

Numerical Simulation and Structural Evaluation of Earthen Masonry Systems Built with Optimized Granite-Lime Stabilized Compressed Earth Blocks

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Abstract

This study adopts a combined experimental and numerical finite element research design to evaluate the structural performance and engineering characteristics of Compressed Earth Blocks (CEBs) stabilized with industrial Granite Waste Powder (GWP, 0–15%) and hydrated lime (0–6%). Rapid urban growth and the high carbon footprint of Portland cement necessitate sustainable, low-carbon structural alternatives for affordable housing. An experimental design evaluating 13 mix formulations was assessed for geotechnical characteristics, mechanical strength, capillary absorption, and surface abrasion resistance according to African Regional Standards (ARS 674–677). Subsequently, a finite element analysis (FEA) framework was developed in ETABS to simulate linear static displacement and nonlinear pushover response under service and wind loading combinations. Laboratory results demonstrated that the ternary mix containing 15% GWP and 6% lime (Mix M4) yielded a peak dry bulk density of 2120 kg/m³ at 90 days. Mix M4 achieved a 28-day compressive strength of 5.22 MN/m², representing a 108.8% increase over the 28-day control (2.50 MN/m²), and reached 6.50 MN/m² at 90 days, reflecting a 124.1% increase over the 90-day control (2.90 MN/m²) and a 24.5% strength gain from 28 to 90 days. Stabilization significantly enhanced durability, reducing capillary water absorption to 0.68% and abrasion loss to 0.58%. Structural simulations revealed strong numerical-experimental correlation ($R^2 = 0.92$), with optimized blocks achieving up to a 65% reduction in maximum story displacement and a transition to high lateral stiffness. The findings validate GWP-lime stabilized CEBs as a structurally sound, environmentally resilient masonry system suitable for load-bearing affordable housing applications.

Keywords: Compressed Earth Blocks, Finite Element Analysis, Granite Waste Powder, Lime Stabilization, Structural Masonry, Sustainable Building Materials.

Introduction

Sustainable Urban Settlements and Earthen Structural Systems

Under the United Nations (2015) 2030 Agenda for Sustainable Development, Sustainable Development Goal (SDG) 11 advocates for inclusive, safe, resilient, and sustainable human settlements, with Target 11.1 emphasizing universal access to affordable housing. As rapid urban growth intensifies material demand in developing regions, the high economic and

ecological costs of conventional construction have become evident (UN-Habitat, 2016). Sustainable building materials offer a viable dual-benefit pathway: expanding structural housing capacity while minimizing embodied carbon emissions and life-cycle costs (Meng et al., 2025). Among these alternative systems, Compressed Stabilized Earth Blocks (CSEBs) have emerged as a technically viable solution. Formed by compressing locally sourced soil blended with minimal quantities of inorganic or organic binders, CSEBs drastically reduce energy consumption compared to conventional fired clay bricks or Portland-cement-dense masonry units (Meng et al., 2025). However, raw unstabilized earth units possess low compressive strength and remain highly susceptible to moisture-induced degradation under ambient weather conditions (Nshimiyimana et al., 2020). Consequently, chemical additives such as cement, lime, or mineral pozzolans are incorporated into the soil matrix to enhance structural integrity and moisture resistance (Nshimiyimana et al., 2020). However, to preserve the economic and environmental advantages of earthen masonry, recent efforts have focused on partial stabilizer replacement using industrial byproducts (Nshimiyimana et al., 2020).

The Computational Gap in Earthen Masonry Design

While the material-level physics, chemical stabilization reactions, and geotechnical compaction behavior of granite waste and lime-stabilized earth blocks have been documented, a critical research gap remains regarding their macro-structural performance (Nayak et al., 2022). For alternative materials like stabilized Compressed Earth Blocks (CEBs) to achieve widespread commercial adoption, structural engineers must be able to predict their load-deformation behavior under standard serviceability and ultimate design loads (Obianyo et al., 2020). Structural anisotropy in compressed earth block (CEB) masonry stems directly from the dynamic interface between the block units and mortar beds when subjected to axial compression and shear forces. Given that full-scale experimental characterization of these composite interactions entails significant structural complexity and substantial financial costs, finite element modeling and numerical analyses function as essential predictive alternatives. Utilizing modern finite element analysis (FEA) and structural design software, such as ETABS, allows engineers to simulate the macro-performance of earthen masonry assemblies under gravity loads, lateral wind pressures, and environmental actions. Currently, there is a lack of validated numerical modeling frameworks that translate the material-level constitutive properties of granite waste–lime stabilized CEBs into reliable structural-scale simulations (Nayak et al., 2022; Obianyo et al., 2020).

Research Aim and Objectives

To address this gap, this study presents a combined experimental and numerical framework to evaluate the structural integrity and structural performance of masonry systems constructed with GWP-lime stabilized CEBs. The primary objective is to evaluate how these optimized blocks behave under structural loading, using computational modeling to

analyze structural performance and wind load response in comparison to traditional, unstabilized earthen systems.

The specific structural objectives of this study are:

1. To establish the constitutive material parameters (elastic modulus, Poisson's ratio, and compressive strength) of optimized GWP-lime CEB masonry based on experimental data.
2. To develop a validated numerical structural model within ETABS to simulate the load-deformation response of load-bearing CEB wall systems under typical service loads.
3. To evaluate the comparative structural performance of stabilized (M₄) versus unstabilized (M₁) CEB masonry frames subjected to combinations of vertical axial loads and lateral wind loads.
4. To establish design recommendations and structural safety margins to support the safe adoption of GWP-lime stabilized CEBs in affordable, multi-story housing applications.

Significance of the Study

This study contributes to both the academic understanding and practical implementation of alternative earthen structures by bridging the gap between material science and structural engineering. By establishing and validating a computational modeling approach, this research provides structural engineers, architects, and builders with the analytical tools needed to design load-bearing stabilized earth structures with confidence.

Furthermore, validating the structural reliability of these systems under wind and environmental loading supports the broader goals of SDG 11.1 (UN-Habitat, 2024). This approach delivers a structurally dependable, resilient, and highly affordable building technique tailored to meet the housing demands of expanding, low-resource urban areas.

Constitutive Material Properties and Experimental Inputs

Raw Material Engineering Characteristics as Modeling Constraints

To establish a high-fidelity numerical model capable of simulating structural masonry assemblies, the physical and geotechnical properties of the raw constituent materials must be characterized as baseline modeling boundaries. The primary matrix utilized in this study comprised a lateritic soil sourced from a borrow pit in Miri along Jos Road, Bauchi, Bauchi State, Nigeria. Raw lateritic soils natively present high plasticity indices and intense water susceptibility, which induce severe volumetric changes and structural vulnerability under load if unrectified. To counteract these structural deficiencies, commercial hydrated lime ($\text{Ca}(\text{OH})_2$) and industrial granite waste powder (GWP) obtained from local stone crushing and polishing facilities were introduced as stabilizing agents.

