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Reviving the Oasis Heritage: Thermodynamic Analysis and Regulatory Bottlenecks of Contemporary Rammed Earth under the Scope of RPCT 2011

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Abstract

In response to the climate emergency, reviving vernacular building cultures is a critical paradigm. This paper investigates the transferability of vernacular architecture from Southern Moroccan oases—characterized by rammed earth (pisé) and high-density urban morphology (ksour)—into contemporary practice. While their bioclimatic efficiency is documented, a major gap remains regarding practical operationalization under modern industrial needs, the Moroccan Earthen Buildings Seismic Code (RPCT 2011), and market realities. Using triangulation, this research combines morpho-typological analyses in the Drâa and Ziz valleys, stakeholder field surveys (_n_ =24), and a meta-analysis of local geo-resources. Quantitative findings corroborate the thermodynamic superiority of optimized contemporary rammed earth (10– 12 hours thermal lag) and ksour morphology, which reduces global radiative load by 35%. However, a complex triple trade-off restricts the sector: strict altimetric limits (maximum R+1) under RPCT 2011, lack of insurance frameworks, and an economic distortion making optimized rammed earth 1.5 to 2 times more expensive than concrete due to labor intensity. Furthermore, life cycle assessment (LCA) shows that hydraulic binders compromise the material's initial ecological reversibility, while interviews highlight the fragility of this orally transmitted craft, which faces demographic extinction. Ultimately, the paper advocates for a technological hybridization strategy based on decentralized industrialization (prefabricated components), supported by normative updates and adapted public procurement frameworks to establish raw earth as a sustainable, sovereign, and economically viable pillar of architectural modernity in Morocco.

Keywords: *Construction costs, Contemporary rammed earth, Decentralized industrialization, Life cycle assessment, Seismic regulations (RPCT 2011), Socio-technical gap, Vernacular passive architecture*

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1. Introduction and Literature Review

1.1. Introduction and Global Contextualization

Confronting the triple challenge of abiotic resource depletion, systemic climate change, and the dominant carbon footprint of the construction sector, which alone accounts for nearly 40% of global greenhouse gas emissions (El Fgaier et al., 2023), the overhaul of building paradigms has become an epistemological urgency. Contemporary architecture, dominated by the standardized use of the cement-steel complex, has induced a metabolic rupture with its host territories. This has generated building typologies that are energetically dependent and disconnected from local microclimats (Odghiri & Mahdane, 2023). In arid and semi-arid regions, this industrial standardization proves particularly deleterious: it replaces building envelopes historically optimized for passive comfort with thermally pathogenic reinforced concrete structures, whose viability depends exclusively on massive reliance on active mechanical air conditioning (Azzaoui et al., 2023).

The earthquake of September 8, 2023, in the High Atlas (Al Haouz) serves as the starting point for a major reassessment of vernacular building frameworks in Morocco. By causing the collapse or severe degradation of nearly 60,000 homes, this catastrophe laid bare the structural vulnerability of a large portion of the traditional building stock made of raw earth masonry and unjointed stones. Post-crisis field expertises highlighted recurrent failures: poor quality of empirical binders, heterogeneity of geo-resources used without quality control, and the absence of horizontal ring beams or adequate connections between walls and roofs.

To avoid a systematic standardization through reinforced concrete, which is thermally unsuited to the extreme variations of mountainous and pre-Saharan zones, Morocco has committed to a vast reconstruction program (2024–2028) backed by a budget of 120 billion dirhams. National directives mandate the preservation of typological specificities and local architectural identity, effectively placing earth materials at the center of institutional debates. It is within this perspective of regulatory overhaul that the Moroccan Earthen Buildings Seismic Code (RPCT 2011) operates, approved by ministerial decree (Royaume du Maroc, 2012). Designed to lift raw earth out of the informal sector, this historic text currently clashes with its own theoretical and altimetric limitations when faced with urban densification needs.

Yet, beyond regulatory bottlenecks, the emergence of a modern raw earth sector faces a **major economic distortion** within the national construction market. Although the raw material is locally available and free to extract, implementing contemporary stabilized rammed earth requires high labor intensity and complex shuttering systems (Meziani, 2021). The direct cost of optimized formulations (low-carbon binders, lime, cement, plant fibers) combined with the inherent drying times of the material drives up the price per square meter, making contemporary rammed earth 1.5 to 2 times more expensive than conventional concrete block masonry. This

structural financial differential creates a paradox: earth materials find themselves economically excluded from mass social housing and confined to niche markets or elite tourist projects, even though they stem from a popular culture of subsistence economy.

1.2. Critical Literature Review

To overcome this socio-ecological crisis, a growing body of research in civil engineering and architecture is focusing on the rehabilitation and modernization of ancestral raw earth building cultures (Anger, 2012). Contemporary scientific literature addresses this material heritage from three main angles:

1.2.1. Intrinsique Hygrothermal Performance

The works of Koutous (2020) and Ouzaani (2024) have demonstrated, through numerical simulations and laboratory experiments, that rammed earth (compacted soil) possesses a volumetric heat capacity and thermal flow resistance that make it an exceptional passive regulator. Its porous behavior allows continuous wall perspiration, stabilizing indoor relative humidity within physiologically ideal ranges (Anger, 2012). The dynamics of mass and heat transfer under transient regimes generate an optimal thermal lag of 10 to 12 hours, drastically reducing energy consumption related to heating and cooling (Chérif & Belkadi, 2023).

1.2.2. Urban Morpho-Typological Analysis

At the human settlement scale, the seminal research by Zerhouni et al. (2001) highlighted the organizational genius of the *ksour* and *kasbahs* of Southern Morocco. This high-density urbanism, based on maximum morphological compactness and mutual self-shading of structures, successfully modifies the local public microclimate by limiting albedo and annihilating urban heat islands (Odghiri & Mahdane, 2023). The high compactness index of these traditional fabrics generates a proven reduction in the global radiative load of approximately 35% compared to modern discontinuous suburban developments (Odghiri & Mahdane, 2023).

1.2.3. Hybridization and Stabilization of Eco-Materials

To mitigate the intrinsic limitations of raw earth (water sensitivity, mechanical variability), recent research focuses on rationalizing its formulation. Azzaoui et al. (2023) investigated the incorporation of plant fibers (such as Alfa or date palm) to improve tensile strength and limit shrinkage cracking, while Madi (2025) validated physico-chemical stabilization protocols using hydraulic or low-carbon binders to normalize compressive strength (f_c) beyond the critical threshold of 2.5 MPa. However, Life Cycle Assessments (LCA) of these contemporary formulations are beginning to reveal a degradation of the material's initial perfect circularity: the addition of cement or lime irreversibly fixes the matrix, transforming demolished raw earth into an inert waste that cannot be immediately re-plasticized on site (Mansouri et al., 2024).

1.3. Identification of the Epistemological Gap (Research Gap) and Objectives

Despite the profusion of these sectoral data, the literature suffers from a marked disciplinary compartmentalization. A major epistemological gap persists between the thermal and physical validation of earth materials in laboratory settings and their practical operationalization within the large-scale contemporary construction sector. Very few studies simultaneously articulate the thermodynamic properties of rammed earth, the socioeconomic realities related to direct market costs (a 1.5 to 2-fold cost premium over concrete), the risk of permanent loss of strictly oral traditional know-how, and the seismic regulatory constraints of the RPCT 2011 code (Royaume du Maroc, 2012). In Morocco, this triple disconnection (technical, legislative, and financial) confines earth materials either to a museum-like logic of elite tourist conservation or to marginalized, uninsured rural self-construction (Soulé, 2025).

