frontiers | Frontiers in Built Environment

TYPE Original Research
PUBLISHED 30 October 2025
DOI 10.3389/fbuil.2025.1697128

OPEN ACCESS

EDITED BY
Bjorn Birgisson,
University of Georgia, United States

REVIEWED BY
Salmabanu Luhar,
University of Bradford, United Kingdom
Carlos Rolando Rios Soberanis,
Centro de Investigación Científica de Yucatán, Mexico

*CORRESPONDENCE
Jorge Buele,
jorgebuele@uti.edu.ec

RECEIVED 01 September 2025
ACCEPTED 17 October 2025
PUBLISHED 30 October 2025

CITATION
Pinto-Almeida C, Jordán-Buenaño N, Armas-Robalino NA, Cáceres BC, Cajas-Corrales JC, Medina-Medina RS and Buele J (2025) Experimental analysis of ecuadorian adobe reinforced with natural fibers.
Front. Built Environ. 11:1697128.
doi: 10.3389/fbuil.2025.1697128

Experimental analysis of ecuadorian adobe reinforced with natural fibers

Carlos Pinto-Almeida[1], Nancy Jordán-Buenaño[2], Nahomy Anahí Armas-Robalino[1], Bianca Christina Cáceres[1], Juan Carlos Cajas-Corrales[1], Ronald Steeven Medina-Medina[1] and Jorge Buele[3]*

[1]Facultad de Ingenierías, Universidad Tecnológica Indoamérica, Ambato, Ecuador, [2]Facultad de Arquitectura, Diseño y Artes, Universidad Tecnológica Indoamérica, Ambato, Ecuador, [3]Centro de Investigación en Mecatrónica y Sistemas Interactivos (MIST), Facultad de Ingenierías, Universidad Tecnológica Indoamérica, Ambato, Ecuador

Introduction: In Latin America, the use of adobe as a building material remains highly relevant due to its low cost, local availability, and low environmental impact. Nevertheless, its limited mechanical strength and lack of standardization constrain broader implementation in contemporary architecture.
Methods: This study addresses that gap by experimentally evaluating the mechanical performance of adobe blocks stabilized with fine sand and wild straw, produced with red clay from Puyo (Ecuador). The research followed an applied, descriptive–comparative design encompassing material characterization, a 30-day natural curing process, and compressive strength testing using a SHIMADZU Concreto 2000X machine.
Results: The stabilized blocks achieved an average compressive strength of 9.63 kg/cm^2 (≈ 0.94 MPa), a mean displacement of 2.98 mm, and a maximum load of 14.16 kN, values that confirm their suitability for low-rise load-bearing structures. The inclusion of wild straw improved ductility, internal cohesion, and post-fracture integrity, while controlled shade drying minimized microcracking. Compared with traditional handmade bricks (31 kg/cm^2), the material showed lower strength but significantly higher environmental and economic sustainability.
Conclusion: The results provide empirical indicators to guide the standardization and scalability of stabilized adobe as a low-carbon, structurally viable alternative for rural and peri-urban housing in seismic regions.

KEYWORDS
adobe, compressive strength, sustainable construction natural fibers4, earthen materials, Ecuador

1 Introduction

Cement production accounts for between 5% and 8% of global CO_2 emissions (Cheng et al., 2023). If it were considered a country, it would rank as the third or fourth largest emitter, releasing 1.6 billion metric tons in 2022. Projections for developing countries (excluding China) indicate an increase to 1.4–3.8 billion metric tons by 2050 (Purton, 2024). Approximately half of these emissions originate from the chemical calcination process (Rothenberg, 2023; Guo et al., 2024). Additionally, while clinker production, dependent on fuel, electricity, and transport, represents another significant source (Carbone et al., 2022).

Given this scenario, research on sustainable building materials has generated alternatives that substantially reduce environmental impact. Among them, calcined clays stand out for requiring lower activation temperatures (600 °C–950 °C) than those needed for clinker production, thereby reducing the carbon footprint (Bustán-Gaona et al., 2023). Moreover, recent studies highlight their technical and economic feasibility (Kanagaraj et al., 2024). These solutions align with the Sustainable Development Goals (SDGs), specifically SDG 9, focused on resilient infrastructure and innovation (Costa, 2024), and SDG 11, aimed at sustainable cities (Lind et al., 2019). According to (Kwakye et al., 2024), the adoption of low-impact materials accelerates the fulfillment of these goals. The construction sector, which accounts for 13% of global GDP, 36% of energy consumption, and 39% of energy-related CO_2 emissions (Kiani Mavi et al., 2021), plays a strategic role in this transition, as emphasized by (Bhatt et al., 2022).

In South America, the sustainability of materials intersects with another critical challenge: seismic vulnerability. The western region, within the Pacific Ring of Fire, is among the most earthquake-prone areas (Combey et al., 2022). In Peru, many traditional adobe houses and historical temples show structural fragility due to the material's low strength, weak joints, and lack of reinforcement (Nochebuena-Mora et al., 2025; Romero Huaman et al., 2023) found that in Andean cities, self-built clay frame structures with infill masonry further increased risk. In response, the technical standard NTP E.080 was developed to establish parameters for design and construction with reinforced earth (Sencico, 2020).

Within this context, the present study evaluated clay from Puyo, Pastaza Province (Ecuador) as a raw material to produce reinforced adobe blocks (Figure 1). The suitability of the material was determined through the "mud ribbon test," which measures plasticity and cohesion cohesion (Swart et al., 2023), complemented by regulatory requirements on maximum moisture content (20% of dry weight) and controlled drying conditions (Sencico, 2020). Following these guidelines, blocks reinforced with straw and fine sand were produced and subjected to destructive compression tests to analyze their mechanical strength. The aim of this work is to provide scientific evidence supporting the environmental sustainability and structural viability of adobe, contributing to its standardization and its application in safe and responsible construction practices.

2 Materials and methods

2.1 Research approach

The study had an applied nature, employing a simple experimental design with a descriptive–comparative approach. Adobe blocks made of clay stabilized with straw and sand were produced and compared with commercial bricks under controlled conditions of manufacturing, curing, and testing. This design allowed for a systematic analysis of adobe performance and ensured the reproducibility of the results.

2.2 Testing and quality control

The compressive strength of the adobe was evaluated through compression tests using a SHIMADZU Concreto 2000X universal testing machine under controlled axial load. The maximum stress was calculated as $\sigma max = Fmax/A$, where Fmax represents the maximum applied load and A the cross-sectional area. Strain was estimated as $\varepsilon = \Delta L/L_0$. Based on these data, a stress–strain curve was constructed to identify the material's elasticity, creep, and failure behavior. To standardize the testing conditions, Table 1 summarizes the technical parameters applied during the compression tests of the adobe blocks.