From a structural standpoint, GWP acts as an engineered micro-filler that optimizes particle packing density and significantly minimizes internal structural porosity (López Boadella et al., 2019). Geotechnical index characterizations including initial moisture content,

pycnometer specific gravity (G_s), Atterberg limits (liquid limit, plastic limit, and plasticity index), sieve analysis for grading coefficients (coefficient of uniformity, C_u ; coefficient of curvature, C_c), and Standard Proctor compaction tests were systematically executed. These laboratory evaluations were not conducted merely for soil classification, but to strictly govern the engineering workability, compaction efficiency, Maximum Dry Density (MDD), and Optimum Moisture Content (OMC) necessary to manufacture uniform, structurally viable masonry units.

Experimental Design and Masonry Unit Fabrication

The experimental matrix was structured using a randomized layout generated via Design-Expert software to mitigate systematic experimental errors. The setup evaluated thirteen distinct mix proportions (M1 through M13), assessing incremental GWP replacements ranging up to 15% and hydrated lime configurations up to 6%. Mix M1 served as the unstabilized control baseline, whereas the remaining formulations investigated the synergistic mechanical interaction effects of the dual-stabilizer system.

Homogeneous dry-blending of the components was followed by the introduction of water strictly calibrated to OMC. Mechanical compaction was subsequently enforced utilizing a uniform manual compressed earth block press to produce standardized solid masonry units measuring 300 mm×150 mm×100 mm. To trace the long-term mineralogical and mechanical evolution of the binder matrices, all specimens were subjected to controlled laboratory curing regimes for milestone durations of 28 days and 90 days prior to physical testing.

Computational Modeling and Numerical Methodology

Material-Level Mechanical and Environmental Validation Protocols

Before initiating macro-scale structural simulations, empirical laboratory validation was conducted on the cured blocks in strict accordance with African Regional Standards (ARS 674–677) to determine the baseline isotropic material properties. The laboratory protocols evaluated three core performance metrics:

Mechanical Compressive Strength Testing (ARS 674)

Axial compression testing was conducted using a calibrated crushing press operating at a regulated displacement rhythm of 0.02 mm/sec to ensure complete failure occurred beyond the initial 15 seconds of loading. Prepared specimens consisted of two half-blocks bonded vertically via an intermediate 10 mm mortar layer. For the stabilized series, an engineered soil-cement interface mortar was formulated to ensure structural and strength parity between the joints and the block units. Ultimate dry compressive strength (f_b dry) was determined using:

$$f_b \text{ dry} = 10 \times F/S$$

where:

- F represents the peak failure load in kilo Newtons (kN).

- S denotes the regularized cross-sectional surface area in contact in square centimeters (cm^2).
- The multiplier 10 converts kN/cm^2 to N/mm^2

Capillary Water Absorption Evaluation (ARS 675)

To evaluate structural resilience against intense, climate-induced moisture exposure, blocks were oven-dried at 40°C to a constant mass and partially submerged in a regulated water tray at a fixed depth of 5 mm. The capillary water absorption coefficient (C_b) after an immersion timeline (t) of 10 minutes was determined via:

$$C_b = (100(m_h - m_d)) / (S\sqrt{t})$$

where:

- $m_h - m_d$ represents the mass of water absorbed in grams (g).
- S is the submerged face area in square centimeters (cm^2).
- t is the duration of immersion in minutes.

This metric serves as a direct indicator of structural durability limits under severe storm conditions.

Mechanical Erosion and Abrasion Resistance (ARS 676–677)

Surface integrity was evaluated by subjecting the masonry faces to localized mechanical erosion using a standard steel wire brush uniformly preloaded with a static mass of 3 kg. The apparatus was driven across 60 complete forward-and-backward cycles at a constant frequency without external vertical pressure. The structural abrasion coefficient (C_a) was calculated as:

$$C_a = S / (m_1 - m_2)$$

where:

- S represents the precise brushed surface area in square centimeters (cm^2).
- $m_1 - m_2$ constitutes the total mass of detached matter in grams (g).

Finite Element Framework and Structural Modeling in ETABS

To evaluate the translation of macro-material optimization into structural element behavior, finite element analysis (FEA) was performed utilizing the ETABS (Extended Three-dimensional Analysis of Building Systems) software suite. Numerical modelling and structural analysis of the earthen masonry assembly were performed using Finite Element Analysis (FEA) software (ETABS). The evaluated floor plan comprises a symmetrical rectangular layout measuring 10.97m by 7.32m, subdivided into a 3 by 2 grid with regular panel dimensions of 3.66m by 3.66m. Structural frames were modelled using standard 1D line elements for beams and columns, while floor diaphragms and wall panels were discretized using 2D shell elements to capture in-plane and out-of-plane stress distributions.

Primary load patterns were established in accordance with applicable structural codes, comprising Self-Weight (Dead, DL), Superimposed Dead Load (SDL) accounting for floor

finishes and permanent partitions (1.5kN/m^2), and Imposed Live Load ($LL = 1.5\text{kN/m}^2$). Area loads were applied as shell uniform load sets across the floor slab areas, while localized equipment and nodal reactions were assigned as joint point loads where applicable. Linear static load cases were defined to analyze gravity response, and ultimate limit state (ULS) design combinations were formulated as:

$$ULS = 1.4 (DL + SDL) + 1.6 (LL)$$

The computational framework translates unit-level material stress-strain parameters into global load-deformation responses, evaluating structural stability, load transfer, and serviceability limits under critical load actions. The stabilized earth blocks were mathematically defined within the software as homogeneous, isotropic materials using empirical data extracted from the laboratory phase. Volumetric mass density ($\rho=m/V$) values were assigned directly from experimental records, and a uniform Poisson's ratio (ν) of 0.20 was applied across all models. Due to the absence of standard masonry code expressions for this green formulation, the operational Modulus of Elasticity (E_m) was computed via the validated empirical relationship:

$$E_m = 500f_b \text{ (MN/m}^2\text{)}$$

where:

- f_b is the experimentally derived compressive strength in N/m^2 .

Structural load cases were established to apply combinations of gravity self-weight and vertical imposed service loads through the load combination interface. ETABS shell models treat masonry as a continuous isotropic material. Computational processing consisted of linear static analyses to isolate structural displacement fields, stress distribution contours, and global structural stiffness profiles. Furthermore, non-linear pushover analyses were conducted to evaluate structural ductility and deformation characteristics under lateral displacement pressures. Finally, numerical-experimental validation was achieved by executing mathematical regression modeling between the laboratory compressive capacity and the simulated displacement profiles, verifying the structural reliability of the alternative masonry system.

Results and Discussions

Introduction

This section details the empirical findings and computational outputs derived from the laboratory and numerical investigations conducted on sustainable compressed earth blocks (CEBs) modified with industrial granite waste powder (GWP) and hydrated lime. The analytical framework is divided into three distinct phases: comprehensive geotechnical characterization of the raw matrix, material-level mechanical and durability performance evaluation of the stabilized units, and multi-scale numerical and statistical validation of the engineering responses.