The objective of this contribution is to bridge this integration deficit by proposing a triangulated methodological model. This model systematically confronts:

- The physical performance and real life cycle of optimized contemporary rammed earth;
- The structural verification equations and altimetric limits imposed by the RPCT 2011 code;
- The direct economic production costs and the socio-technical vulnerability of the workforce gathered from the field.

This integrative approach aims to outline the scientific, legislative, and financial perspectives for a raw earth construction sector that is simultaneously sovereign, low-carbon, seismic-resistant, and economically competitive in Morocco.

2. Analysis Protocol for the Discussion Part: Cross-Examination Matrix

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To avoid a systematic standardization through reinforced concrete, which is thermally unsuited to the extreme variations of mountainous and pre-Saharan zones, Morocco has committed to a vast reconstruction program (2024–2028) backed by a budget of 120 billion dirhams. National directives mandate the preservation of typological specificities and local architectural identity, effectively placing earth materials at the center of institutional debates. It is within this perspective of regulatory overhaul and constructive sovereignty that the Moroccan Earthen Buildings Seismic Code (RPCT 2011) operates, approved by ministerial decree (Royaume du Maroc, 2012). Designed to lift raw earth out of the informal sector, this historic text currently clashes with its own theoretical and altimetric limitations when faced with urban densification, industrialization, and financial competitiveness needs.

To structure a rigorous discussion, we establish a cross-analytical framework in the form of a matrix. This matrix systematically confronts each validated technical performance with its corresponding regulatory, insurance, and economic bottlenecks, while formulating the required scientific and operational leverage strategy.

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Table 1. Analytical Triangulation Matrix Confronting Technical Performances with Regulatory and Socio-Economic Bottlenecks

Analysis Axis	Physical & Technical Data (The Potential)	Regulatory, Insurance & Economic Bottlenecks (The Constraint)	Scientific & Operational Leverage Strategy (The Solution)
Axis I: Altimetric Limitation and Urban Density	Optimized stabilized and fiber-reinforced rammed earth achieves compressive strengths (f_c) exceeding 2.5 MPa, theoretically compatible with R+3 structures under vertical loads (Koutous, 2020; Madi, 2025).	The RPCT 2011 code (Art. 5.2) imposes a strict altimetric height restriction of R+1 (maximum 7 meters) in moderate-to-high seismicity zones, preventing its use in dense urban areas.	Develop finite element models integrating hybrid structures (low-carbon concrete frames / rammed earth infill) or timber bracing cores, validated by shaking table tests (Ouzaani, 2024).
Axis II: Geo-resource Variability, Standardization and Costs	Wide availability of soils with optimal clay-silt fractions in the Haouz plains and Southern valleys, offering a zero initial carbon footprint (Ibnoussina, 2016).	The lack of certified National Professional Rules blocks structural insurance (ten-year guarantee). Implementing contemporary walls costs 1.5 to 2 times more than concrete due to labor intensity. Chemical stabilization alters LCA at end-of-life (Mansouri et al., 2024).	Draft a National Soil Characterization Guide based on granular and colloidal approaches (Anger, 2012). Integrate real life cycle assessments (crushing of inert stabilized aggregates) into financial models.
Axis III: Hygrothermal Comfort vs. Thermal Regulations	Thermal lag of 10 to 12 hours and passive hygrothermal inertia keeping the building within the comfort zone without active cooling (Anger, 2012; Ouzaani, 2024).	The Moroccan Thermal Building Regulations (RTCM) evaluate walls using a steady-state thermal transmittance coefficient, penalizing heavy walls and ignoring dynamic capacitive benefits.	Substitute the steady-state approach with a coupled transient Heat-Air-Moisture (HAM) Dynamic Thermal Simulation (DTS) methodology, incorporating simplified correction charts for practitioners (Chérif & Belkadi, 2023).
Axis IV: Know-how Transmission & Industrialization	Morpho-typological analysis proves the centuries-old resilience of manual shuttering and tamping techniques (Zerhouni et al., 2001).	Demographic erosion of a skilled workforce relying on strictly oral and informal transmission. High labor surcosts and tamping defects critical for seismic safety (Youbi, 2024).	Transition toward decentralized industrialization: on-site or workshop prefabrication of Compressed Earth Blocks (CEB) or mechanically pre-compacted rammed earth macro-panels under rigorous digital control.

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2.1. Critical Synthesis of the Analytical Triangulation: Toward a Constructive Paradigm for Contemporary Rammed Earth

Axis I: The Altimetric Contradiction in Seismic Zones: Structural Modeling vs. Public Safety Imperatives

The mechanical characterization of contemporary stabilized and fiber-reinforced rammed earth formulations has revealed remarkable performance, with uniaxial compressive strength (f_c) breaking through the critical threshold of 2.5 MPa (Koutous, 2020; Madi, 2025). From a pure vertical load descent perspective, this load-bearing capacity is amply sufficient to consider residential or commercial typologies up to R+3 (Madi, 2025). Nevertheless, the transition from laboratory theory to dense urban application runs into a major regulatory barrier: the Moroccan Earthen Buildings Seismic Code (RPCT 2011). By strictly limiting the height of earthen buildings to an R+1 level, representing a physical ceiling of seven meters (RPCT 2011, Art. 5.2), the legislature neutralizes the applicability of this material in high-population density areas where vertical densification is a land and economic necessity.

To provide nuance to this confrontation, it is crucial to analyze the physical foundations of this restriction. Rammed earth, even stabilized, remains a high-density material with very low intrinsic tensile and shear strength (Ouzaani, 2024). Under transient seismic loads, horizontal accelerations generate overturning moments and shear stresses that monolithic rammed earth struggles to dissipate without major structural disorganization. Consequently, the strategy to bypass this roadblock cannot rely solely on over-engineering the compressive strength (f_c). The solution lies in abandoning the pure load-bearing wall model in favor of structural hybridization (Ouzaani, 2024; Tarik, 2023). By coupling rammed earth with a primary or secondary frame made of timber or low-carbon concrete designed to handle global lateral bracing, the sector can bypass the R+1 threshold. However, justifying the feasibility of such multi-story hybrid structures cannot rely solely on vertical load-bearing capacity. The immediate scientific challenge consists of accurately modeling and governing the complex kinematic and mechanical interactions at the interfaces between the rigid skeleton and the raw earth infill. Under seismic excitation, this boundary zone dictates in-plane shear transfer, out-of-plane overturning stability (which necessitates dedicated mechanical anchoring systems) and localized stress concentrations at frame joints induced by equivalent diagonal strut action (Miccoli et al., 2014; El Gharbi & Amrani, 2022).

Addressing these critical mechanisms requires advanced nonlinear numerical modeling frameworks to capture the progressive degradation of interfacial stiffness and global ductility under cyclic lateral loading. Specifically, finite element modeling (FEM) incorporating cohesive zone models (CZM) and frictional contact laws based on the Mohr–Coulomb failure criterion enables the simulation of interfacial sliding, joint opening, and hysteretic energy dissipation prior to full-scale validation through complex dynamic shaking table tests (Miccoli et al., 2015; Nowamooz & Chazallon, 2011; Ouzaani, 2024).