The construction process was monitored under conditions similar to those of an actual worksite. The documentation included dosage (proportions and mixture moisture), mixing (homogeneity and plasticity), molding (layered filling, manual compaction, flatness, and edge definition), and curing. To minimize subjectivity, a standardized photographic record was implemented at each stage, with a fixed angle, visible metric scale, and consistent lighting.

Qualitative observations were organized in an incidence matrix (edge cracking, surface flaking, detachment) and linked to the mechanical compression results: failure modes (truncated cone, diagonal shear, edge detachment), maximum strength, and strain. This integrated analysis helped explain the shape of the stress–strain curve, provided deeper insight into failure modes, and established application criteria such as minimum performance thresholds for load-bearing walls.

2.3 Validity and ethical considerations

Internal validity was ensured by controlling materials, dosage, and curing, as well as by following a standardized loading protocol (speed, alignment, calibrated equipment), guaranteeing that differences resulted from the material itself rather than the testing procedure. Reliability was reinforced through a detailed logbook documenting the entire process (mixing, molding, curing, testing). Regarding external validity, the contextual nature of the study is acknowledged (local raw materials, specific climatic conditions), and replication in other settings with variations in clay, straw, and sand is proposed to assess transferability. From an ethical standpoint, the use of personal protective equipment (PPE), supervised workshop sessions, and transparency in procedures were prioritized to ensure a safe and technically sound process.

2.4 Materials and procedure

The study stems from the need to provide sustainable and resilient construction solutions for areas exposed to seismic and volcanic activity, exploring how the use of local resources can lead to materials with adequate structural performance. The preparation, curing, and testing of the adobe blocks were organized into sequential stages. Each phase was monitored to ensure reproducibility and control potential variations in the material. Table 2 summarizes the main steps, execution conditions, and key observations recorded throughout the process.

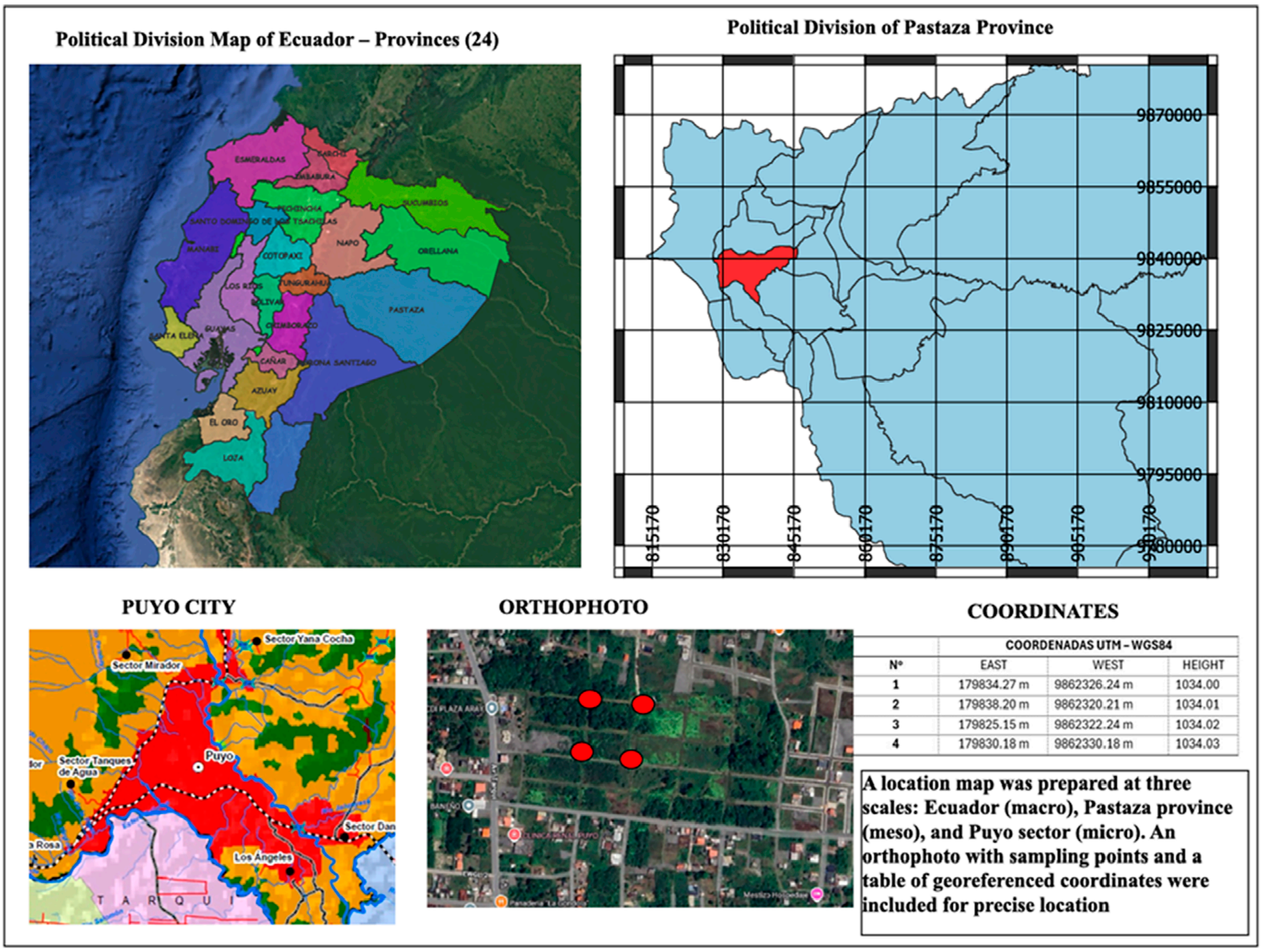

FIGURE 1
Location map of sampling sites in Puyo, Pastaza, Ecuador.

TABLE 1 Technical parameters of the compression tests.

Parameter	Description
Testing equipment	Universal testing machine SHIMADZU – Model CONCRETO 2000X
Maximum load capacity (Load Cell)	2000 kN
Testing condition	Specimens tested in dry state (natural curing for 30 days, humidity <5%)
Standard applied	ASTM C140 – Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units
Loading rate (Cross-head speed)	0.25 MPa/s
Cross-sectional area	150 cm^2 (15 cm × 10 cm)
Testing temperature	12 °C
Conditioning time (Warm-up)	15 min before testing

2.4.1 Justification of curing time and drying conditions

Although in traditional practice adobe blocks are usually exposed to solar drying for a period of 3–5 days before being used in construction, in this research a natural curing period of 30 days was chosen in order to ensure complete stabilization of the moisture content, minimize residual internal stresses, and guarantee the homogeneity of mechanical properties during laboratory tests.