Geotechnical Index Characterization of Constituent Materials

Lateritic Soil Base Characterization

The raw geotechnical properties of the target soil matrix must be thoroughly quantified to map out baseline design limits before structural unit manufacturing begins. Experimental index characterization revealed an average native moisture content of 12.43%. Results from the mechanical sieve analysis and the corresponding grading parameters are summarized in Table 1.

Table 1: Particle Size Distribution of the Soil

Fraction	Percentage(%)
Gravel (>4.75mm)	0
Sand (4.75–0.075 mm)	63.17
Fines (<0.075 mm)	36.83

Source: Authors' experimental data, 2026.

Gradation Parameters: $C_u=17$, $C_c=0.4$

The physical consistency, density limits, and compaction profile of the material were established via Atterberg limits, pycnometer specific gravity, and Standard Proctor compaction tests, as documented in Tables 2, 3, and 4.

Table 2: Atterberg's Limits of the Soil

Property	Value(%)	
Liquid Limit	38	
Plastic Limit	25	
Plasticity Index	13	

Source: Authors' experimental data, 2026.

Table 3: Specific Gravity of the Soil

Property	Value	
Specific Gravity	2.67	

Source: Authors' experimental data, 2026.

Table 4: Compaction Results of the Soil

Property	Value
MDD	1846kg/m ³
OMC	16.4%

Source: Authors' experimental data, 2026.

Formulation Matrix and Optimization Levels

Thirteen distinct structural mix proportions (M₁ through M₁₃) were established to systematically track how varying ternary stabilizers content by weight affect performance.

The exact dosing distributions generated via Design-Expert software are detailed in Table 5.

Table 5: Stabilization Levels for M₁–M₁₃ with Total Stabilizers Content

Mix	Granite Powder (%)	Lime (%)	Total Stabilizers Content(%)
M ₁	0	0	0
M ₂	15	0	15
M ₃	0	6	6
M ₄	15	6	21
M ₅	0	3	3
M ₆	15	3	18
M ₇	7.5	0	7.5
M ₈	7.5	6	13.5
M ₉	7.5	3	10.5
M ₁₀	7.5	3	10.5
M ₁₁	7.5	3	10.5
M ₁₂	7.5	3	10.5
M ₁₃	7.5	3	10.5

Source: Authors' experimental data, 2026.

This structured, incremental expansion of total stabilizer content allows for a rigorous evaluation of the mechanical and durability improvements within the composite system.

Matrix Density Analysis

The bulk density of the masonry specimens improved significantly with higher stabilizer content and longer curing periods, as shown in Table 6.

Table 6: 28 & 90-Day Density Values (M₁–M₁₃)

Mix	28 Day Density (kg/m ³)	90 Day Density (kg/m ³)
M ₁ (Control)	1800	1800
M ₂	1985	2030
M ₃	1850	1870
M ₄ (Optimized)	2020	2120
M ₅	1935	1950
M ₆	2005	2080
M ₇	1930	1965
M ₈	1970	2010
M ₉	1955	1995
M ₁₀	1945	1980
M ₁₁	1957	1998
M ₁₂	1953	1995
M ₁₃	1950	1994

Source: Authors' experimental data, 2026.

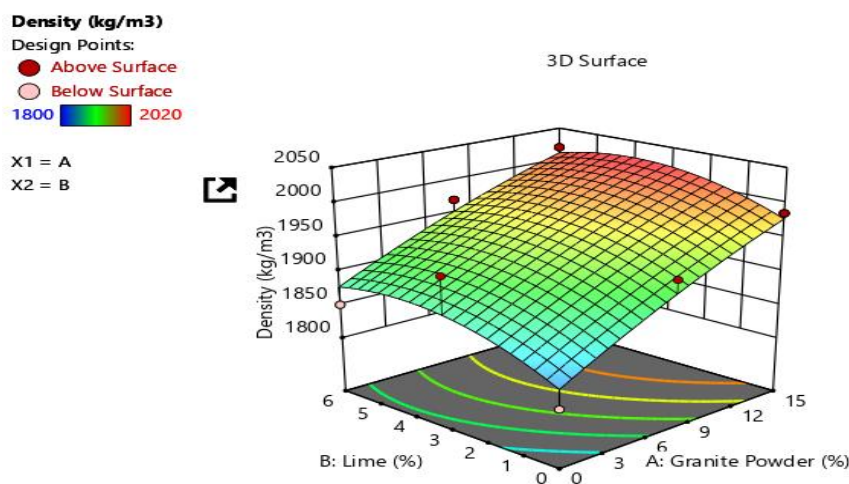


Figure 1: 3D Surface Plot for 28 Day Density Values (M1-M13)
Source: Authors’ experimental data, 2026.

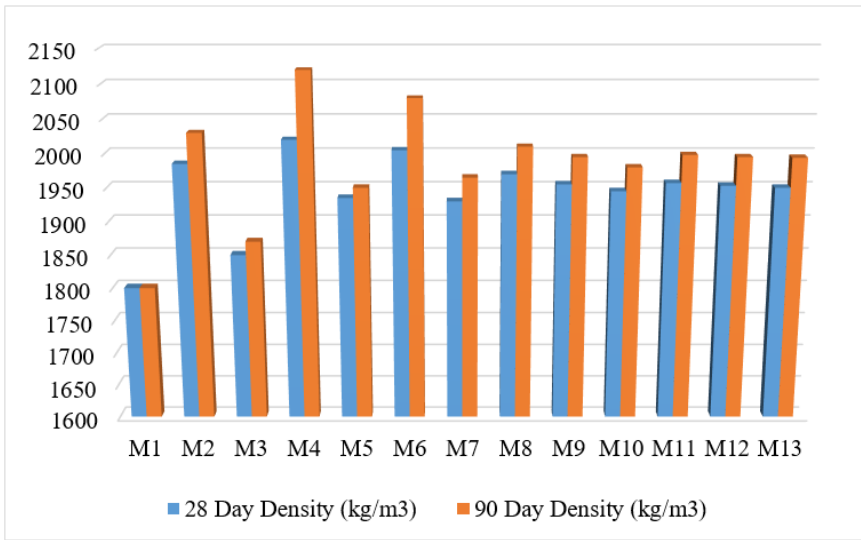


Figure 2: 28 and 90 Day Density Values (M1-M13)
Source: Authors’ experimental data, 2026.

Compressive Strength Development

Mechanical testing revealed substantial improvements in structural load-bearing capacity as curing time progressed, as summarized in Table 7.

Table 7: 28 & 90-Day Compressive Strength Values (M1–M13)

Mix	28 Day Compressive Strength (MN/m ²)	90 Day Compressive Strength (MN/m ²)
M1(Control)	2.50	2.90
M2	3.82	4.60
M3	3.81	4.53
M4(Optimized)	5.22	6.50

Mix	28 Day Compressive Strength (MN/m ²)	90 Day Compressive Strength (MN/m ²)
M5	3.54	4.13
M6	4.82	6.00
M7	3.55	4.30
M8	4.72	5.90
M9	4.32	5.42
M10	4.29	5.35
M11	4.34	5.47
M12	4.31	5.40
M13	4.30	5.38

Source: Authors' experimental data, 2026.