Furthermore, the long-term structural integrity of these hybrid systems requires accounting for time-dependent and hygrothermal phenomena. Differential thermal expansion and, more critically, drying shrinkage of the rammed earth panels relative to the confining frame can trigger premature interfacial debonding and parasitic internal stresses (Hall & Allinson, 2009; Beckett & Ciancio, 2014). Coupled thermo-hydro-mechanical (THM) simulations, paired with engineered constructive solutions such as compressible isolation joints or controlled sliding connections, therefore represent a vital prerequisite for ensuring sustained composite action and securing final approval by technical control bureaus (El Gharbi & Amrani, 2022; Ouzaani, 2024).

Axis II: The Internal Paradox of the Geo-Resource: Local Ecological Potential vs. Financial Realities and Post-Stabilization Boundaries

On environmental and geological levels, the Haouz plains and pre-Saharan zones of Southern Morocco possess a sedimentary deposit of exceptional quality (Ibnoussina, 2016). The clay-silt fraction naturally exhibits a grain-size distribution and mineralogy suitable for tamping, guaranteeing a short-supply chain with a near-zero initial carbon footprint (Ibnoussina, 2016; Meziani, 2021). However, the insurance and technical control sectors are structured around the paradigm of perfect reproducibility inherited from Eurocodes and standardized binders. The inherent variability of local geo-resources represents a risk factor deemed unacceptable by controllers. This normative vacuum prevents the underwriting of structural defects by ten-year insurance policies, blocking large-scale investments.

The evaluation of contemporary rammed earth also suffers from a major economic distortion in the Moroccan market. Although the raw material itself is free, its implementation through contemporary stabilized rammed earth generates labor and shuttering costs significantly higher than those of the concrete block sector. In Morocco, the price per square meter of an optimized rammed earth wall can be 1.5 to 2 times higher than equivalent conventional masonry, confining this material to eco-tourism niche markets rather than mass social housing.

Furthermore, the material's life cycle assessment (LCA) must be qualified by its end-of-life realities. Unstabilized ancestral rammed earth offers perfect circularity: it returns 100% to the ecosystem via simple erosion. Conversely, incorporating 3% to 4% cement or lime into contemporary formulations shatters this reversible metabolisme. Irreversible chemical hydration turns demolished rammed earth into an inert solid aggregate. Consequently, the material loses its capacity for immediate on-site re-plasticization and must be treated as conventional demolition waste, requiring energy-intensive mechanical crushing to be downcycled as road sub-base layers or backfill aggregates (Mansouri et al., 2024; Meziani, 2021).

Axis III: The Asymmetry of Hygrothermal Evaluation: Steady-state Modeling vs. Molecular Dynamics of the Material

The analysis of the thermophysical properties of rammed earth highlights a glaring gap between the real behavior of buildings and their regulatory transcription. Academic literature agrees on the excellence of raw earth envelopes, which generate a thermal lag oscillating between 10 and 12 hours while passively regulating indoor relative humidity (Anger, 2012; Chérif & Belkadi, 2023; Ouzaani, 2024). This phenomenon ensures remarkable adaptive comfort conditions, drastically reducing energy consumption for heating and cooling (Chérif & Belkadi, 2023). Paradoxically, the Moroccan Thermal Building Regulations (RTCM) heavily penalize these walls. By relying exclusively on a steady-state calculation model, regulations evaluate rammed earth solely through its dry thermal conductivity. Due to its high density, earth displays a mediocre intrinsic thermal resistance compared to lightweight synthetic insulation, leading regulatory software to declare rammed earth non-compliant.

Nuancing this observation implies admitting the systemic limitations of the current regulatory framework. Rammed earth does not behave like a passive insulating material, but as a dynamic and capacitive thermodynamic system. It stores latent heat flows through continuous adsorption and desorption cycles of moisture within its macromolecular pores (Anger, 2012; Mansouri et al., 2024). To do justice to this performance, substituting steady-state calculation methods with coupled transient Heat-Air-Moisture (HAM) Dynamic Thermal Simulation (DTS) protocols is vital. However, from an operational perspective, generalizing DTS poses a challenge regarding skills and financial accessibility for most local architectural firms (Tarik, 2023). To lift this bottleneck, scientific efforts must focus on producing simplified decision-making tools: transient thermal correction charts and weighted inertia coefficients easily integrable into standard regulatory software, allowing designers to simulate heavy walls' real impact without over-complicating their workflow (Chérif & Belkadi, 2023; Meziani, 2021).

Axis IV: The Socio-Technical Gap of the Workforce and the Fragility of Empirical Qualitative Data

The heritage dimension of earth construction in Morocco historically relies on the empirical skills of corporations of master artisans (*Maâlems*) (Zerhouni et al., 2001). However, field fieldwork highlights a critical methodological and human vulnerability: the transmission of this millenary know-how remains strictly informal, purely oral, undocumented, and ultra-localized within the Drâa and Ziz valleys. This geographical and generational shrinkage of knowledge explains the immense difficulty in identifying valid respondents during our field campaign. It required long weeks of prospection and local intermediation before stabilizing contact with only two active master artisans who agreed to share the reality of their practice.

The field interviews force a definitive break from an idyllic or museum-like view of vernacular construction, revealing a systemic abandonment driven by economic imperatives and modern comfort expectations. The rejection of the material by new generations of local builders and contractors articulates around three main divides: maintenance labor burden, the collapse of local demand, and financial precarity.

Firstly, the domestic labor burden related to wall maintenance pushes builders toward standardized industrial materials. Brahim, a 33-year-old mason operating in the valley, summarizes this sociological shift perfectly:

> *"As soon as someone has money, they look to build with concrete blocks, because it is secure against bad weather, you don't have to maintain it after every rain. It's clean and you are not forced to live in dust every single day."*

This quest for modernity is accompanied by a radical market transformation, where rammed earth is no longer financially viable unless integrated into elite, globalized, or tourist networks far out of reach for isolated local craftsmen. Hassan, a 51-year-old *Maâleme*, describes this structural shift:

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> *"If you don't have a good address book and the means to travel everywhere, you won't survive. Orders usually come from people wanting to build guest houses, or special requests from very far away. People here in the south-west don't want to live like before and local orders are almost non-existent. You need major capital and a specific taste to even think about building your home with earth or using earth as a material in your house."*

Finally, the most alarming finding lies in the categorical refusal of the last guardians of this building culture to pass their trade down to their children, sentencing the sector to imminent demographic extinction unless industrialization steps in. Assou, a 42-year-old *Maâleme*, expresses this economic disenchantment:

> *"There is no interest in traditional building here, and orders are rare. What opportunities we get are seasonal, and I am forced to rely on what I grow in my fields and on local cement brick construction sites. This field won't sustain you; there is zero interest from the arriving generations for this trade, and I am definitely not going to advise my own son to enter it."*

These direct qualitative insights demonstrate that saving rammed earth cannot occur through simple moral injunctions for heritage conservation. To reconcile the lived experience of residents and conservation goals, the sector must break free from the labor intensity and uncertainty of traditional building sites (Youbi, 2024). A transition toward decentralized industrialization (compressed earth blocks or prefabricated macro-panels) emerges as the ideal technical response. It rationalizes labor time for contractors while integrating the qualitative expertise of *Maâlems* within semi-mechanized and controlled local production units, capable of guaranteeing the uniform (f_c) values required by the RPCT 2011 code without alienating workers.