TABLE 2 Stages of the adobe production process.

Process stage	Conditions/Main activity	Key observations
Mixture preparation	Clay 40.5%, sand 32.2%, water 24.1%, straw 3.2% (cut into 10 cm pieces)	Good cohesion and workability
Molding	Wooden molds (15 × 10 × 10 cm), layer-by-layer compaction	Uniform surface, no detachment
Curing (0–10 days)	Shade drying, natural ventilation, periodic rotation	High humidity, appearance of surface microcracks
Curing (11–20 days)	Continued drying under the same conditions	Progressive decrease in humidity and weight
Curing (21–30 days)	Stable drying without direct sun or rain exposure	Dimensional stability and reduction of microcracks
Compression testing	SHIMADZU Concreto 2000X machine, controlled axial load	Measurement of σ and ε; construction of stress–strain curve

This experimental decision is based on: 1) Moisture control and reduction of variability in tests: A residual moisture content can significantly alter compressive strength, generating dispersion in the results. Prolonged drying allows moisture levels below 5% to be reached, a condition recommended for the mechanical characterization of earthen materials. 2) Better microstructural development: The progressive evaporation of water and the slow drying process favor the formation of a denser and more cohesive internal matrix, especially in mixtures reinforced with plant fibers, where the water-fiber interaction directly influences the toughness of the material.

Additionally (Sencico, 2020), supports the use of different preparation and curing methodologies to ensure the quality of adobe. The standard establishes that crack control does not depend exclusively on the presence of fibers, since it can be achieved through the addition of coarse sand and adjustments in the mixture.

2.4.2 Moisture absorption test

In order to evaluate the water absorption capacity and dimensional stability of the adobe blocks produced, a moisture absorption test was carried out in accordance with the Standard NTE INEN 296 (Servicio Ecuatoriano de Normalización, 2015). This procedure allowed determining the variation in mass before and after immersion in water, quantifying the percentage of absorption and the behavior of the material under high humidity conditions. Table 3 summarizes the test phases, the methods applied, and the controlled experimental conditions during the process.

2.5 Characterization of red clay

The clay used comes from the same geographic corridor of Puyo–Santa Clara (Pastaza Province, Ecuador), located in alluvial deposits of volcanic origin and subgrade horizon (0.50–1.00 m depth). To describe the properties of the clayey soil in this corridor, results from grain size analysis, moisture content, and Atterberg limits were used from a geotechnical study conducted in the same area (Santa Clara–San Vicente), with identical sampling depth and applicable ASTM standards. This study classifies the material as a cohesive fine soil with a high percentage of fines and medium–high plasticity, consistent with clays suitable for adobe production. The procedures applied included ASTM D422 (grain size analysis) and ASTM D2216 (moisture content), among others.

According to the USCS/AASHTO criteria reported in the sectoral study, the soil corresponds to an inorganic plastic clay (USCS family CL/CH based on measured limits) and A-7-5 in AASHTO, typical of clayey soils with sufficient cohesion for molding and good workability in the plastic state. The combination of a dominant fine fraction, intermediate plasticity, and observed cohesion in the Puyo–Santa Clara corridor justifies its use as a matrix for fiber-reinforced adobe, as it facilitates compaction and block integrity during drying and the hygrothermal cycles characteristic of the region.

2.5.1 Grain size analysis

The grain size analysis shown in Table 4 was performed in the Santa Clara Parish, with a sampling depth between 0.50 m and 1.00 m. The procedure followed ASTM D421-58 and ASTM D422-63 standards, which establish the technical guidelines for soil sample preparation and particle size distribution determination. The study was carried out on October 1, 2025. Figure 2 presents the granulometric curve corresponding to the percentage of material passing through each sieve size, illustrating the predominance of fine particles characteristic of cohesive clayey soils in the region.

2.5.2 Origin and nature of the fiber

The straw used in this study is an agricultural by-product obtained after harvesting grasses, mainly rice, barley, and wheat. In the Ecuadorian context, this plant fiber, commonly known as paja de monte or ichu (Stipa ichu), is characterized by its abundance, low cost, renewable nature, and biodegradability, making it a strategic resource for sustainable construction. The incorporation of plant fibers into the adobe matrix results in a significant improvement in ductility, toughness, and the material's capacity to absorb energy. Compressed straw bundles help distribute internal stresses and reduce the formation of microcracks, while their contribution to shear stress resistance can reach increases of up to 41.57%. These findings highlight the active structural role of the fiber, particularly in enhancing tensile and flexural strength (Ramos and Viera, 2025).

2.5.3 Inclusion of unreinforced adobe

To more accurately determine the effect of natural reinforcement on the mechanical and physical properties of the experimental

TABLE 3 Moisture absorption test phases.

Test phase	Procedure description	Method applied	Test conditions	Observations
Sample selection	Previously produced adobe blocks were selected, ensuring uniformity in composition and dimensions	Five representative blocks from the batch were chosen	—	The blocks showed structural integrity and no visible cracks
Sample identification	A unique number was assigned to each block to ensure traceability during the test	Numbering from 1 to 5	—	Marked with wax pencil or permanent marker on the surface
Determination of initial weight	The weight of each block was recorded before immersion, constituting the initial reference mass	Weighed on a precision digital scale (±0.1 g)	Room temperature (20 °C–25 °C)	Denoted as initial mass (M_0)
Immersion in water	The absorption capacity was evaluated through complete immersion of the blocks	Each block was completely submerged in a laboratory pool	24 h at room temperature	Ensure blocks were fully covered and without air bubbles
Surface drying	After immersion, the blocks were removed and excess surface water was eliminated	Dried with a clean absorbent cloth before the final weighing	Immediately after immersion	Avoid exposure to sunlight or air currents that could alter the measured mass
Determination of final weight	The weight of each block was recorded again after immersion, constituting the final mass	Weighed on the same scale to ensure consistency	Room temperature	Denoted as wet mass (M_1)
Calculation of moisture absorption	The water absorption of each block was calculated using the NTE INEN 296 formula	% Absorption = $[(M_1 - M_0)/M_0] \times 100$	—	The batch average was calculated for comparative analysis

adobe, an additional batch of specimens was produced without the incorporation of plant fibers, using only red clay and fine aggregates under the same dosage, molding, and drying conditions as the reinforced mixtures. This "control" sample provided a direct point of comparison to identify the influence of reinforcement on structural behavior.

