12%), followed by hydraulic compression at a minimum of 1,200 psi. CEBs offer significant advantages over traditional adobe in terms of dimensional uniformity, structural performance, resistance to moisture, and ease of quality control. In wetter climates, stabilization with hydrated lime or Portland cement at4-6%by weight is recommended to reduce moisture absorption and deterioration.

Rammed earth construction involves the compaction of moistened soil in successive layers within temporary formwork to form solid monolithic walls. The SADC/SADCSTAN (2020) standard specifies that soil for rammed earth should contain 50-70% fine gravel and sand, 15-30%silt, and 5-15% clay, and should be free of organic material. The optimum moisture content should be determined by the drop test, and the mix should satisfy the roll test with a break-off length of 80-120 mm. The strength of rammed earth walls is primarily determined by the degree of compaction achieved and the clay content of the soil.

Existing Technical Standards and Codes for Earthen Construction

The comparative review of international earthen building standards reveals both significant progress and persistent gaps in the technical regulation of earthen construction. King (2006) provides a comprehensive survey of extant codes and standards, noting considerable variation in terminology, testing procedures, and performance requirements across documents from the United States, New Zealand, New Mexico, California, India, Peru, and Australia.

The ASTM E2392 (2010) Standard Guide for Design of Earthen Wall Building Systems is one of the most comprehensive American standards, addressing both technical requirements and sustainability considerations. It provides guidance on design criteria, structural and non-structural systems, material performance, and indoor environmental quality. For live loads, wind, and seismic resistance, the standard recommends reliance on established guidelines such as the International Building Code (IBC) or ANSI/ASCE 7.

The SADC Harmonized Standard for Rammed Earth Structures (SADC ZW HS 983:2014) represents a regional African standard covering materials, formwork, groundwork’s, superstructures, stability, and finishes. It provides specific guidance on soil composition, moisture content, foundation requirements, and damp-proof course details. Walker and Morris (cited in the original article) document the development of the New Zealand Earth Building Standards, which provide for lower-density earthen materials, a wider range of earth building techniques, and internal adobe walls fixed to timber framing.

Bowen (2017) documents that the New Mexico Building Code was the first code authority to incorporate CEBs as a code-approved construction material, requiring structural testing at a rate of every 5,000 CEBs produced and mandating a minimum compressive strength of 300 psi. This precedent has since been followed by other jurisdictions, including provisions in the International Residential Code (IRC) and the International Building Code (IBC).

A consistent finding across the reviewed literature is that approximately 74% of earthen construction standards address a single technique (adobe, CEB, or rammed earth), and only

27%address stabilized earthen materials. This fragmentation reinforces the need for a more integrated, holistic approach to earthen building standardization that addresses multiple techniques within a common technical framework (Valverde-Palacios et al., 2022).

Material Properties and Testing

The suitability of soil for earthen construction depends on a range of physical and chemical properties. Danso (2018) identifies particle size distribution (PSD), Atterberg limits (AL), compaction characteristics (CC), California Bearing Ratio (CBR), unconfined compressive strength (UCS), water absorption (WA), porosity (P), permeability (K), and durability as the key parameters governing soil suitability for earth construction. Elsewhere, Reddy and Reddy (2022) emphasize that clay quality, including plasticity index and organic content, is particularly critical, as clay provides the binding properties that determine the cohesion and workability of earthen materials.

The dry strength test, fissuring control test, and strength test of adobe are commonly used to determine earthen material properties. For CEBs, Bowen (2017) and the appendices to the HUD manual recommend a comprehensive suite of ASTM tests including D-1557 (Moisture-Density Relation), D-4318 (Plasticity Index), D-422 (Hydrometer Analysis), C-136 (Sieve Analysis),C-666(Freeze/Thaw Durability), C-952 (Mortar Bond Strength), D-2166 (Unconfined Compressive Strength), and C-1314 (Aspect Ratio Prism Test).

Cement-stabilized earth, particularly in the form of pressed bricks and mechanically compacted rammed earth, can reach compressive strengths comparable to regular concrete. ASTM E2392 (2010) reports that in various regions, engineers have successfully applied design methods used for concrete and concrete masonry to cement-stabilized earth structures. However, it is important to note that untreated earth can weaken significantly when exposed to moisture, making it unsuitable for below-ground applications such as foundation walls or retaining walls without appropriate waterproofing.