2.2. Sampling and Qualitative Field Approach

Empirical data collection relied on a **four-day** intensive field campaign of semi-structured interviews conducted with twenty-four ($n = 24$) key stakeholders across the Drâa and Ziz valleys. The sample was rigorously stratified to cross-reference technical, heritage, financial, and sociological perspectives on the contemporary use of rammed earth. Interviews were conducted in the participants' two vernacular languages, **Moroccan Arabic (Darija)** and **local Tamazight**, to ensure linguistic spontaneity and semantic accuracy, particularly regarding traditional building terminology. The typology of respondents is structured as follows:

Table 2. Stratified Socio-Technical Sampling and Stakeholder Typology within the Drâa and Ziz Valleys

Stakeholder Category	Sample Size (n)	Profile and Representativeness	Reference Code
Traditional Know-how	2	*Maâlemine* (Master artisans), guardians of oral empirical rules of the craft.	MS-01 to MS-02
Local Construction Sector	4	Local small contractors and masons, active in conventional modern masonry.	TC-01 to TC-04
Vernacular Governance	3	Representatives of the *Ksour* (including 1 woman), local decision-makers.	RK-01 to RK-03
Civil Society & Activists	9	NGO members (5 women, 4 men) actively engaged in architectural heritage safety.	MA-01 to MA-09
Users / Citizens	6	Residents of ancient *Ksour* (living in moderately to severely degraded buildings).	HB-01 to HB-06

Interview Protocol and Qualitative Analysis

The semi-structured interview guide was organized around four core thematic axes: (1) perceptions of the technical performance and durability of rammed earth against climatic and seismic hazards; (2) economic, land-tenure, and regulatory bottlenecks affecting rehabilitation; (3) the transmission of vernacular craftsmanship and skilled labor availability; and (4) social acceptability and contemporary housing aspirations.

All interviews were audio-recorded with informed consent, verbatim transcribed, and translated with cross-verification of vernacular architectural terms. The textual corpus was subsequently examined using thematic content analysis (Braun & Clarke, 2006), employing a hybrid coding strategy that combined deductive codes derived from the interview guide with inductive codes capturing emergent field realities. Furthermore, data collection was governed by the principle of thematic saturation: sampling concluded at ($n = 24$) once additional interviews within the primary stakeholder subgroups ceased to yield novel analytical insights, thereby ensuring the empirical robustness and internal validity of the findings.

3. Historical Context and Technical Analysis of Formulations

3.1. Historical Context and Vernacular Climate Engineering

The architecture of *ksour* and *kasbahs* in the pre-Saharan territories of Morocco represents the ultimate expression of an engineering of subsistence. Subjected to extreme diurnal-nocturnal temperature fluctuations and structural water stress, oasis communities configured a high-density urban morphology characterized by optimized compactness. Narrow, frequently covered horizontal pathways (*saba*) transcend simple defensive or socio-spatial segregation functions; they operate as authentic active microclimatic devices, minimizing the exposure of building envelopes to direct solar radiation and maximizing cooling via the mutual self-shading of walls.

At the building scale, the exclusive exploitation of local geo-resources and bio-resources, raw earth implemented as rammed earth or sun-dried adobe bricks, date palm stipes for horizontal structural elements, and reeds for floor assemblies, materializes a holistic integration into ecosystemic cycles. Rammed earth, through its high bulk density and volumetric heat capacity, dampens and delays desert heat fluxes, maintaining indoor environments within the boundaries of the homeostatic comfort zone without reliance on active energy systems. Nevertheless, this empirical equilibrium is undergoing severe destabilizing pressures. The dominant introduction of reinforced concrete and industrial concrete blocks into

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oasis ecosystems, falsely associated with vectors of modernity and socio-economic advancement, has ruptured this thermal homeostasis, generating thermally pathogenic building typologies completely reliant on energy-intensive, uninterrupted artificial air conditioning.

While the climatic performance of oasis builders provides historical validation for the efficacy of passive architecture, the simple mimetic or nostalgic replication of these typologies clashes with contemporary economic, normative, and construction contingencies. The transition from a contextualized empirical model to a reproducible and industrializable architectural practice requires overcoming the sterile dichotomy between *low-tech* approaches (manual raw earth craftsmanship) and *high-tech* systems (reinforced concrete, active fluids). The revitalization of this material heritage lies not in evicting modernity, but in a reasoned technological hybridization strategy. It is essential to infuse advanced material science tools, such as physico-chemical binder stabilization, mechanized component prefabrication, and dynamic thermal simulation (DTS), into this millenary material matrix (Hernandez, 2014; Madi, 2025).

This technological convergence is capable of standardizing the mechanical properties of rammed earth while preserving its intrinsic hygrothermal and breathable attributes (Koutous, 2020). Consequently, the descriptive analysis of *ksour* undergoes an epistemological paradigm shift: it transitions away from mere heritage conservation to become a catalog of future-oriented technical solutions, apt to inspire new eco-responsible construction standards in Morocco while integrating the imperative of cost competitiveness on the free market (Meziani, 2021; Odghiri & Mahdane, 2023).

3.2. Detailed Methodology

To scientifically evaluate the transferability potential of the oasis model to contemporary architectural praxis, our methodological protocol deploys an analytical triangulation combining morpho-typological analysis, qualitative field surveys, and normative physical characterizations.

Firstly, the architectural and sociological phase focused on case studies of several representative structures located within the Drâa and Ziz river basins (Zerhouni et al., 2001). A field campaign using semi-structured interviews was deployed among a stratified sample of residents ($n = 24$) of traditional *ksour* and local practitioners. This allowed the collection of qualitative empirical data regarding perceived indoor thermal comfort, spatial usage dynamics, and the determinants behind abandoning earth construction for concrete systems. Particular attention was paid to the verbatims of local craftsmen and builders to assess the socio-technical gap related to implementation costs, maintenance constraints, and the difficulties of oral trade transmission.

Secondly, the technical phase consisted of a meta-analysis of the thermophysical and mechanical properties of earthen materials (traditional rammed earth and stabilized compressed earth blocks) documented in recent civil engineering literature in Morocco (Azzaoui et al., 2023; El Fgaier et al., 2023; Ibnoussina, 2016). These physical quantities were systematically confronted with the performance thresholds required by the Moroccan Thermal Building Regulations (RTCM).

Finally, operational implementation was assessed through a critical analysis of the structural calculation equations and mechanical resistance criteria (f_c) imposed by the Moroccan Earthen Buildings Seismic Code (RPCT 2011) within moderate-to-high seismicity zones (Royaume du Maroc, 2012). This structural review was expanded to include market financial variables (cost per square meter) and real lifecycle impacts under a full life cycle assessment (LCA) framework.

3.3. Synthesis Table of Formulation Properties

This table reorganizes consolidated experimental and theoretical data (Azzaoui et al., 2023; Koutous, 2020; Madi, 2025) to accurately characterize the impact of physical and chemical innovations on the ancestral raw earth matrix.