During visual evaluation and post-fracture analysis, the fiber-free blocks showed a surface cracking pattern characterized by more pronounced longitudinal and transverse fissures, loss of internal cohesion, brittle fragmentation, and granular disintegration under load application. This behavior results from the absence of fibrous elements that, in the reinforced blocks, act as tension bridges distributing stresses, limiting crack propagation, and increasing material toughness. The observed performance aligns with previous studies on the role of natural fibers as reinforcement in earthen materials, where their inclusion improves energy absorption capacity, deformation before failure, and performance under compressive loads (Sanchez-Calvillo et al., 2021).

3 Results

The practical experience enabled the identification of key findings related to the production of adobe stabilized with natural materials. Results are presented in terms of the properties of the soil used, emphasizing the role of clay as the fundamental component that provides cohesion, plasticity, and thermal behavior. Table 5 summarizes the most relevant characteristics of the red clay extracted from the El Canelo sector, Puyo city, Pastaza province.

The characterization of clay not only made it possible to describe its physical properties but also to relate them to principles of materials physics and bioclimatic architecture. The plasticity limits (LL, PL, PI) highlighted their workability in a wet state, which favors molding and provides initial strength before drying. Natural moisture varies depending on the extraction site, while real density showed values consistent with low porosity, translating into good structural performance of adobe.

During the initial phase, the clay from Puyo presented a rigid consistency that required manual handling with shovel and spatula. In the stage of progressive hydration, the roll test served as an empirical indicator to balance moisture and plasticity. The addition of dry straw improved cohesion and reduced the appearance of cracks during drying, while the use of fine sand increased compaction and resistance to moisture. The molded blocks retained a regular shape, and shade drying allowed controlled solidification, preventing surface fissures. The results showed that adobe quality depends largely on the control of materials, dosage, and mixing technique. To better understand block performance, it was also necessary to analyze the fine sand used in the mixture. Table 6 summarizes its main properties and their relevance in adobe production, highlighting its role in density and compressive strength.

In earthen construction, sand plays a decisive role in the porosity and durability of blocks, making its characterization not

TABLE 4 Grain size analysis of red clay.

Sieve	mm	Wretained (g)	Cumulative wretained (g)	% CUM. RET.	% PASSING
No. 4	4.75	7.36	7.36	0.74%	99.26%
No. 8	2.36	18.80	26.16	2.62%	97.38%
No. 10	2.00	21.60	47.76	4.78%	95.22%
No. 16	1.18	24.20	71.96	7.20%	92.80%
No. 30	0.60	63.80	135.76	13.58%	86.42%
No. 40	0.43	79.60	215.36	21.54%	78.46%
No. 50	0.30	87.20	302.56	30.26%	69.74%
No. 60	0.25	105.80	408.36	40.84%	59.16%
No. 100	0.13	131.60	539.96	54.00%	46.00%
No. 200	0.05	107.60	647.56	64.76%	35.24%
Pan	–	343.20	990.76	99.08%	0.92%

Total sample weight (Showed Weight): 1,000.00 g; % CUM. RET., percent cumulative retained; % PASSING, percent passing.

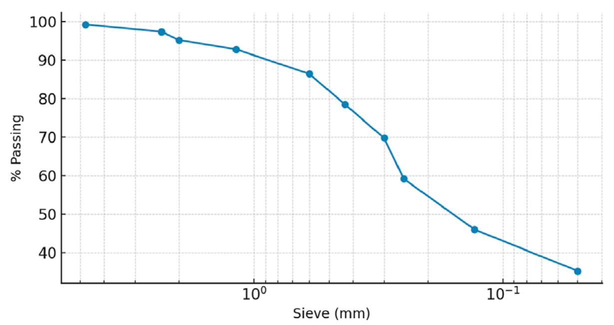

FIGURE 2
Granulometric curve of red clay.

optional but critical to ensuring the quality of artisanal adobe. The quantification of each component in the mixture provides a clearer understanding of its mechanical behavior and service life under real usage conditions. In this study, the formulation included clay, fine sand, water, and straw, each fulfilling a specific function within the microstructure: clay provided cohesion, sand-controlled porosity and improved strength, water regulated plasticity, and straw acted as a natural reinforcement against cracking.

The mass distribution of the components used for the fabrication of small adobe blocks measuring 10 × 10 × 15 cm was as follows: clay 40.5%, sand 32.2%, water 24.1%, and straw 3.2%. This proportion ensured a balanced contribution of each element, with clay as the cohesive matrix, sand as the stabilizing filler, water as the regulator of plasticity, and straw as a reinforcement to mitigate cracking. The application of this proportion resulted in blocks with good compaction, cohesion, and internal adhesion, which translated into improved compressive performance. Likewise, appropriate dosing contributed to maintaining a balance among mechanical, physical, and chemical properties, ensuring a more stable material with greater potential for long-term use in construction applications.

The compression analysis was conducted in the laboratories of a university. For this purpose, the dimensions and mass of the adobe blocks were first characterized, followed by mechanical strength testing. Figure 3 shows the block used in the tests, with dimensions of 15 cm in length, 9 cm in width, and 9 cm in height, corresponding to a prismatic geometry close to cubic form. The weight of each sample was determined using a precision electronic balance, as illustrated in Figure 4. The analyzed block recorded a mass of 1.5865 kg, a key value for relating volume, density, and structural performance.

Finally, the blocks were subjected to compression tests using the SHIMADZU Concreto 2000X universal testing machine (Figure 5), which allowed precise control of the applied load and accurate recording of mechanical parameters. The results, summarized in Table 7, indicate an average maximum load of 9.08 kN and an average compressive stress of 0.62 N/mm^2. The average displacement and deformation reached 2.98 mm, while the maximum compressive strength of the stabilized adobe was determined to be 0.944 N/mm^2 (≈9.63 kg/cm^2), confirming the load-bearing capacity of the material within acceptable ranges for traditional construction systems.

The compressive strength values obtained in blocks reinforced with natural fiber ranged between 0.62 and 0.94 MPa (approximately 6.2–9.63 kg/cm^2), confirming their suitability for small-scale and artisanal building systems. Several studies report that the typical compressive strength of earth-based construction materials, such as adobe blocks and compacted soils, ranges from 0.49 to 4.9 MPa (5–50 kg/cm^2), depending on clay content, soil gradation, compaction method, and the presence of fibrous reinforcements (Peraza-Gongora et al., 2023).

TABLE 5 Properties of red clay, el Canelo sector, Puyo city, Pastaza province.