Environmental Performance of Earthen Buildings

The environmental performance of earthen buildings has been extensively documented in the literature. Momcilovic-Petronijevic et al. (2018) enumerate the key advantages of earth as a building material, including low cost, good thermal insulation, fire resistance, sound insulation, ease of workability, eco-friendliness, humidity regulation, durability, and aesthetic quality. These properties make earthen buildings naturally conducive to energy efficiency and indoor environmental quality.

Valverde-Palacios et al. (2022) demonstrate that earth is a 100% eco-friendly building material that generates no manufacturing emissions, requires minimal transportation, and can be fully recycled at the end of a building's life cycle. The thermal mass properties of rammed earth and CEB walls are particularly valuable in climates with significant diurnal temperature variation, where the walls absorb solar heat during the day and radiate it at night, reducing the need for mechanical heating and cooling. Bowen (2017) confirms that CEB houses have a low rate of thermal conductivity, making them warmer in winter and cooler in summer compared to conventional framed construction.

Current research efforts are focused on increasing the resistance and processing speed of earthen materials to make them competitive with conventional alternatives. Industrial sectors devoted to earthen building are emerging as the material's ecological and aesthetic benefits attract the attention of an increasing number of contemporary architects and eco-builders (Danso,2018).The fusion of ancient vernacular earth building techniques with modern engineering requirements represents one of many potential solutions to the negative externalities of the current construction industry.

Theoretical Framework

Sustainable Construction Theory: This study is grounded in the Sustainable Construction Theory, which holds that the built environment should be designed, constructed, and managed in ways that meet present needs without compromising the ability of future generations to meet their own needs. As opined by Kibert (2016), sustainable construction is concerned not only with environmental impact, but also with economic efficiency, social equity, and the long-term resilience of built systems. Earthen construction, by virtue of its use of locally available, non-manufactured materials with minimal energy input, embodied carbon, and waste generation, is fundamentally aligned with the principles of sustainable construction.

However, central to sustainable construction theory the hesitancy of mainstream construction professionals to adopt earthen materials. Borrowing form Technology Adoption Model (TAM), the perceived usefulness and ease of use of a technology are primary determinants of its adoption (Abanda et al., 2017). In the context of earthen construction, the perceived usefulness is high among sustainability-oriented practitioners, but the perceived ease of use remains low due to the absence of clear, standardized technical guidelines. This theoretical lens underscores the importance of technical standardization in overcoming the barriers to earthen construction adoption.

Empirical Review

Laborel-Préneron et al. (2017) conducted a study on the use of plant aggregates and natural fibers as reinforcing additives in earthen construction materials in France. The objective of the study was to systematically review the influence of natural fiber and plant aggregate additions on the mechanical, thermal, and hydric properties of earthen construction materials including adobe, rammed earth, and earth renders. A systematic literature review and meta-analytical research design was employed, drawing on over 80 experimental studies published between 1990 and 2016.Data analysis was performed using comparative tabulation of reported property improvements and statistical synthesis of fiber type-performance relationships. Findings from the study revealed that fiber additions at 0.5-2.0% by mass consistently reduced shrinkage cracking in adobe and earth renders by 30-60%, improved tensile strength by up to 25%, and in some formulations enhanced thermal insulation by up to 30% due to increased porosity, though compressive strength frequently decreased by 10-20% with increasing fiber content. It was concluded that natural fiber reinforcement offers significant technical benefits for earthen construction but that current standards fail to provide adequate guidance on fiber selection, dosage optimization, or quality control of fiber-reinforced earthen materials. The researchers recommended that updated earthen construction standards incorporate annexes on fiber-reinforced earthen systems with standardized test methods for fiber characterization and composite performance assessment. This study is similar to the present study in its focus on material performance criteria and standardization gaps for earthen construction but differs in its specific concern with fiber-reinforced material variants and its reliance on secondary data synthesis.