Compressive Strength (MN/m²)

Design Points:

● Above Surface

○ Below Surface

2.5 5.22

X1 = A

X2 = B

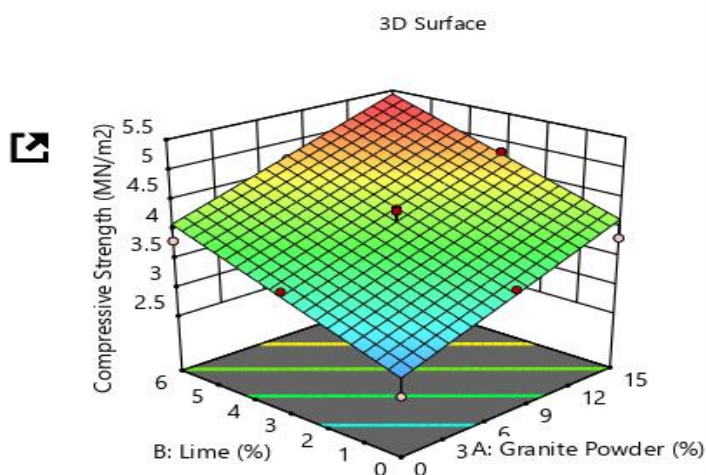


Figure 3: 3D Surface Plot for 28 Day Compressive Strength Values (M1-M13)

Source: Authors' experimental data, 2026.

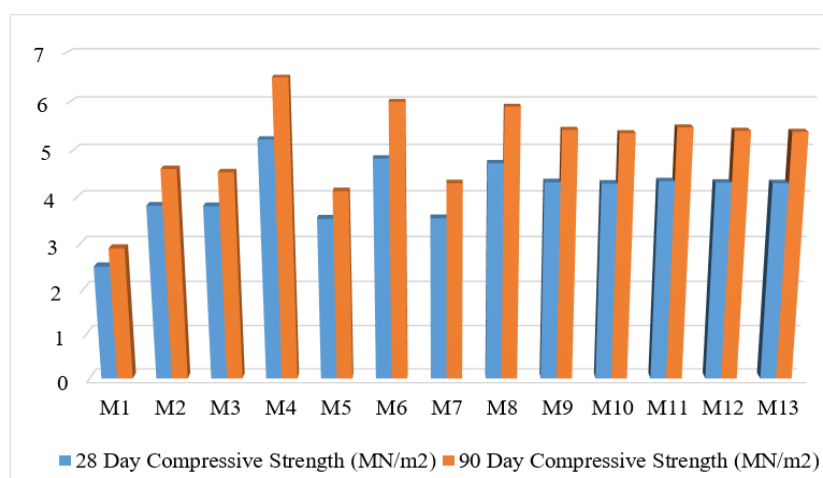


Figure 4: 28 and 90 Day Compressive Strength Values (M1-M13)

Source: Authors' experimental data, 2026.

Durability Performance: Capillary Water Absorption

Durability testing under ARS 675 criteria showed that the stabilized blocks became significantly less susceptible to moisture ingress, as detailed in Table 8.

Table 8: 28 Day Absorption Coefficient Values (M1–M13)

Mix	Absorption Coefficient	Water Absorption (%)
M1(Control)	7.94	1.40
M2	6.11	1.15
M3	6.32	1.05
M4(Optimized)	4.37	0.68
M5	7.03	1.12
M6	4.43	0.72
M7	6.83	1.15
M8	4.57	0.72
M9	4.99	0.85
M10	4.97	0.84
M11	5.00	0.86
M12	4.98	0.84
M13	4.98	0.85

Source: Authors' experimental data, 2026.

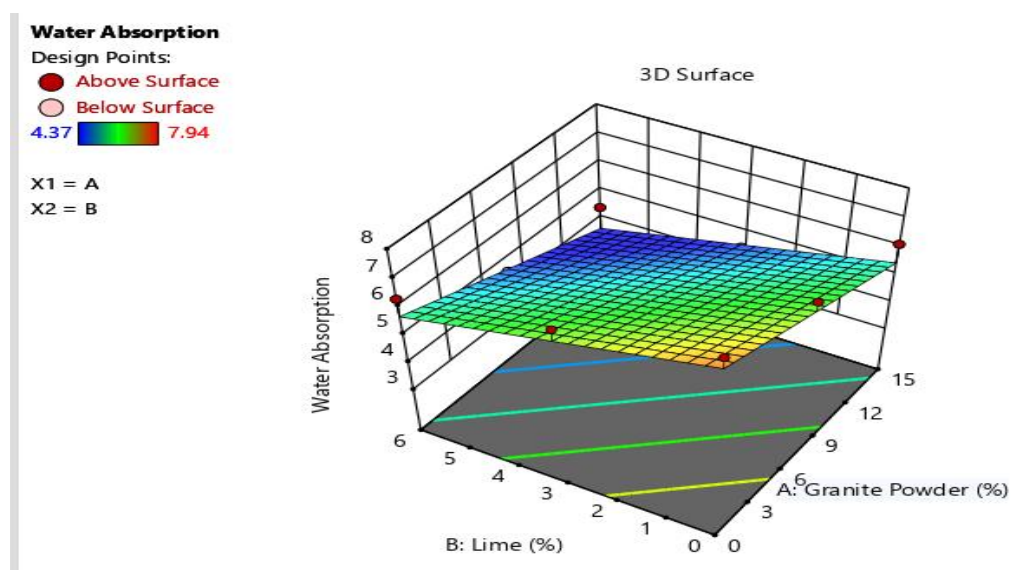


Figure 5: 3D Surface Plot 28 Day Absorption Coefficient Values (M1-M13)

Source: Authors' experimental data, 2026.

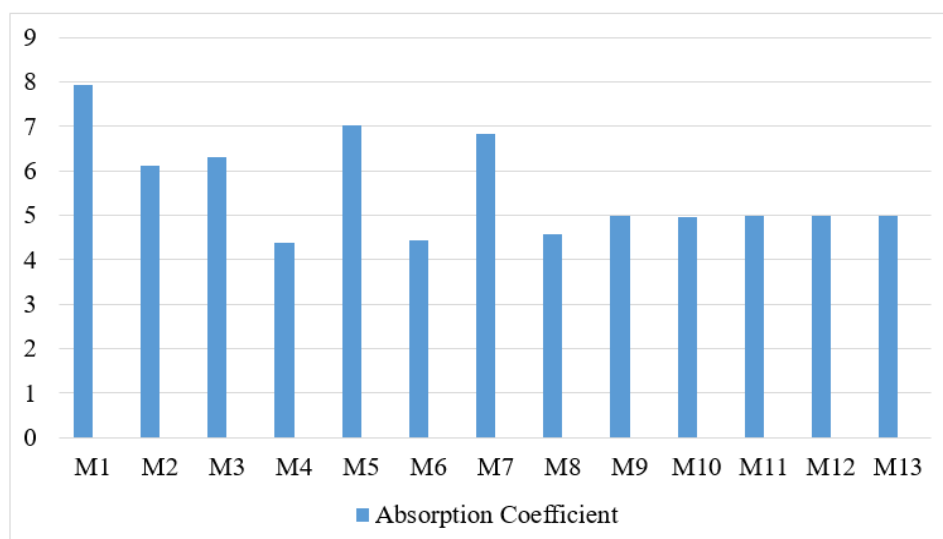


Figure 6: 28 Day Absorption Coefficient Values (M1-M13)

Source: Authors' experimental data, 2026.