3.4. Extended Comparative Analysis: Quantitative Evaluation of Innovative Formulations vs. Conventional Benchmarks

3.4.1. The Mechanical Spectrum: Compressive Strength Evaluation and Seismic Code Constraints

The quantitative characterization of the different constructive matrices reveals a clear stratification of mechanical performances, marking a distinct rupture between ancestral rammed earth and optimized contemporary formulations (Azzaoui et al., 2023; Koutous, 2020; Madi, 2025). The control ancestral rammed earth displays a compressive strength (f_c) ranging from 0.8 to 1.2 MPa. This intrinsic weakness, combined with extreme vulnerability to moisture ingress and structural heterogeneity, justifies the historical reluctance of control bureaus and explains the severe restrictions imposed by the RPCT 2011 code (El Gharbi & Amrani, 2022).

Conversely, the introduction of low-carbon stabilizers (4% hydraulic lime NHL 3.5) drives the target strength into a range of 1.8 to 2.3 MPa while securing excellent durability against rainfall. This mechanical advancement reaches its peak with the optimized fiber-reinforced rammed earth formulation (containing 0.5% doum palm fibers and 3% cement), whose ultimate compressive stress (f_c) achieves 2.1 to 2.6 MPa. These values fully validate theoretical predictions of behavioral stability under pure vertical dead loads for medium-rise structures (Madi, 2025).

However, a nuanced reading of these physical data prevents drawing a direct parallel with conventional concrete benchmarks, which develop compressive strengths between 25.0 and 30.0 MPa. Although optimized fiber-reinforced rammed earth technically unlocks compliance at the R+1 level due to enhanced seismic ductility induced by the distributed plant fiber reinforcement network, it remains structurally distinct from the orders of magnitude of reinforced concrete (Azzaoui et al., 2023; Ouzaani, 2024). Attempting to force rammed earth to match concrete performance through aggressive chemical stabilization would be a profound scientific error. Overloading the mix with hydraulic binders deeply alters the material's nature, causing brittle failure mechanisms incompatible with the absence of conventional steel rebar configurations. Consequently, lifting altimetric height restrictions does not depend on a race toward raw (f_c) values, but rather on exploiting this 2.5 MPa range within well-regulated structural hybridization systems (Tarik, 2023).

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Table 3. Physico-Mechanical and Thermophysical Properties of Earthen Formulations compared to Conventional Concrete Benchmarks

Formulation Designation	Composition / Stabilization Rate	Soil Matrix, Particle Size Distribution & Curing Conditions (Testing Parameters)	Target Compressive Strength (f_c) (MPa)	Thermal Conductivity (λ) (W/m.K)	Vapor Resistance Factor (μ)	Initial Embodied Energy (kWh/m³)	Estimated Direct Cost per m² (40 cm wall)	Initial Compliance & Regulatory Framework
Ancestral Rammed Earth (Control)	Raw on-site soil (0% additives)	Soil: Gravelly-sandy (GTR A1/B5). Grading: 15–20% clay/silt (predominantly illite/kaolinite), 50% sand, 30% gravel. Curing: Air-drying (20°C, 50% RH), 28 days, $W_{opt} \approx 9–11\%$	0.8 to 1.2	0.75 to 0.85	5 to 8	15 to 30	Reference Base (Low material cost)	Limited by RPCT 2011 (Water-sensitive, high statistical dispersion)
Low-Carbon Stabilized Rammed Earth	Soil + 4% Hydraulic lime (NHL 3.5)	Soil: Amended sandy-clay (PI = 10–15). Gradation: 18–22% reactive clay fines (illitic/kaolinitic fraction). Curing: Controlled moist curing (20°C, RH > 90% for 7 days, followed by ambient conditions), 28–90 days. $W_{opt} \approx 10–12\%$	1.8 to 2.3	0.90 to 1.00	10 to 12	120 to 150	+ 45% to 60% vs. control	Compliant with R+1 limits (Excellent water and durability resistance)
Optimized Fiber-Reinforced Rammed Earth	Soil + 0.5% Palm fibers + 3% Cement	Soil: Sandy-gravelly, with low plasticity (PI < 10). Grading: 12–16% fines (predominantly kaolinite), with added fibers (L = 20–30 mm). Curing: 7 days under plastic sheeting, followed by 28 days in ambient air (20°C, 50% RH), $W_{opt} \approx 12–13\%$	2.1 to 2.6	0.80 to 0.90	8 to 11	180 to 220	+ 70% to 90% vs. control	Compliant with R+1 limits (Enhanced seismic ductility)
Conventional Concrete (Ref.)	Portland Cement CEM I (350 kg/m³)	Matrice : Granulats alluvionnaires concassés (0/20 mm), rapport E/C ≈ 0,50. Cure : Normative en eau / chambre humide (20 °C, HR ≥ 95 %), 28 j.	25.0 to 30.0	1.70 to 2.50	Waterproof (Out of range)	1500 to 2000	Standard Market Reference	Non-applicable under RPCT / Governed by NM & Eurocodes (No height limits)

Methodological Note on Cross-Study Comparability: The comparative properties compiled in this table are synthesized from distinct experimental campaigns involving inherently variable raw soil matrices. To ensure rigorous benchmarking, the reported performance ranges correspond to reference soils falling within standard grading envelopes for rammed earth (clay-silt fraction between 12% and 22%, plasticity index PI < 15, compacted near optimum moisture content (W_{opt}). Nevertheless, the efficiency of chemical stabilization, particularly with natural hydraulic lime (NHL 3.5), is strongly governed by clay mineralogy. Kaolinite-dominated clays exhibit rapid initial setting but limited pozzolanic reactivity, whereas illitic fractions promote progressive cementitious hydrate formation (C-S-H and C-A-H) over extended curing periods (28 to 90 days). Conversely, expansive smectite clays (such as montmorillonite) increase compaction water demand, exacerbate drying shrinkage, and can inhibit strength gain unless binder dosages are adjusted (Walker, 1995; Ciancio et al., 2014; Rojat et al., 2020). Accordingly, these values represent comparative benchmarks tailored to low-expansivity gravelly-sandy soils typical of arid and semi-arid Moroccan regions.

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3.4.2. The Thermophysical Dilemma: Conductivity and Vapor Permeance of Building Envelopes

The cross-examination of thermophysical properties highlights the engineering trade-offs linked to stabilizing granular media. Ancestral rammed earth exhibits a highly favorable thermal conductivity (λ) oscillating between 0.75 and 0.85 W/m.K, coupled with a remarkably low vapor resistance factor (μ) between 5 and 8. These indicators translate to maximum open porosity, which is optimal for coupled heat and mass transfer and effective passive hygrothermal regulation (Anger, 2012).

In contrast, low-carbon stabilized rammed earth undergoes a degradation of its insulation properties, with its thermal conductivity rising to a zone between 0.90 and 1.00 W/m.K. This phenomenon stems from the densification of the sedimentary matrix caused by lime carbonation and hydration, which reduces insulating air pore volume in favor of a more conductous solid phase (Mansouri et al., 2024). The vapor resistance factor nearly doubles, establishing itself between 10 and 12, thereby restricting the natural breathability and moisture transit through the wall.

This modification of hygrothermal performance must be analyzed in light of the requirements of the Moroccan Thermal Building Regulations (RTCM). The optimized fiber-reinforced formulation succeeds in mitigating this thermophysical drift: the incorporation of palm fibers, characterized by a very low intrinsic conductivity, partially offsets the densifying effect of the 3% cement addition, maintaining thermal conductivity between 0.80 and 0.90 W/m.K and the vapor resistance factor between 8 and 11. Comparatively, conventional concrete acts as a highly conductive thermal screen (1.70 to 2.50 W/m.K) that is entirely vapor-tight. Thus, while the chemical stabilization indispensable for parasismic safety slightly reduces the breathability and insulation properties of raw earth, contemporary rammed earth maintains an overwhelming thermophysical superiority over concrete structures. These nuances reinforce the necessity of abandoning steady-state thermal calculation methods in favor of transient dynamic models capable of capturing these sub-molecular variations (Chérif & Belkadi, 2023).