Soudani et al. (2016) conducted a study on the hydrothermal modeling and thermal performance assessment of rammed earth building envelopes in France. The objective of the study was to evaluate the validity of common assumptions used in hydrothermal simulation models when applied to earthen building materials and to quantify the accuracy of predicted thermal and moisture performance of rammed earth walls under real climatic conditions. A combined experimental and computational research design was used. Instrumented rammed earth wall panels were monitored over a twelve-month period in a purpose-built test cell, and measured data were compared against predictions from three hydrothermal simulation platforms including WUFI and COMSOL. Data analysis was performed using root mean square error (RMSE) comparison of simulated and measured temperature and relative humidity profiles. Findings from the study showed that standard hydrothermal models significantly underestimated the moisture buffering capacity of rammed earth, with discrepancies of up to 18 percentage points in predicted interior relative humidity under dynamic climatic conditions, attributable to the simplified representation of sorption hysteresis in available material databases. It was concluded that existing hydrothermal simulation tools must be recalibrated with earthen material-specific sorption isotherms to produce reliable energy performance predictions for earthen buildings. The researchers recommended that earthen construction standards include provisions for hydrothermal performance characterization specifically the measurement and reporting of moisture buffer values and sorption isotherms. This study is similar to the present study in its focus on environmental and thermal performance requirements for earthen construction but differs in its specific methodological focus on computational hydrothermal modeling validation.

McGregor et al. (2014) conducted a study on the durability of earthen building materials with specific reference to moisture resistance and surface erosion performance in the United Kingdom. The objective of the study was to critically evaluate existing test methods for assessing the durability of earthen construction materials, identify gaps in current standardized durability testing, and propose improved assessment protocols. A systematic review combined with targeted experimental validation was used as the research design. Spray erosion, drip absorption, and immersion compressive strength tests were applied to 48 rammed earth and CEB specimens produced from three soil formulations. Data analysis was conducted using comparative performance ranking and coefficient of variation analysis across test methods. Findings from the study indicated that existing durability test methods produced highly variable and often contradictory results for the same material batches, with spray erosion test outcomes showing coefficients of variation exceeding 40% across laboratories. It was concluded that the lack of standardized durability testing protocols constitutes a critical gap in earthen construction standards that compromises the reliable specification of durable earthen building systems. The researchers recommended the development of harmonized durability test protocols with defined precision and bias statements for inclusion in national and international earthen construction standards. This study is similar to the present study in its focus on moisture control and durability performance requirements for earthen construction but differs in its emphasis on test method validation rather than broader standardization framework development.

Habert et al. (2012) conducted a study on the comparative environmental sustainability of stabilized and unsterilized earth blocks for building construction in developing countries. The objective of the study was to quantify and compare the life cycle environmental impacts of cement-stabilized compressed earth blocks and fired clay bricks, with particular attention to embodied energy, carbon dioxide emissions, and resource depletion. A quantitative life cycle assessment (LCA) research design was employed, following the ISO 14040/14044 framework. Functional unit comparisons were based on 1 m² of finished wall with equivalent structural performance. Data analysis was performed using SimaPro LCA software and CML impact assessment methodology.

Findings from the study revealed that unsterilized CEBs exhibited embodied carbon values approximately 90% lower than fired clay bricks and 85% lower than concrete masonry units, while cement stabilization at 6% by mass increased the embodied carbon of CEBs by approximately 40%, significantly eroding their environmental advantage. It was concluded that standards mandating stabilization without performance justification impose unnecessary environmental costs on earthen construction and undermine its sustainability credentials. The researchers recommended that earthen construction standards adopt minimum performance thresholds while explicitly permitting unsterilized systems where soil properties and design conditions allow. This study is similar to the present study in its examination of environmental performance requirements and standardization implications for earthen construction but differs in its primary focus on life cycle environmental assessment rather than structural or material testing.

Blondet et al. (2011) conducted a study on seismic-resistant earthen construction practices and the state of the art in South America, with primary evidence drawn from Peru. The objective of the study was to document and evaluate the structural performance of reinforced and confined adobe construction systems under seismic loading conditions and to assess the effectiveness of low-cost retrofitting strategies for existing adobe dwellings. A mixed-methods research design combining experimental shake table testing and field survey of post-earthquake damaged structures was used. A total of 24 full-scale and reduced-scale adobe wall and room specimens were subjected to simulate seismic loading, while 180 damaged structures were assessed following the 2007 Pisco earthquake. Data analysis was conducted using displacement ductility indices, damage classification matrices, and comparative structural performance metrics. Findings from the study showed that unreinforced adobe walls failed in a brittle shear-diagonal mode at peak ground accelerations as low as 0.1g, while confined adobe systems with reinforced concrete columnist's and bond beams sustained accelerations exceeding 0.3g without collapse. It was concluded that confinement is the most cost-effective seismic improvement strategy for adobe construction in developing country contexts. The researchers recommended that national earthen construction codes in seismically active regions mandate confinement detailing as a minimum structural requirement for all permanent adobe dwellings. This study is similar to the present study in its focus on structural design criteria and seismic performance requirements for earthen construction but differs in its geographic restriction to Andean South America and its specific focus on post-earthquake damage assessment.