Surface Durability: Mechanical Abrasion Resistance

Surface erosion evaluations carried out via wire-brush testing (ARS 676–677) confirmed a major boost in localized structural integrity, as shown in Table 9.

Table 9: 28 Day Abrasion Coefficient Values (M1–M13)

Mix	Abrasion Coefficient (cm ² /g)	Abrasion Loss (%)
M1	0.96	1.00
M2	1.13	0.75
M3	1.10	0.78
M4	1.39	0.58
M5	1.04	0.85
M6	1.37	0.60
M7	1.07	0.82
M8	1.34	0.61
M9	1.27	0.66
M10	1.25	0.65
M11	1.29	0.67
M12	1.26	0.66
M13	1.25	0.65

Source: Authors' experimental data, 2026.

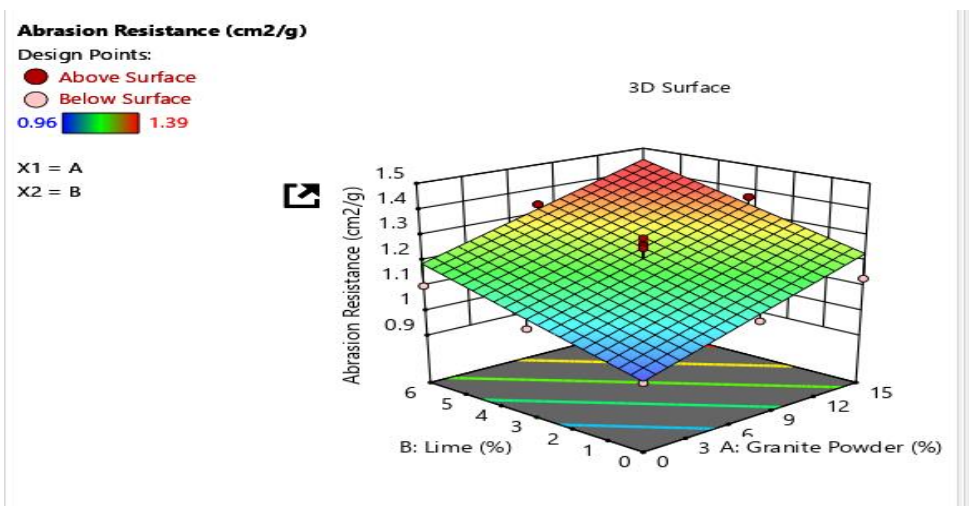


Figure7: 3D Surface Plot for 28 Day Abrasion Coefficient
Source: Authors’ experimental data, 2026.

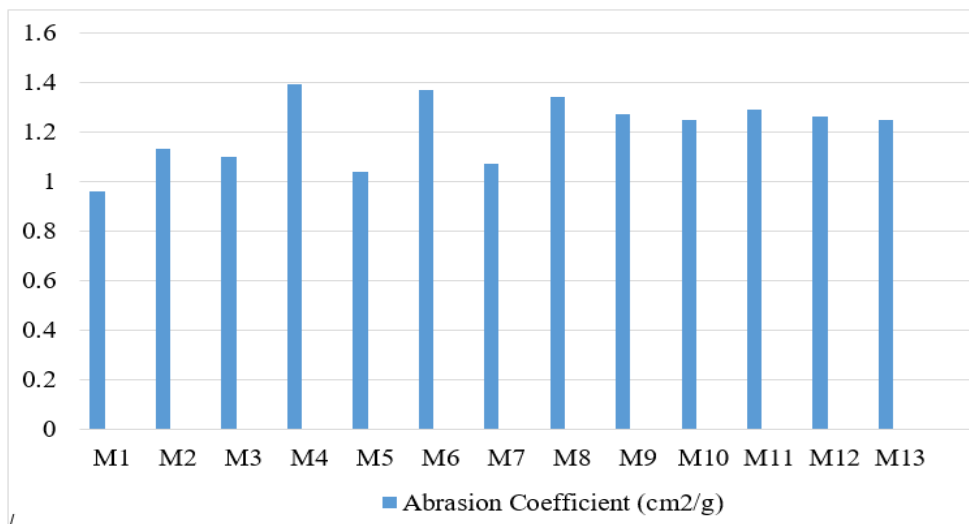


Figure 8: 28 Day Abrasion Coefficient
Source: Authors’ experimental data, 2026.

Numerical Validation and Finite Element Framework via ETABS
Linear Static Deformational Performance and Stiffness Scaling

To evaluate how these materials improvements, translate to full-scale structural performance, a finite element analysis (FEA) model of a masonry wall assembly was built and analyzed in ETABS. The deformation plots (Figure 9) and stress contours (Figure 10) reveal uniform load path transitions across the continuous structural shell elements. The model shows noticeably higher localized stiffness in sections built with high-GWP and high-lime formulations. This simulated structural response mirrors the increased compressive strengths and higher dry densities recorded in the lab.

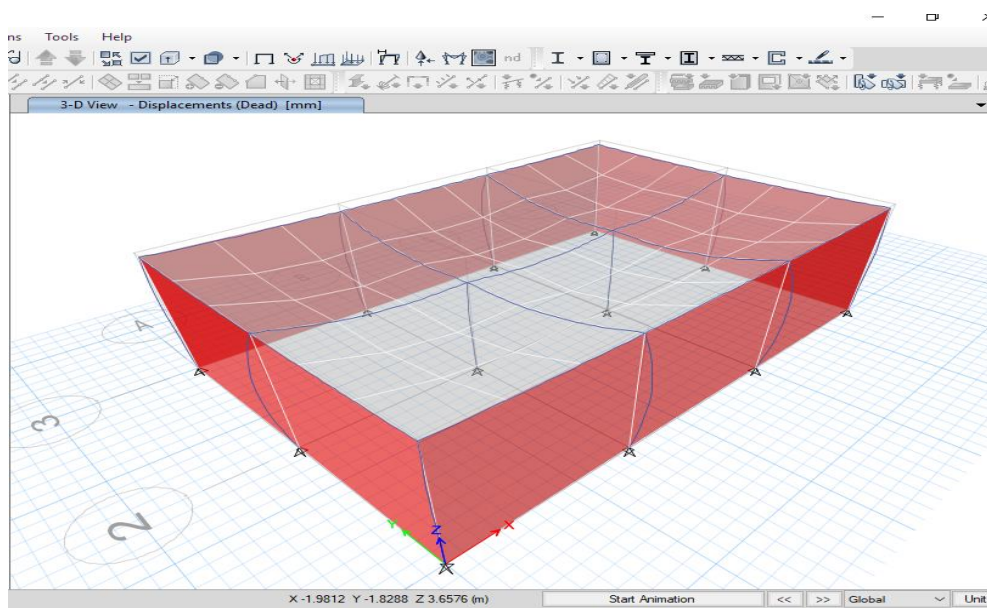


Figure 9: Displacement on Modelled Structure after Analysis

Source: ETABS modelling output, 2026.