Property	Value/Description	Technical observation
Liquid limit (LL)	35%–45%	Moderate plasticity; ensures workability during molding
Plastic limit (PL)	15%–25%	Good workability in wet state
Plasticity index (PI)	20%–25%	High plasticity; reduces risk of premature cracking
Natural moisture	12%–24%	Variable depending on site and depth; may require stabilization
Real density	2.30–2.55 g/cm^3	Suitable values for low porosity and optimal strength in ceramic units

Table adapted from (Gandia et al., 2019).

TABLE 6 Properties of fine sand.

Property	Technical description	Relevance in adobe
Texture/granulometry	Fine; improves density and compaction	Provides filler and structural stability
Permeability	Reduces seepage up to 50%	Limits weakening caused by water infiltration
Chemical reactivity	Low if washed	Impurities of volcanic origin must be checked
Compatibility with cement	Favors physical adhesion	Increases stability in mixtures with stabilizers
Compaction	Enhances overall cohesion	Facilitates uniform drying without cracks
Technical warning	No granulometric curve available	Requires laboratory validation before large-scale use

Adapted from (Moon et al., 2019).

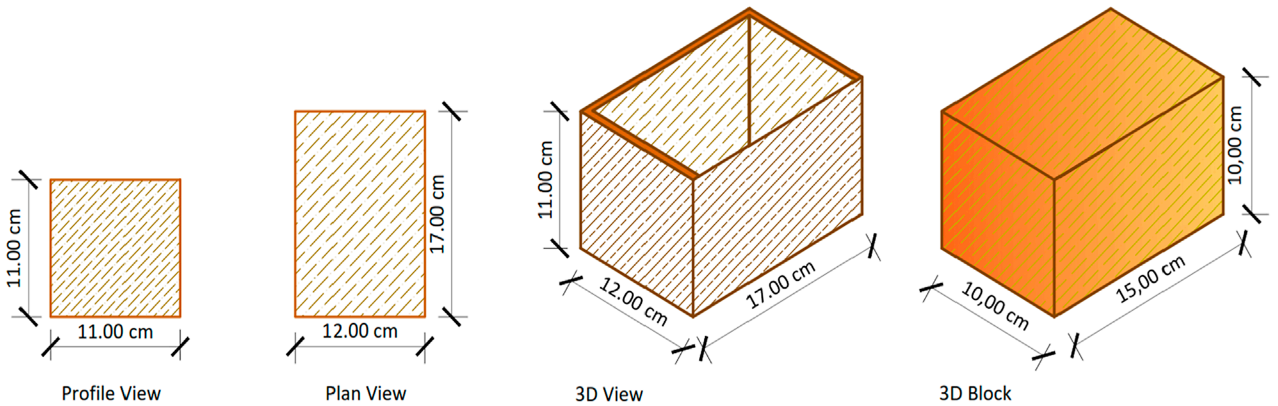

FIGURE 3
Dimensions of the adobe block used in the compression test.

In this context, the obtained results demonstrate that the studied material falls within internationally accepted parameters, ensuring adequate structural performance for load-bearing walls, enclosures, and low-rise buildings typical of traditional construction systems. Furthermore, the inclusion of natural fibers not only increased the average strength but also improved the post-failure behavior, reducing material brittleness and promoting a more ductile fracture pattern, desirable features in seismically active regions.

The stress–strain diagram obtained from the compression test of the adobe block is presented in Figure 6. The curve illustrates the relationship between applied force and material displacement, showing a clearly defined proportionality range up to the maximum compressive stress of 0.9 N/mm^2. This analysis is essential to understanding both the structural capacity and the ductility of adobe under load. During the test, it was observed that the incorporation of straw into the mixture enhanced internal compaction, which translated into an increase in compressive mechanical strength.

FIGURE 4
Weighing process of an adobe block.

FIGURE 5
Compressive strength test of the adobe block.

3.1 Comparative analysis with a traditional handmade brick

To contextualize the performance of adobe against a material widely used in Ecuador, a compression test was carried out on traditional handmade bricks. These bricks have a rectangular geometry of 27 cm in length, 12 cm in width, and 8 cm in height (Figure 7), dimensions that define a load area of 324 cm^2 and allow the evaluation of their structural behavior under axial loading. The stress–strain diagram obtained (Figure 8) shows a well-defined proportionality in the elastic stage, reaching a maximum compressive stress of 31 kg/cm^2, which is characteristic of their resistance under standard manufacturing and curing conditions.

In contrast, the experimentally produced adobe blocks had smaller dimensions (15 × 10 × 10 cm) and, consequently, a reduced load area (150 cm^2). The compression test yielded a maximum load of 14.16 kN, equivalent to an ultimate compressive stress of 9.63 kg/cm^2. This difference highlights not only the dimensional variability between the two materials but also the contrast in mechanical properties derived from their composition, dosage, and curing processes.

Table 8 summarizes comparative analysis, showing that the handmade brick withstands loads approximately three times greater than those of the stabilized adobe. However, this difference should not be interpreted simplistically. While commercial bricks benefit from a more standardized production process, adobe retains the advantage of being a low-impact, locally available material with potential for optimization through dosage adjustments and improved curing techniques. In this sense, comparative analysis highlights not only differences in resistance but also opportunities for innovation in sustainable construction, where adobe can play a relevant role if its mechanical performance is strengthened through stabilization strategies and normalization of the production process.

The compression tests were carried out at the Materials Testing Laboratory of Universidad Tecnológica Indoamérica (Santa Rosa Technological Campus, Ambato, Ecuador). In addition to recording loads and deformations, a macroscopic analysis of the cracking and fracture process of the blocks was performed during the tests to understand the evolution of damage and its relationship with the material's structural strength.

Direct observation made it possible to identify three distinct stages in the deterioration process. In the initial stage of surface cracking, as the axial load increased, small longitudinal and transverse cracks appeared on the adobe surface, mainly in areas of lower density. These initial fissures were associated with internal stresses resulting from natural discontinuities and differences in compaction.

In the controlled crack propagation stage, as the load progressively increased, the surface fissures developed into more defined cracks, spreading along preferential planes of weakness. The presence of natural fibers slowed the propagation rate, acting as tension bridges that redistributed stresses. In the failure and fracture pattern stage, the final rupture occurred due to the coalescence of major cracks, forming oblique failure planes typical of earthen materials with pseudo-brittle behavior. In most cases, the specimens maintained structural integrity after collapse, without complete pulverization, indicating a good degree of internal cohesion.