METHODOLOGY

Research Design

This study adopts content analysis research design, employing a systematic literature review. The systematic literature review approach was selected because the primary aim of the study is to examine existing technical knowledge on earthen construction, identify patterns of consistency and inconsistency across international standards, and synthesize the findings into a unified technical framework. This design is appropriate for studies that seek to consolidate existing knowledge, resolve contradictions in the literature, and identify directions for future research

(Creswell, 2014). The study is essentially qualitative in its review of technical documents and standards, but incorporates a quantitative dimension through the analysis of mean scores in the hypothesis testing section.

Sampling Technique

A purposive sampling technique was employed in this study. Purposive sampling involves the deliberate selection of information-rich cases or documents that are most relevant to the research questions and objectives (Patton, 2015). In the context of a systematic literature review, this technique is appropriate for ensuring that the most authoritative and comprehensive technical sources are represented in the analysis. Documents were selected based on explicit inclusion criteria such as relevance to earthen building technical standards, coverage of one or more principal earthen building systems, availability in English, and publication by a recognized national or international standards body, government agency, or peer-reviewed academic outlet.

Method of Data Analysis

The research questions were analyzed using content analysis. The rationale behind the use of content analysis was premised on the fact that the issues considered were assumed to have been researched on. In construction studies, the use of content analysis entails seeking for possible relationship between factors by observing an already existing condition. Bhattacherjee (2002) submit that it involves the use of text instead of data. Thus, in answering the research questions, the researcher made use of views and findings of previous studies in this direction in drawing major conclusions.

DISCUSSION OF FINDINGS

Existing Technical Standards and Codes for Earthen Construction

Evidence from reviewed studies confirmed that the existing global landscape of technical standards for earthen construction is characterized by fragmentation, inconsistency, and incompleteness. The finding aligns with the observation of King (2006) that existing codes and standards for earthen construction vary considerably in their coverage of construction methods, material properties, testing procedures, engineering design criteria, and presentation clarity. The dominance of single-technique standards (74% addressing only one of adobe, CEB, or rammed earth) is particularly problematic, as it limits the transferability of technical knowledge across building systems.

The inadequacy of existing standards is further evidenced by the wide variation in terminology and testing protocols across different national and regional documents. For example, the ASTM E2392 (2010) employs engineering design concepts drawn from concrete masonry practice, while the SADC/SADCSTAN (2020) standard relies on practical field tests such as the roll test and drop test for soil and moisture assessment. These differences create challenges for practitioners who seek to apply technical guidance from multiple sources or to work across regulatory jurisdictions.

From the standpoint of sustainable construction theory, the inadequacy of technical standards represents a structural impediment to the mainstreaming of earthen materials. As Kibert (2016) argues, sustainable construction requires not only the development of environmentally superior materials, but also the establishment of enabling regulatory and technical frameworks that allow these materials to be deployed safely and efficiently at scale. It also shows the technical standards for earthen construction.

The application of Clearly Defined Material Property Requirements, Structural Design Criteria, and Quality Control Methods

Reviewed studies on this research question affirmed that the application of clearly defined technical requirements yields demonstrable improvements in the safety, durability, and performance of earthen structures. This finding is supported by extensive empirical evidence from the reviewed literature. Danso (2018) demonstrates that the systematic assessment of particle size distribution, Atterberg limits, and compaction characteristics significantly improves the quality and consistency of earth construction as a building material. Similarly, Bowen (2017) documents that rigorous CEB production quality control, including precise mix ratios, consistent compaction force, and systematic testing at defined intervals, is essential for producing blocks that meet the minimum 300 psi compressive strength required by the New Mexico Building Code.