3.4.3. The Environmental Balance: Embodied Energy as the Technology Arbitrator

Introducing initial embodied energy as a primary indicator allows a decisive environmental arbitration between constructive options. Ancestral rammed earth embodies the ecological optimum with an exceptionally low energy expenditure, between 15 and 30 kWh/m³, attributable solely to manual extraction and on-site implementation phases. The addition of hydraulic binders inevitably induces a higher energy toll due to industrial calcination processes of lime and cement. Low-carbon stabilized rammed earth generates a consumption of 120 to 150 kWh/m³, while the optimized fiber-reinforced formulation

rises to a value of 180 to 220 kWh/m³, reflecting the heavy carbon footprint of Portland cement, even at a low dose.

However, these quantitative increases must be contextualized within a complete Life Cycle Assessment (LCA) framework. Compared to the 1500 to 2000 kWh/m³ required to manufacture standard reference concrete, optimized earthen formulations represent an embodied energy saving of 85% to 90%. The initial energy investment required to stabilize rammed earth (180 to 220 kWh/m³) is largely offset by the structural safety gains and the enhanced durability of the material, which mitigates early structural degradation risks (Azzaoui et al., 2023; Meziani, 2021).

However, a major environmental dilemma emerges when expanding the Life Cycle Assessment (LCA) system boundaries from a conventional "cradle-to-gate" scope (modules A1–A3) to a comprehensive "cradle-to-grave" (incorporating deconstruction and end-of-life waste processing, modules C1–C4) or "cradle-to-cradle" framework (module D). While unstabilized reference rammed earth offers closed-loop circularity by reverting to reusable raw soil through simple plastic rehydration, the incorporation of conventional hydraulic binders (Portland cement or hydraulic lime) disrupts this reversible metabolism. Irreversible hydration and carbonation reactions transform demolished rammed earth into an inert solid conglomerate that loses its capacity for immediate on-site re-plasticization. Consequently, at end-of-life, the material must be managed as conventional construction and demolition waste, requiring energy-intensive mechanical crushing to be downcycled into road sub-base or fill aggregates (Mansouri et al., 2024; Meziani, 2021).

To resolve this trade-off between mechanical performance and circularity, emerging research explores alternative stabilizers capable of lowering the carbon footprint while preserving matrix recyclability. On the one hand, alkali-activated binders and geopolymers (derived from metakaolin or industrial by-products such as slags) substantially reduce embodied CO_2 emissions compared to Portland cement while achieving high compressive strengths (Cristelo et al., 2012; Provis & Bernal, 2014); nevertheless, the formation of a rigid aluminosilicate gel still results in irreversible lithification, restricting closed-loop soil recovery. On the other hand, bio-based stabilizers, including biopolymers (such as xanthan gum, sodium alginate, and chitosan), tannins, and casein, present a promising pathway to balance mechanical stabilization, low embodied energy, and controlled moisture-induced reversibility or biodegradability, thereby enabling end-of-life re-plasticization without generating inert mineral waste (Chang et al., 2016; Losini et al., 2021).

3.4.4. Synthetic Analysis of Approval Tracks and Industrial Integration

Cross-examining regulatory compliance criteria and economic constraints reveals the separate pathways these formulations must take to integrate into modern construction workflows. Ancestral rammed earth is trapped in an operational impasse. Its restricted initial compliance under the RPCT 2011 code, dictated by its vulnerability to water ingress and high statistical dispersion, condemns it to remain a marginal material, limited to heritage restoration or uninsured rural self-building. On the other end, conventional concrete enjoys a complete, standardized normative ecosystem (NM / Eurocodes) and highly optimized production costs, but at the cost of an environmental footprint that has become unsustainable.

The genuine technological breakthrough occurs within the two intermediate formulations (stabilized low-carbon and optimized fiber-reinforced rammed earth) which both secure validated compliance for R+1 typologies. However, their market uptake runs into a major financial distortion: the intense labor required for traditional manual shuttering and the complexity of tamping rigs make these contemporary walls 1.5 to 2 times more expensive per square meter than local concrete block masonry (Meziani, 2021).

To overcome the current structural insurance vacuum and these prohibitive manual surcosts, the sector must transition toward decentralized industrialization (Youbi, 2024). The fiber-reinforced cement formulation, with its superior parasismic ductility, emerges as the primary candidate for on-site or workshop prefabrication of Compressed Earth Blocks (CEB) or mechanically pre-compacted rammed earth macro-panels. Fabricating components under rigorous quality control stabilizes the (f_c) value, slashes on-site drying times, and drastically reduces labor hours, thereby delivering a reproducible, insurable, and economically competitive alternative to the monopoly of conventional reinforced concrete frames (El Gharbi & Amrani, 2022; Tarik, 2023).

3.5. Deepened Results and Technical Analysis

The quantitative analysis of physical properties highlights the thermodynamic superiority of oasis eco-materials over conventional industrial baselines. Characterizing contemporary rammed earth, optimized through controlled grain-size distribution and low binder additions, reveals insulation and inertia capabilities that no classical concrete block wall assembly can replicate without additional synthetic insulation layers (Anger, 2012; Koutous, 2020).

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Table 4. Comparative Analysis of Technical and Environmental Indicators: Contemporary Rammed Earth vs. Conventional Reinforced Concrete

Performance Indicators	Contemporary Rammed Earth / Raw Earth (Stabilized/Fiber-Reinforced)	Conventional Reinforced Concrete (Portland Cement Benchmark)	Impact on Comfort, Design, and Economics
Thermal Conductivity (λ)	0.8 to 1.1 W/m.K (Low)	1.7 to 2.5 W/m.K (High)	Rammed earth limits direct heat transfer, reducing active air-conditioning loads (Chérif & Belkadi, 2023).
Thermal Lag (40 cm thickness)	10 to 12 hours (Excellent)	4 to 6 hours (Insufficient)	Allows nocturnal release of stored diurnal solar heat, which is ideal for pre-Saharan climates.
Hygrometric Regulation	Excellent (Breathable/perspirant material, naturally regulates relative humidity)	Null (Vapor-tight material, requires continuous mechanical ventilation)	Ongoing enhancement of indoor air quality and sensory comfort parameters (Anger, 2012).
Embodied Energy (Manufacturing)	Approx. 100 to 300 kWh/m³ (Very low if extracted on site)	Approx. 1500 to 2000 kWh/m³ (Very high)	Drastic reduction in the building's initial carbon footprint.
Lifecycle & Recyclability	Reversibility compromised by binders (Generates inert aggregates, non re-plasticizable)	Low (Generates non-biodegradable debris, complex downcycling)	Needs mechanical crushing at end-of-life, altering raw earth's initial circular profile (Mansouri et al., 2024).
Direct Construction Cost per m²	High (1.5 to 2 times more expensive than concrete due to labor intensity)	Standard Baseline (Fully optimized and mastered by local supply chains)	Financial surcost excludes rammed earth from mass social housing, restricting it to elite developments (Meziani, 2021).
Regulatory Framework (Morocco)	Governed by RPCT 2011 (Strict R+1 height limitations in seismic zones, specific (f_c) requirements)	Governed by NM / Eurocodes (No standard height restrictions)	Reinforced concrete remains structurally favored by insurance companies and control bureaus (El Gharbi & Amrani, 2022).