This fractographic behavior is consistent with findings reported in the scientific literature, where the incorporation of natural fibers alters the damage pattern of traditional adobe, reducing crack density and transforming the failure mode from brittle to progressively ductile (Peraza-Gongora et al., 2023; Rios-Soberanis et al., 2025).

TABLE 7 Results of the compression analysis using the SHIMADZU Concreto 2000X machine.

Name	Max. Force (kN)	Max. Stress (N/mm^2)	Max. Displacement (mm)	Max. Strain (%)
1_1	812.213	0.54148	337.125	337.125
1_2	788.053	0.52537	435.125	435.125
1_3	963.020	0.64203	241.575	241.575
1_4	269.222	0.17948	251.900	251.900
1_5	541.274	0.36085	294.200	294.200
1_6	756.327	0.50422	290.625	290.625
1_7	918.547	0.61236	285.625	285.625
1_8	1.054.540	0.70303	286.088	286.088
1_9	1.176.580	0.78439	285.975	285.975
1_10	1.293.820	0.86255	289.950	289.950
1_11	1.416.180	0.94412	288.100	288.100
Average	908.162	0.60544	298.754	298.754
Standard Deviation	330.597	0.22040	0.51291	0.51291
Range	1.146.960	0.76464	193.550	193.550

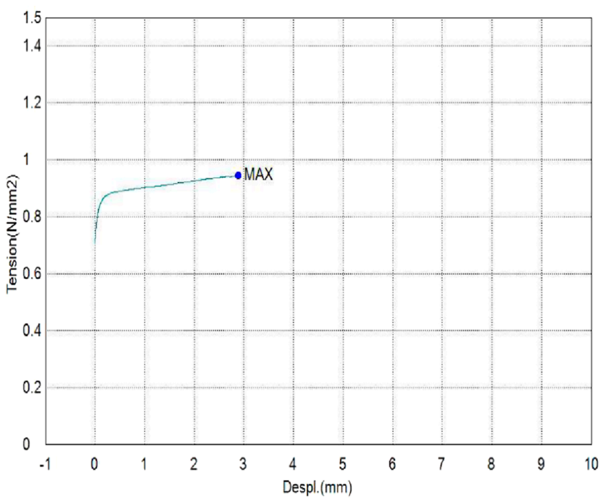

FIGURE 6
Stress–strain diagram of the adobe block.

4 Discussion

4.1 Mechanical behavior and structural performance

The results obtained in this study show that adobe stabilized with red clay from Puyo, fine sand, and wild straw achieved an average compressive strength of 9.63 kg/cm^2. While this value is lower than that reported for industrialized materials such as handmade brick (31 kg/cm^2), it falls within the range described for raw earth blocks stabilized with plant fibers in Latin American contexts. This strength, combined with controlled deformation and predictable failure modes, confirms the feasibility of adobe as a load-bearing material in low-rise constructions and as a sustainable alternative to inputs with a higher environmental footprint. Although the compressive strength results demonstrate the structural viability of the material, recent studies on shear resistance and scale effects in earthen walls (Ruiz et al., 2025) suggest that values obtained from small specimens may overestimate the actual resistance of full-scale walls. Incorporating correction factors, such as those established in AIS-610 and Andean building standards, is therefore essential to ensure safe and representative designs in seismic contexts.

Complementary research has also explored the inclusion of recycled expanded polystyrene (EPS) in traditional adobe for the conservation and restoration of heritage structures (Puy-Alquiza et al., 2025). Adobes with 5%–6% EPS (mesh #14) achieved compressive strengths between 0.99 and 1.08 MPa, meeting Peruvian and Ecuadorian regulatory thresholds (≥0.98 MPa). Although their resistance remains lower than that of the adobe in this study (9.63 kg/cm^2) and traditional handmade bricks (31 kg/cm^2), these mixtures represent a sustainable alternative with improved mechanical behavior for restoration and social housing. Similarly, stabilized adobes incorporating lime, cement, and Vetiver grass fibers in Thailand (Wang and Wang, 2025), reached only 2.14 kg/cm^2 after 10 years of exposure, considerably below the values obtained in this research, but showed excellent thermal

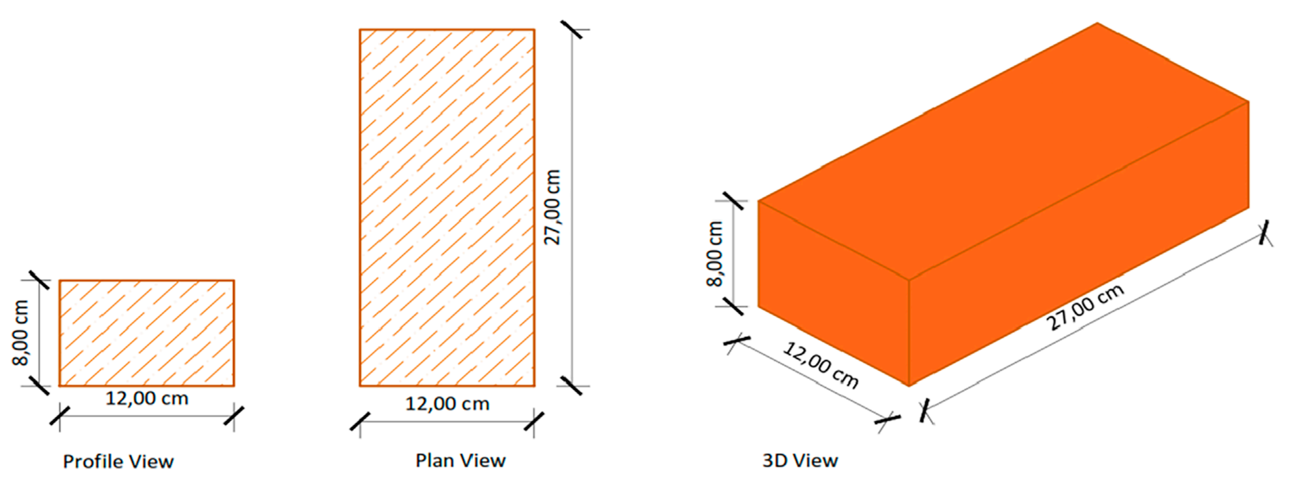

FIGURE 7
Dimensions of the handmade brick.