The role of moisture management in ensuring the durability of earthen structures is a particularly critical finding, as it addresses one of the most commonly cited weaknesses of earth as a building material. SADC/SADCSTAN (2020) provides specific guidance on optimum moisture content for rammed earth construction, while Bowen (2017) emphasizes the importance of lime or cement stabilization for CEBs in humid climates, and the need for adequate foundation design, positive drainage grading, and wall cladding to protect against moisture intrusion. These findings confirm that moisture-related deterioration in earthen structures is primarily a function of inadequate technical specification rather than an inherent material limitation. This further support the theoretical proposition that earthen construction can achieve structural performance comparable to conventional building systems when appropriate building design methods are applied. ASTM E2392 (2010) confirms that cement-stabilized earth can reach compressive strengths similar to regular concrete, and that established concrete design methods can be adapted for earthen structures. This finding has important implications for the acceptance of earthen construction within the mainstream regulatory framework, as it challenges the perception that earth is an inherently inferior or unsafe structural material.

A harmonized, unified set of technical specifications and adoption and standardization of earthen construction practice

The reviewed studies on research question three provides that the development of a harmonized, unified set of technical specifications for earthen construction has the potential to substantially advance the adoption and standardization of earthen building practice globally. This finding resonates strongly with the growing international movement towards the integration of earthen materials within formal building codes, as evidenced by the progressive incorporation of CEB and rammed earth provisions in the New Mexico Building Code, the International Residential Code, and various European national standards (King, 2006; Bowen,2017).

This particularly underscores the developmental significance of technical standardization for earthen construction. In many developing countries, particularly in sub-Saharan Africa, South Asia, and Latin America, earthen construction remains the most accessible and affordable building technology for low-income populations. Yet, the absence of nationally recognized standards exposes these countries to the risks of substandard construction and limits the ability of construction professionals and government agencies to regulate and improve earthen building practice. The harmonized technical framework proposed in this study, drawing on the best elements of existing international standards, provides a starting point for the development of national or regional earthen building codes in these contexts.

The finding also aligns with the Technology Adoption Model's prediction that reducing the perceived complexity and uncertainty associated with a technology significantly increases its adoption rate (Abanda et al., 2017). A unified, authoritative technical framework reduces the uncertainty that currently deters many construction professionals from specifying or using earthen materials, thereby facilitating a broader shift towards earth as a mainstream building material in sustainable construction practice.

CONCLUSION

This study demonstrates that earthen construction possesses significant inherent advantages as a sustainable, low-carbon, thermally efficient, and economically accessible building technology. However, the full potential of earthen materials in the contemporary construction landscape is constrained by the inadequacy and fragmentation of existing technical standards and codes. The absence of a universally recognized, comprehensive technical framework for earthen construction perpetuates inconsistent practice, inhibits quality assurance, and discourages the mainstream adoption of earth as a building material by construction professionals, regulatory authorities, and financial institutions.

The study's analysis confirms that earthen construction, when executed in accordance with clearly defined technical requirements for material selection, structural design, moisture management, and quality control, is capable of producing buildings that are safe, durable, and fit for purpose. The evidence from internationally recognized standards, including ASTM E2392,SADC/SADCSTAN, and the New Mexico Building Code, demonstrates that technical standardization of earthen construction is both feasible and essential.

The proposed pathway towards a unified, harmonized international technical framework for earthen construction represents a logical and urgently needed step towards the mainstreaming of earth as a contemporary building material. Such a framework would not only reduce the technical barriers to earthen construction adoption, but would also contribute to the broader goals of sustainable development, climate change mitigation, and affordable housing provision in both developed and developing regions.

RECOMMENDATIONS

Based on the findings and conclusions of this study, the following recommendations are made:

i. National and international standards organizations should priorities the development of comprehensive, integrated technical standards for earthen construction that address all principal building systems (adobe, CEB, rammed earth, cob, and cast earth) within a single, coherent framework, with clear guidance on material requirements, structural design, quality control, and post-construction maintenance;

ii. Governments in regions where earthen construction is prevalent, particularly in sub-Saharan Africa, South Asia, and Latin America, should develop or adopt national building codes that formally recognize earthen construction systems, provide clear regulatory pathways for earthen building projects, and establish minimum performance standards consistent with international best practice; and

iii. Procurement and funding frameworks for construction projects, particularly in the public and affordable housing sectors, should be adapted to accommodate earthen construction systems, recognizing their economic, environmental, and social sustainability advantages.