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3.5.1. Analysis of Thermal Inertia and Seasonal Bioclimatic Regulation

The data compiled in Table 1 elucidate the physical determinants of thermal comfort in oasis environments while underscoring the necessity of a seasonally differentiated bioclimatic strategy. Under summer conditions, the moderate thermal diffusivity of the rammed earth matrix ($\lambda \approx 0.80$ W/m.K) coupled with high specific heat capacity effectively retards the propagation of the exogenous heat wave. Combined with a 40 cm wall thickness, this thermal mass induces an optimal phase shift (time lag) of 10 to 12 hours alongside a substantial decrement factor (Hall & Allinson, 2008). Phenomenologically, the peak diurnal heat flux (frequently exceeding 40 °C) reaches the interior wall surface only during the middle of the night, enabling efficient heat dissipation via passive nocturnal cross-ventilation. Conversely, reinforced concrete ($\lambda \approx$ 1.70–2.50 W/m.K) transmits this thermal wave in under 5 hours, triggering severe indoor overheating that necessitates continuous mechanical cooling.

Nevertheless, this inertial advantage must be nuanced across the annual cycle given the extreme seasonal temperature amplitudes of arid pre-Saharan regions, where winter nocturnal temperatures frequently drop near freezing (0 °C). While high thermal mass dampens diurnal temperature swings, the steady-state thermal resistance of an uninsulated 40 cm rammed earth wall remains modest ($R \approx 0.50\,m^2$.K/W), which is insufficient to prevent conductive heat losses during cold spells and can cause radiative discomfort due to cold interior wall surfaces (Beck et al., 2010; Soudani et al., 2017). Consequently, achieving year-round thermal comfort requires pairing the thermal mass of rammed earth with two complementary passive strategies: first, maximizing passive solar gains (via south-facing glazing with summer shading overhangs or Trombe-wall configurations) to charge the high-inertia wall during sunny winter days for nocturnal heat release; and second, incorporating bio-based thermal insulation (such as lime-hemp renders, date-palm fiber boards, or expanded cork), ideally applied on the exterior face to suppress conductive losses while preserving the internal thermal storage capacity of the earthen core (Rempel & Rempel, 2013; McGregor et al., 2016).

Simultaneously, the open porosity of raw earth functions as a passive hygrometric buffer. Acting as a breathable material, the envelope adsorbs excess water vapor generated by indoor human activities and desorbs it when the indoor relative humidity drops. This buffering mechanism dampens relative humidity levels within a stable homeostatic zone (40% to 60%), significantly alleviating sensory discomfort under arid climates (Anger, 2012; Ouzaani, 2024). However, this fine moisture transit behavior is directly impacted by the hydraulic stabilization needed to satisfy parasismic (f_c) rules: densifying the soil matrix can double the vapor resistance factor (μ), requiring careful microclimatic monitoring of contemporary walls (Mansouri et al., 2024).

3.5.2. Urban Morphology and Public Microclimate

Beyond component-scale indicators, our morpho-typological modeling confirms the structural efficiency of the compact *ksar* framework. Calculating the compactness index (defined as the ratio between the exposed building envelope surface and the total constructed volume) demonstrates that the high-density urban fabric of *ksour* yields a 35% reduction in the global radiative load compared to modern discontinuous suburban patterns (villas, open grids) (Odghiri & Mahdane, 2023).

Mutual structural shading preserves the thermal integrity of façades and maintains ground surface temperatures in public corridors at thresholds significantly lower than asphalt roads, completely eliminating the urban heat island (UHI) effect. Nonetheless, this horizontal high-density engineering runs directly into the altimetric vertical limitations of the RPCT 2011 code, which effectively prevents transposing this historic density under modern vertical standards without utilizing structural hybridization frames (Soulé, 2025; Tarik, 2023).

4. Study Limitations and Future Perspectives

4.1. Normative and Legislative Bottlenecks

Although this research provides empirical evidence supporting the bioclimatic and socio-cultural relevance of Moroccan oasis architecture, its operational transfer into contemporary construction markets faces systemic technical and regulatory bottlenecks.

The primary constraint stems from the rigid structural limitations imposed by the current national regulatory framework. While the promulgation of the Moroccan Earthen Buildings Seismic Code (RPCT 2011) marked a historic milestone toward the institutional recognition of raw earth, its deterministic design equations impose drastic geometric boundaries (Royaume du Maroc, 2012). By capping the altimetric configuration of load-bearing earth masonry at a maximum of two levels (R+1, total height $\leq$ 7 m) in moderate-to-high seismic risk zones, the RPCT 2011 code prevents the deployment of this material in dense urban areas characterized by high land costs (Soulé, 2025). Furthermore, the legislative framework remains confined to informal, decentralized rural applications. It fails to provide viable operational mechanisms for large-scale real estate developers or public procurement agencies.

4.2. Socio-Economic Barriers and Material Variability

The second limitation relates to deep socio-economic dynamics, market access costs, and material characterization methodologies. Unlike industrial materials subjected to standardized factory quality controls, raw earth exhibits significant intrinsic variability depending on its geographic quarry of origin (Ibnoussina, 2016). In the absence of standardized, nationally certified protocols to test the rheological and mechanical properties of local soils, the performance of rammed earth remains subject to high statistical fluctuations, rendering the material uninsurable by structural engineers and technical control bureaus.

Compounding this is a major economic distortion: contemporary stabilized rammed earth generates labor and shuttering costs significantly higher than those of the concrete block sector, proving to be 1.5 to 2 times more expensive per square meter (Meziani, 2021). This financial reality excludes the material from mass social housing, confining it to a luxury niche market. Finally, the material's Life Cycle Assessment (LCA) must be qualified. While raw earth possesses perfect circularity, the incorporation of hydraulic binders necessary to stabilize the (f_c) value shatters this metabolism. At its end-of-life, contemporary rammed earth cannot return to a plastic soil state through simple rehydration; it must be treated as conventional inert demolition debris requiring heavy mechanical processing (Mansouri et al., 2024).

4.3. Research Trajectories and Perspectives

4.3.1. Dynamic and Probabilistic Updates to the Seismic Code

Future investigations must abandon simplified deterministic calculations in favor of probabilistic finite element models. This transition will allow the structural validation of hybrid engineered systems, such as timber-earth composites or low-carbon concrete frames with rammed earth panel infills. This will optimize the allowable vertical height (beyond R+1) while guaranteeing structural resilience against seismic loads and maintaining acceptable public safety criteria (Royaume du Maroc, 2012; Soulé, 2025).

4.3.2. Decentralized Industrialization of Eco-Materials

Research efforts must prioritize the standardization of local production lines for Compressed Earth Blocks (CEB) and prefabricated macro-panels. Optimizing binder formulations by incorporating agricultural by-products from the oasis agroecosystem (such as date palm or alfa fibers) will normalize compressive strength (f_c) thresholds (Azzaoui et al., 2023; Madi, 2025). This on-site mechanized prefabrication will bypass weather-related hazards, reduce direct labor costs, and render the material economically competitive.