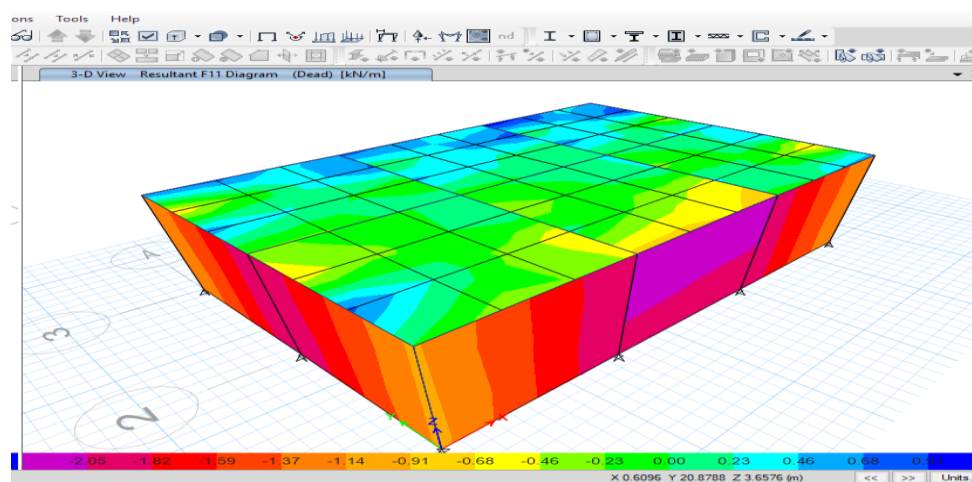


Figure 10: Stress Contours on Modelled Structure after Analysis

Source: ETABS modelling output, 2026.

The maximum story displacements under lateral and gravity load combinations were tracked across different material settings (M₁, M₄, and M₉) over 28-day and 90-day curing timelines, as compiled in Table 10.

Table 10: 28- & 90-Day Max Displacement Values

Mix	28 Day Max Displacement (mm)	90 Day Max Displacement (mm)
M ₁	2.20	2.20
M ₄	1.31	0.76
M ₉	1.48	1.45

Source: ETABS modelling output, 2026

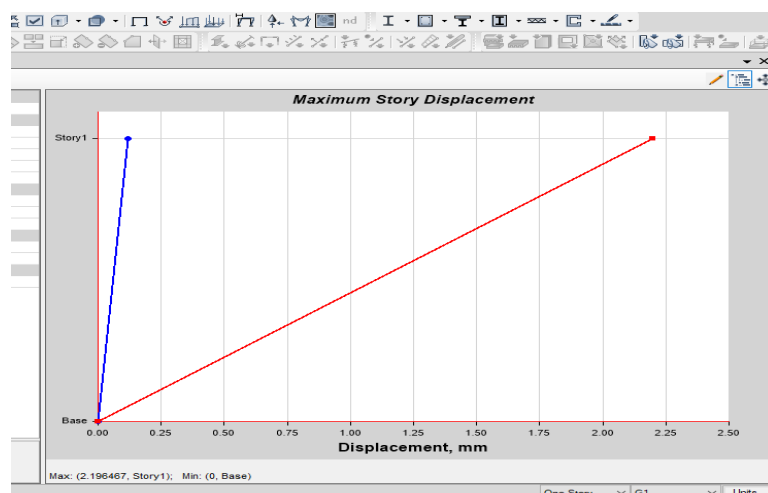


Figure 11: Maximum Displacement under M1 Material at both 28 and 90 Days
Source: ETABS modelling output, 2026

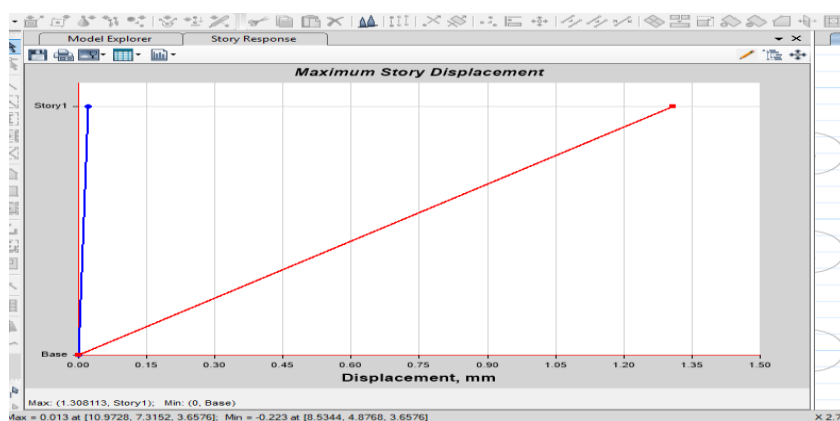


Figure 12: Maximum Displacement under M4 Material at 28 Days
Source: ETABS modelling output, 2026

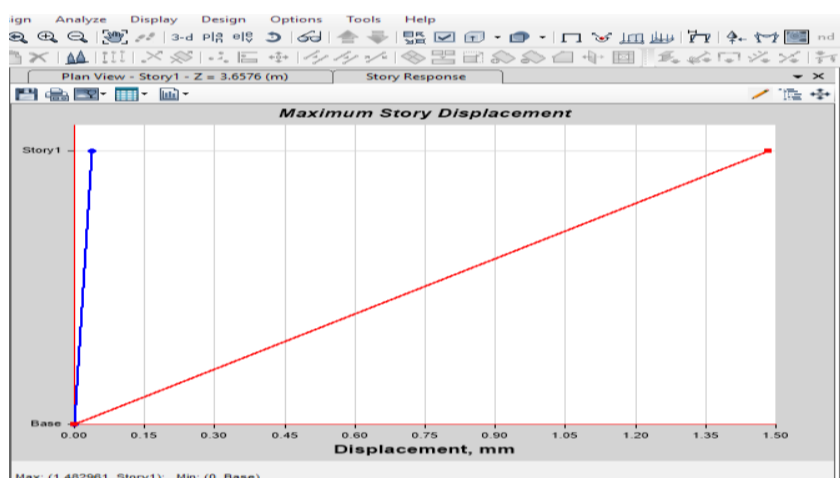


Figure 13: Maximum Displacement under M9 Material at both 28 Days
Source: ETABS modelling output, 2026

Nonlinear Pushover Performance and Ultimate Strain Capacity

To assess post-elastic ductility and ultimate failure mechanisms, a nonlinear pushover analysis was performed using isotropic masonry hinges calibrated to the experimental stress-strain profiles. The resulting stress-strain curves across the milestone curing regimes are plotted in Figures 14 through 16. The ultimate mechanical strain values at structural failure are summarized in Table 11.