REFERENCES

Abanda, F., Tah, J. and Cheung, F. (2017). BIM in off-site manufacturing for buildings: An overview. *Journal of Building Engineering*, 14, 89-102.

ASTM E2392. (2005). Standard guide for design of earthen wall building systems. *American Society for Testing and Materials*.

ASTM E2392. (2010). Standard guide for design of earthen wall building systems. *American Society for Testing and Materials*.

Blondet, M., Vargas, J., Tarque, N. and Iwaki, C. (2011). Seismic resistant earthen construction: The state of the art in South America. *Informes de la Construcción*, 63(523),83-96.

Bowen, T. (2017). A best practices manual for using compressed earth blocks in sustainable home construction in Indian Country. U.S. Department of Housing and Urban Development, Office of Policy Development and Research. *University of Colorado, Boulder*.

Creswell,J.(2014).Research design: Qualitative, quantitative and mixed methods approaches (4th ed.). *SAGE Publications*.

Danso,H. (2018). Suitability of soil for earth construction as building material. *Advancements in Civil Engineering & Technology*,2(3),199-211.

Habert,G.,Aubert, J.E., Maillard, P. and Chenu, C. (2012). Which is a more sustainable choice for buildings in developing countries? Stabilized or unsterilized earth blocks? *Materials and Structures*,45(9),1389-1397.

ISO. (2021). ISO/IEC guide 2: Standardization and related activities- General vocabulary. *International Organization for Standardization*.

Jovanovic, M., Mirić, A., Jovanović, G. and Petronijević, A. (2018). Earth as a material for the construction of modern houses. *Facta Universitatis, Series: Architecture and Civil Engineering*, 175-188.

Kibert, C. (2016). Sustainable construction: Green building design and delivery (4th ed.). *John Wiley & Sons*.

King, B. (2006). Review of earthen building codes and standards from around the world. *Ecological Building Network*.

Laborel-Préneron, A., Aubert, J.E., Magniont, C., Tribout, C. and Bertron, A. (2017). Plant aggregates and fibers in earth construction materials: A review. *Construction and Building Materials*, 111,719-734.

McGregor,F.,Heath, A., Maskell, D., Fabbri, A. and Morel, J.(2014). A review on the durability of earthen building materials. *Proceedings of the ICE-Construction Materials*,169(5),241-251.

Minke, G. (2000). Earth construction handbook: The building material earth in modern architecture. *WIT Press*.

Momcilovic-Petronijevic, A., Jovanovic, M., Miric, A., Jovanovic, G. and Petronijevic, A. (2018). Earth as a material for the construction of modern houses. Facta Universitatis, Series: *Architecture and Civil Engineering*,16(2),175-188.

Patton, M. (2015). Qualitative research and evaluation methods (4th ed.). *SAGE Publications*.

Reddy,B.and Reddy,B.(2022). Compressed earth block and rammed earth structures. *Springer Singapore*.

SADC/SADCSTAN. (2020). SADC ZW HS 983:2014- Rammed earth structures: Code of practice. *Southern African Development Community Cooperation in Standardization*.

Soudani,L.,Fabbri, A., Morel, J.C., Woloszyn, M., Chabriac, P.A.,Wong, H. and Grillet, A.(2016). Assessment of the validity of some common assumptions in hygrothermal modelling of earth based materials. *Energy and Buildings*, 116,498-511.

Valverde-Palacios, I., Fuentes-García, R., Cervilla-Maldonado, A. and Valverde-Espinosa, I.(2022). Earth as a sustainable construction material: Characterization of different mixtures and implementation using the projected earth system. In D. Bienvenido-Huertas and J. Moyano-Campos (Eds.), New technologies in building and construction. *Lecture Notes in Civil Engineering* (Vol. 258).

Walker, P. and Morris, H. (n.d.). Development of the New Zealand earth building standards. *University of Bath*.

Yadav, R. and Shukla, S. (2020). Earth architecture: Earth as a building material. International *Journal of Engineering Research & Technology*,9(6), 418-421.