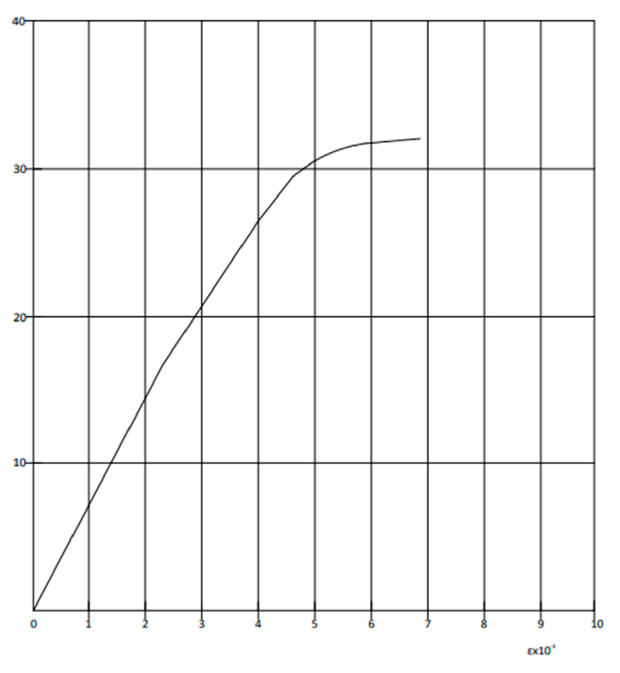

FIGURE 8
Stress–strain diagram of the handmade brick.

TABLE 8 Comparative analysis: handmade brick vs. adobe block.

Property	Handmade brick	Adobe block
Dimensions (cm)	27 × 12 × 8	15 × 10 × 10
Load area (cm^2)	324	150
Maximum load (kN)	70	14.16
Maximum compressive stress (kg/cm^2)	31	9.63

comfort and long-term durability. These comparisons confirm that, even with initially lower strength, combinations of natural fibers and eco-stabilizers can achieve acceptable long-term performance consistent with international standards such as NZS 4297–4299.

4.2 Cohesion and fracture mechanisms

The statement that the blocks exhibited good compaction, cohesion, and internal adhesion is supported not merely by qualitative observation but also by physical evidence obtained after compressive testing. During failure, the material did not disintegrate into loose particles or collapse abruptly; instead, cohesive clusters of clay and natural fibers remained strongly bonded (Figure 9). This internal morphology reflects a well-distributed particle arrangement, a dense matrix, and effective stress-bridging between fibers and the clay fraction, all of which contribute to the adobe's toughness.

The embedded fibers observed within the clay mass after fracture confirm a mechanical anchoring mechanism: the fibers act as internal reinforcement elements that prevent granular detachment and help redistribute stresses during loading. This visual evidence aligns with (Peraza-Gongora et al., 2023), who emphasized that internal cohesion can be evaluated through failure mode and post-test material integrity. The resulting fracture pattern was ductile and cohesive, with no total disaggregation of the block, confirming that the adopted mix proportions promote a dense matrix with high inter-component adhesion and effective compaction, even without resorting to advanced microscopic analysis such as SEM.

4.3 Effect of natural fibers and local adaptation

The role of wild straw proved particularly significant. Its incorporation reduced the appearance of cracks and improved internal compaction, aligning with international reports that highlight the

FIGURE 9
Post-fracture surface showing fiber anchorage and cohesive internal structure.

function of fibers in shrinkage control and stress dissipation. However, studies such as (Dawood et al., 2021), indicate that materials like sawdust can improve strength by up to 60% compared to conventional straw. In this sense, our results open the possibility of testing alternative fibers in future research, while also demonstrating that even with traditional local resources, satisfactory performance can be achieved (Kennedy et al., 2014). Historical and cultural evidence from Anatolia (Sedes, 2025), further highlights that adobe is not only a technical material but also a sociocultural and bioclimatic element. This perspective reinforces the need to preserve and adapt traditional techniques while strengthening technical training to reduce seismic vulnerability without eroding local identity.

In Europe, adobes reinforced with aquatic plant fibers such as bulrush and reed (Rocco et al., 2024) have reached compressive strengths of 1.48 MPa without fibers and between 0.65 and 1.0 MPa with various fiber ratios. Although these values are notably lower than those of the adobe developed in this study (9.63 kg/cm^2) and traditional handmade bricks (31 kg/cm^2), the addition of fibers reduces shrinkage cracks, improves flexural strength and seismic response, and decreases thermal conductivity by up to 20%, complying with international standards such as TS 2514 (Turkey), ASTM, and Australian norms. The addition of rice husk to siliceous and calcareous soils, as reported by (Banaba et al., 2025), resulted in significant improvements in thermal conductivity (reductions of 20%–35%) and moderate increases in compressive strength for certain mixtures, achieving up to 5.47 MPa in fired bricks. Although these values remain below those of our adobe (9.63 kg/cm^2) and the handmade brick (31 kg/cm^2), they highlight the potential of agricultural stabilizers to simultaneously enhance both thermal and mechanical properties.

Additionally, recent mathematical analyses (Vasić et al., 2020) indicate that by optimizing clay composition, approximately 48% fines and 20%–40% clay, and controlling drying conditions, it is possible to achieve compressive strengths of 7–14 MPa in hollow blocks and up to 20 MPa in solid cubes. These values far exceed both our adobe (9.63 kg/cm^2) and the handmade brick (31 kg/cm^2 ≈ 3 MPa), demonstrating that granulometric optimization can effectively bridge the gap between sustainability and mechanical performance.

4.4 Manufacturing methods and technological innovation

The manual forming method was another variable that influenced the results. Layer-by-layer compaction in 5 cm increments produced regular and stable blocks, though it limited density homogeneity and, consequently, maximum strength. Studies employing hydraulic presses and cement-based additives (Hamza and Abdulmuminu, 2021; Rocha et al., 2021) report strengths far exceeding ours, reaching values between 20 and 40 kg/cm^2. Nevertheless, the relevance of such techniques is relative: they require industrial inputs, high costs, and laboratory conditions that do not reflect the realities of self-construction in rural communities. By contrast, the artisanal method used in this study confirms that it is possible to obtain a functional material with minimal resources, if dosage, curing, and drying are rigorously controlled (Sanchez-Calvillo et al., 2021). In this regard, emerging technologies such as additive manufacturing of adobe blocks with optimized internal geometries (Tarek et al., 2025) have shown a twofold increase in compressive strength compared to traditional samples, suggesting a promising path toward modernizing production without compromising sustainability.