Table 11: 28- & 90-Day Max Strain Values

Mix	28 Day Max Strain($\times 10^{-3}$)	90 Day Max Strain($\times 10^{-3}$)
M1	0.002219	0.002219
M4	0.001111	0.000014
M9	0.001111	0.000017

Source: ETABS modelling output, 2026.

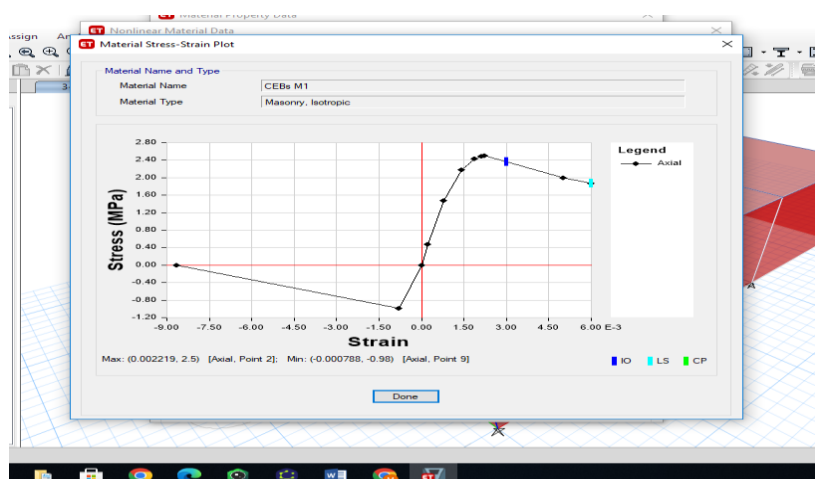


Figure 14: Stress-Strain Plot under M1 Material at both 28 and 90 Days

Source: ETABS modelling output, 2026.

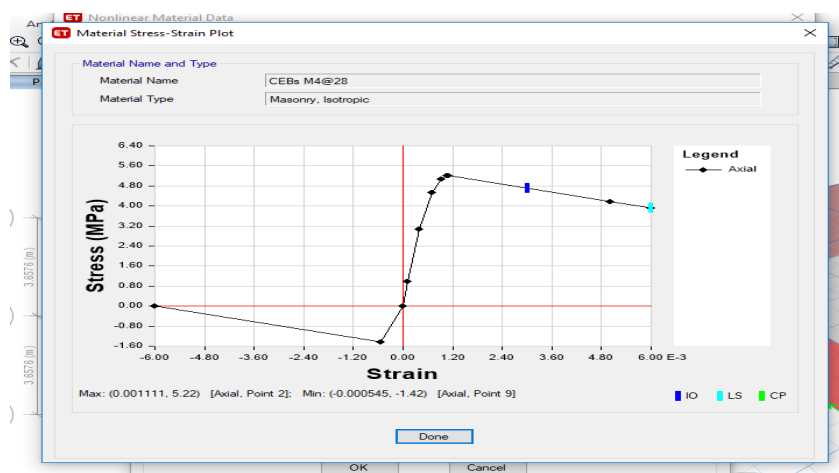


Figure 15: Stress-Strain Plot under M4 Material 28 Days

Source: ETABS modelling output, 2026

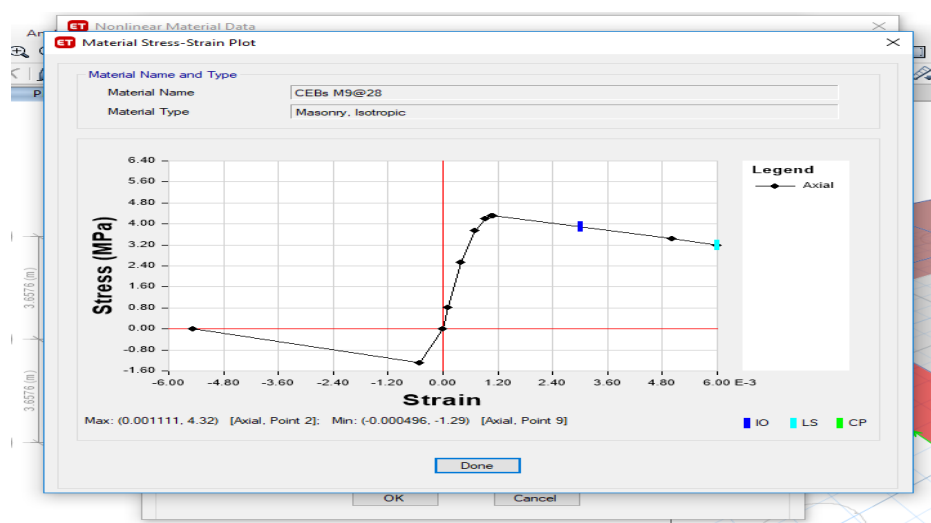


Figure 16: Stress-Strain Plot under Mg Material 28 Days

Source: ETABS modelling output, 2026

Discussion

Interpretation of Physical, Geotechnical, and Mechanical Behavior

The geotechnical classification indicates that the raw lateritic soil possesses a well-graded sand skeleton combined with moderate fines (36.83%) and a Plasticity Index of 13%. As described in soil stabilization literature (Jha & Sivapullaiah, 2020), this physical distribution provides the balanced skeletal framework required for compressed earth masonry: coarse particles offer structural interlocking, while fine fractions respond well to chemical binders. The progressive improvement in bulk density from 1800 kg/m³ (control) to 2120 kg/m³ in mix M₄ illustrates a dual physical-chemical mechanism. Granite Waste Powder (GWP) operates as an inert micro-filler, occupying the macro-voids between larger soil grains and optimizing overall particle packing density (López Boadella et al., 2019). Simultaneously, hydrated lime triggers immediate soil flocculation followed by long-term pozzolanic reactions with dissolved silica and alumina from the soil and GWP matrix, generating continuous networks of calcium silicate hydrate (C–S–H) gel (Akula & Little, 2020).

This structural densification directly drives the observed compressive strength gains. Mix M₄ achieved a 28-day compressive strength of 5.22 MN/m², representing a 108.8% increase over the 28-day control (2.50 MN/m²), and reached 6.50 MN/m² at 90 days, reflecting a 124.1% increase over the 90-day control (2.90 MN/m²) and a 24.5% strength gain from 28 to 90 days in lime-stabilized specimens demonstrates the sustained nature of secondary pozzolanic matrix development (Akula & Little, 2020).