4.3.3. Overhaul of Insurance Frameworks and Professional Rules

Academic and professional bodies must co-develop standardized Regional Execution Rules. Providing a National Soil Characterization Guide, which correlates simple on-site tests (drop test, simplified sedimentometry) with laboratory performance classes, is a mandatory prerequisite to secure the structural liability coverage (ten-year guarantee) demanded by insurance companies (Anger, 2012; El Gharbi & Amrani, 2022). This will finally allow public procurers to integrate environmental clauses encouraging earth construction in their calls for tenders (El Fgaier et al., 2023).

4.4. Socio-Technical Analysis of Field Interviews: Representations, Know-how, and Adoption Inhibitors

4.4.1. The Paradox of Inhabiting: Thermal Comfort versus Social Stigmatization

All interviewed users (HB-01 to HB-06) corroborate the distinct superiority of passive hygrothermal comfort experienced within traditional rammed earth structures, unanimously describing them as ”natural thermal regulators” during summer heatwaves. Nonetheless, a major socio-cultural gap emerges regarding the durability of this housing mode. For residents of degraded *ksour*, earth suffers from a deficit in its symbolic image, remaining heavily associated with material precarity. In the absence of contemporary stabilized renders, cyclical wall maintenance after rainy episodes relies on a heavy domestic workload, driving the choice toward the concrete-block complex, which is falsely perceived as synonymous with modernity and ”zero maintenance”.

4.4.2. The Rupture of Transmission: From Empirical Craft to Impossible Standardization

The transmission of this millenary know-how remains strictly informal, purely oral, undocumented, and ultra-localized within Southern Moroccan valleys. This generational shrinkage explains the immense complexity faced when trying to identify valid respondents during our interview campaign. The core of the socio-technical gap lies in the operational disconnection between the last guardians of traditional expertise and the economic actors of the modern building site. The *Maâlems* (MS-01, MS-02) witness a critical rupture in the transmission of the craft: mastering optimal tamping moisture and selectively choosing geo-resources are lost to expeditious practices.

This erosion of skills translates directly into the practices of local masons (TC-01 to TC-04), who massively abandon rammed earth due to an unfavorable economic model. Manual shuttering requires high labor intensity and drying times incompatible with the cadences imposed by construction profitability. Faced with high execution costs and potential defects, contractors turn to concrete, whose standardized implementation secures their profit margins and technical liability, despite generating proven thermal pathologies.

4.4.3. Synthesis for Decentralized Industrialization

These qualitative field data demonstrate that safeguarding rammed earth cannot be achieved through a mere museum-like approach. To reconcile residents' lived experiences with conservation goals, the sector must break free from the labor intensity and uncertainty of traditional building sites (Youbi, 2024). The transition toward decentralized industrialization (compressed earth blocks or prefabricated macro-panels) emerges as the ideal technical response. It rationalizes

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labor time for contractors while integrating the qualitative expertise of *Maâlems* within semi-mechanized, controlled production units, capable of guaranteeing the uniform (f_c) values required by the RPCT 2011 code without alienating workers.

5. Conclusion: Toward a Sustainable Modernity under the Scope of the Triple Trade-Off

The in-depth analysis of the millenary Moroccan oasis heritage and its contemporary variations demonstrates unequivocally that rammed earth can no longer be approached solely through the lens of vernacular nostalgia or isolated physical performance. To integrate sustainably into 21st-century construction dynamics, earthen materials must now negotiate a **systemic triple trade-off** that conditions their actual viability on the free market:

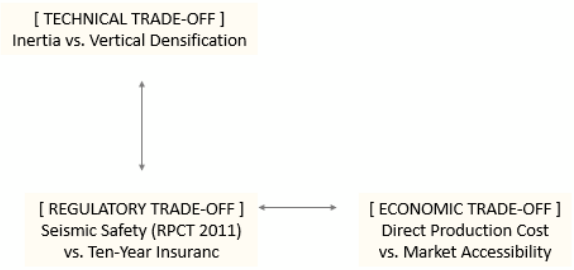

Figure 1. Conceptual Framework of the Systemic Triple Trade-Off Governing Earthen Architecture Modernization in Morocco

- **The Technical Trade-off (Inertia vs. Densification):** Optimized contemporary rammed earth displays exceptional thermodynamic properties, exhibiting an ideal thermal lag of 10 to 12 hours alongside passive hygrothermal regulation capabilities. However, its low intrinsic tensile and shear strength under seismic loads limits its raw structural use. Overcoming this roadblock relies on a reasoned technological hybridization strategy (timber or low-carbon concrete secondary frames with earth panel infills), shifting away from pure load-bearing systems to maximize energy efficiency at the building scale.

- **The Regulatory Trade-off (Safety vs. Assurability):** The promulgation of the RPCT 2011 code successfully lifted raw earth out of the informal rural sector, but its strict altimetric restrictions (maximum R+1) heavily penalize its integration into dense urban areas where land prices are high. Furthermore, the mineralogical variability inherent to local geo-resources clashes with the perfect reproducibility demanded by technical control bureaus. Transitioning toward probabilistic finite element modeling and publishing a National Soil Characterization Guide are mandatory prerequisites to provide the deterministic framework required by insurance companies to underwrite the ten-year guarantee.

- **The Economic Trade-off (Production Cost vs. Accessibility):** This represents the most critical nexus highlighted by this post-2023 review. Although the raw material itself is free, contemporary stabilized rammed earth proves to be 1.5 to 2 times more expensive per square meter than conventional concrete block masonry due to the high labor intensity and structural tamping constraints. This financial reality, exacerbated by the erosion of the *Maâlems'* oral traditional expertise, currently confines the material to an elite eco-tourism niche market.

Ultimately, safeguarding the architectural heritage of oasis settlements requires enacting its structural transformation. Transitioning toward decentralized industrialization, through the mobile prefabrication of Compressed Earth Blocks (CEBs) or mechanically controlled rammed earth macro-panels, offers a viable pathway. This approach ensures the mechanical consistency mandated by building codes, lowers direct construction costs, and elevates traditional artisans to the role of technical quality supervisors.

Nevertheless, strong political and institutional momentum is required to adapt Moroccan public procurement frameworks. Specifically, this transition entails shifting Special Technical Specifications (Cahiers des Prescriptions Spéciales, CPS) and Common Technical Specifications (CPC) from a rigid prescriptive model (based on standardized industrial products) toward a performance-based specification approach (mandating target mechanical, hygric, and thermal thresholds) capable of accommodating local, non-standardized soil formulations, in alignment with the sustainable procurement provisions of Moroccan Public Procurement Decree No. 2-22-431. Operationally, securing approval for prefabricated earthen macro-panels in publicly funded reconstruction projects requires a structured certification protocol overseen by technical control bodies (such as the LPEE, Laboratoire Public d'Essais et d'Études, and accredited inspection bureaus). This homologation pathway should rest on three pillars: (1) establishing Territorial Reference Formulations per geological basin via geotechnical suitability testing; (2) issuing Technical Assessments (Avis Techniques, ATec) to bridge regulatory gaps for hybrid systems falling outside existing IMANOR standards (such as NM 10.1.008 for CEBs); and (3) enforcing batch-level quality control on mobile prefabrication units (compressive strength and durability testing) to guarantee decennial liability insurance for public infrastructure.

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No generative AI was used for analysis or results.

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Competing interests

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