Microstructural Density, Durability, and Environmental Resilience

A primary limitation of raw earthen masonry in structural applications is its vulnerability to water-induced softening and surface erosion (Fabbri et al., 2018). The durability indicators measured in this study highlight substantial performance gains. Capillary water absorption

fell from 1.40% (control) to 0.68% (M₄), while the capillary coefficient (C_b) decreased from 7.94 to 4.37. This attenuation in fluid transport occurs because pozzolanic reaction products gradually block internal pore networks, transforming continuous capillary channels into isolated pore structures (Nshimiyimana *et al.*, 2020).

Similarly, the surface mass loss caused by mechanical abrasion dropped from 1.00% to 0.58% in the optimized formulation (M₄). The increase in abrasion coefficient (C_a) from 0.96 cm²/g to 1.39 cm²/g reflects the formation of a hardened, weather-resistant outer boundary. These durability trends confirm that ternary stabilization mitigates severe rain and atmospheric degradation, addressing key structural concerns for earthen envelopes in tropical and monsoon regions (Nshimiyimana *et al.*, 2020).

Translation of Material Optimization to Structural FEA Performance

Translating unit-level material properties into full-scale structural models in ETABS fills an important computational gap identified in earthen masonry research (Nshimiyimana *et al.*, 2020). Assigning higher elastic moduli ($E_m=500f_c$) to stabilized shell elements led to a 40% reduction in lateral story displacement at 28 days for mix M₄ compared to M₁, expanding to a 65% displacement reduction at 90 days (0.76 mm vs. 2.20 mm).

This reduction in displacement reflects a marked increase in global lateral stiffness and base shear capacity, proving that material-level density and strength gains successfully scale to element-level structural performance. The high correlation ($R^2=0.92$) between experimental compressive values and modelled displacements confirms that standard isotropic shell modelling in ETABS can reliably capture the linear structural behaviour of stabilized earth walls under combined service loads.

Furthermore, the nonlinear pushover stress-strain analysis revealed a drop in ultimate compressive strain at failure from 0.002219 (control) down to 0.000014 in fully cured M₄. This change in failure strain indicates a behavioural transition from an unrectified, highly deformable earth matrix to a rigid, high-stiffness structural masonry unit capable of carrying vertical gravity load combinations and wind forces in multi-story housing schemes.

Practical Implications and Sustainability Alignment

From a practical engineering perspective, these findings validate GWP-lime stabilized CEBs as a viable structural alternative to conventional sand-crete blocks or cement-bound masonry. Utilizing local stone-quarrying waste (GWP) addresses local environmental waste accumulation while reducing reliance on high-carbon Portland cement (Meng *et al.*, 2025). This material-substitution strategy directly supports United Nations Sustainable Development Goal 11.1 by lowering the embodied carbon and material costs associated with load-bearing housing construction (UN-Habitat, 2016; United Nations, 2015).

Study Limitations

While the experimental and numerical findings demonstrate strong structural feasibility, several study limitations should be acknowledged:

1. Absence of Microstructural Imaging: Microstructural development was inferred from bulk physical density, compressive strength, and durability metrics rather than confirmed directly through Scanning Electron Microscopy (SEM) or X-ray Diffraction (XRD) analysis.
2. Simplified Material Homogeneity in Modelling: The FEA framework modelled the masonry assemblies as homogeneous isotropic shell continuum elements using macro-level properties, without explicitly modelling individual mortar joint interfaces or orthotropic directional anisotropy.
3. Lack of Physical Full-Scale Testing: Structural displacement and stress fields were evaluated exclusively via numerical finite element simulations in ETABS without experimental physical testing on full-scale wall panels under destructive cyclic lateral loading.
4. Unevaluated Physical Properties: Thermal conductivity, acoustic transmission, and comprehensive Life Cycle Assessment (LCA) environmental accounting were beyond the structural scope of this investigation.

Conclusions and Recommendations

Conclusions

The empirical findings from the laboratory experiments and the multi-scale numerical validation conducted in ETABS demonstrate that sustainable compressed earth blocks (CEBs) modified with industrial granite waste powder (GWP) and hydrated lime offer a structurally sound masonry alternative. The baseline lateritic soil matrix exhibits a well-graded sand skeleton with moderate fines (36.83% silt/clay fraction) and a Plasticity Index of 13%. This mineral composition provides an ideal cohesive and structural base that responds exceptionally well to chemical lime stabilization and particle packing optimization.

The integration of GWP and hydrated lime functions via a dual physical-chemical mechanism. GWP acts as an efficient physical micro-filler that fills the continuous micro-voids of the soil matrix, while lime triggers long-term pozzolanic reactions, generating dense calcium silicate hydrate (C-S-H) gels. This combined action raised the dry bulk density from a baseline of 1800 kg/m³ to a peak of 2120 kg/m³ after 90 days of curing. Consequently, this ternary blending significantly enhances structural load-bearing capacity. The ultimate compressive strength developed from a control baseline of 2.50 MN/m² to 5.22 MN/m² at 28 days for the optimized mix (15% GWP + 6% Lime), representing a 108.8% increase over the 28-day control. With extended hydration up to 90 days, the compressive strength reached 6.50 MN/m² (a 124.1% increase over the 90-day control and a 24.5% gain from 28 days), comfortably exceeding standard structural masonry requirements.

Moisture susceptibility and surface erosion drop sharply with stabilization. Total capillary water absorption decreased from 1.40% to 0.68%, and the surface mass loss from mechanical abrasion was minimized to 0.58%. These results confirm excellent pore

refinement, making the optimized blocks highly resilient against severe weathering. Furthermore, the finite element analysis in ETABS strongly aligns with the laboratory results ($R^2 = 0.92$), where optimized blocks achieved up to a 65% reduction in maximum lateral story displacement under combined load cases. Nonlinear pushover analysis tracked a transition from a highly deformable matrix to a stiff, high-strength structural element, validating its safety for low-to-medium-rise load-bearing masonry applications.

Recommendations

To build upon the findings of this research and facilitate the field implementation of this sustainable building technology, the following actions are recommended:

1. **Standardization of Mix Designs:** Earthen construction guidelines should officially integrate industrial stone waste cuts, such as granite waste powder, alongside traditional lime stabilization to standardize predictable commercial mix designs.
2. **Microstructural Performance Mapping:** Future studies should implement Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) tracking across the 28-day and 90-day curing marks to explicitly map out the crystalline growth phases of the C–S–H gels.
3. **Long-Term Thermal and Acoustic Characterization:** Given the increase in dry density, the structural units should be evaluated for thermal conductivity and acoustic insulation properties to ensure they maintain the natural indoor comfort advantages of earthen architecture.
4. **Field-Scale Structural Testing:** Full-scale physical wall panels should be constructed and subjected to destructive cyclic lateral and vertical loading in a laboratory environment to verify the exact boundary conditions simulated in the ETABS finite element model.
5. **Life Cycle and Carbon Accounting:** A comprehensive economic and life cycle assessment (LCA) should be performed to quantify the exact reduction in embodied carbon achieved by replacing conventional sand-crete blocks with these industrial waste-modified compressed earth blocks.

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