In Bhutan, the mechanical characterization and numerical modeling of adobe walls incorporating additives (Chettri et al., 2025) reported average strengths between 0.98 and 1.14 MPa with 10% cement and 10% sawdust. Although these values are lower than those of our adobe (9.63 kg/cm^2) and traditional handmade bricks (31 kg/cm^2), the inclusion of sawdust enhanced lateral load capacity and ductility, validated through numerical simulation, providing valuable insights for future seismic design guidelines. Adobe reinforced with biopolymers such as chitosan (Savary et al., 2025) has shown remarkable potential. In tests conducted according to ASTM C349 and Eurocode 6, the optimal blend of 0.2% chitosan +1.5% lime +1.5% cement achieved a compressive load of 35.46 kN, surpassing the recommended thresholds for load-bearing walls. This performance, superior to that of our adobe (9.63 kg/cm^2) and even to handmade bricks (31 kg/cm^2), demonstrates the potential of biocompatible stabilizers to improve both mechanical resistance and sustainability.

The comparative analysis with handmade brick also provides an important perspective. The difference in strength (31 vs. 9.63 kg/cm^2) does not necessarily imply absolute inferiority, but rather the need to situate each material within its application context. Bricks benefit from standardized production processes and a consolidated market, whereas adobe represents a low-cost, adaptable alternative with lower environmental impact. Moreover, the variability observed in adobe blocks reflects both the characteristics of local clay and the climatic conditions of curing, factors that must be acknowledged as part of the challenge in normalizing its production. In Iran, for example, studies on adobe and straw–clay composites used in the restoration of historical buildings (Hejazi et al., 2024) reported moderate compressive strengths ranging from 1 to 3 MPa, influenced by sandy particle size and limited clay expansion. Although these values are lower than those of our adobe (9.63 kg/cm^2) and handmade brick (31 kg/cm^2), they highlight the importance of tailoring mixtures and procedures to specific environmental and cultural contexts. Recent research employing computational optimization and 3D-printed molds for adobe walls (Gonidakis et al., 2024) has demonstrated notable improvements in natural lighting and thermal regulation without compromising stability, revealing new possibilities for hybrid and prefabricated construction systems.

The prolonged natural curing process of 30 days allowed the adobe blocks to reach an adequate balance between moisture loss and internal consolidation. This decision was based both on the environmental conditions of Ambato (≈15 °C, with high variability in solar radiation and frequent rainfall) and on the need to preserve dimensional stability of the pieces. Although this period exceeds the normative recommendation of 28 days, the strategy aligns with traditional practices observed in other regions, such as Iraq, where surface integrity and final strength are prioritized over production speed (Dawood et al., 2021). In contrast, research on accelerated drying in controlled environments, such as constant-temperature chambers reinforced with organic fibers in Romania (Surdu et al., 2023), achieves results in less time but relies on infrastructures that are difficult to reproduce in rural contexts, thus limiting their practical transferability.

In Brazil, stabilized adobe with a 12:1 soil-to-cement ratio was used in a double-wall system for passive food refrigeration on a real scale (Cassundé et al., 2022). This "Resfriador do Cerrado" demonstrated that handcrafted adobe can be integrated into innovative passive cooling solutions for vulnerable communities, extending its use beyond housing while contributing to energy efficiency without electrical refrigeration. Moreover, adobe walls have been successfully applied as thermal mass in agro-industrial systems. In indirect solar dryers for semi-arid regions (Bailou et al., 2025), adobe increased drying-air temperature by 4 °C–6 °C and stabilized internal conditions, reducing drying time without fossil fuels. These findings show that, beyond residential applications, adobe also holds promise as a passive component in energy-efficient systems.

4.5 Comparative sustainability and applicability

Regarding the compression test, the average strength of 9.63 kg/cm^2 positions the adobe produced in this study above formulations based exclusively on organic matter, such as bovine manure blocks (1.33 kg/cm^2) (Brito et al., 2023), and slightly superior to experimental mixtures with plant-based additives like prickly pear gum (8.8 kg/cm^2) (Vidales et al., 2022). These results confirm that the controlled combination of wild straw and fine sand tangibly improves load-bearing capacity without the need for costly external inputs. Nevertheless, the resistance remains lower than that reported for materials stabilized with mineral additives or geopolymers, such as blocks reinforced with fly ash and nanostructured polyaniline in Egypt, which reached 79.5 kg/cm^2 and significantly reduced water absorption (Morsy et al., 2024). These differences reflect both the degree of industrialization of the processes and the costs and technical complexity of the additives employed.

Beyond initial strength, durability is also crucial. Studies on accelerated weathering in historical adobe structures (Tauta Camacho et al., 2023) propose deterioration factors that can be integrated into design practices to ensure long-term performance against climate and aging. Similarly, experimental evaluations of multilayer walls in Turkey (Kıpçak and Erdil, 2025) showed that compressive strength decreased from 3.54 MPa in single-layer systems to 0.96 MPa in five-layer systems, although still meeting ASTM C1314 and Eurocode 6 requirements for the first three layers. These findings suggest that, in addition to composition, wall height and joint configuration play a decisive role in structural performance. For seismic contexts, complementing adobe with handcrafted brick or other load-bearing elements is recommended when greater heights are required, aligning with our own comparative observations.

The comparison across different approaches reveals a clear pattern: the highest strengths derive from processes using mechanical compaction and industrial additives; intermediate improvements are achieved through adjustments in granulometry and plant fibers; while purely organic formulations, though yielding lower strength, stand out for their low environmental impact and social relevance in self-construction contexts. In the case of compressed earth blocks (CEB) (Price et al., 2024), a mix containing 77% silt, 19% clay, and only 3% sand produces a fine-textured material molded with mechanical pressing. Although it lacks mechanical reinforcements, it exhibits electromagnetic properties suitable for non-destructive monitoring and radar-based assessment in earthen structures. Along this line, the inclusion of piasava fiber (Attalea funifera) (Da Conceição Gomes et al., 2024) in a sand-to-clay ratio of 4:6 with 3% fiber achieved 15%–30% increases in compressive strength and reduced water erosion. While still below the strength of handcrafted brick (31 kg/cm^2), these values are comparable to our adobe (9.63 kg/cm^2) and enhance durability and insulation, offering economic benefits to extractive communities.

In the Andean context, reinforcement with local fibers has also shown remarkable improvements. For example, adobes incorporating 5% Ichu straw (Stipa ichu) reached 42.75 kg/cm^2 (Loli Gutierrez et al., 2025), surpassing both our adobe (9.63 kg/cm^2) and handcrafted brick (31 kg/cm^2). Even mixtures containing 5% feathers exceeded the minimum compressive strength of 10.2 kg/cm^2 established by standard E.080, confirming that fiber dosage and type are key factors for meeting regulatory requirements without abandoning traditional resources. Similarly, adobes made with local clay soil stabilized with 4% Portland cement (CEM II/A-42.5) and reinforced with coconut fibers (Sanou et al., 2024) achieved strengths of 2–3.5 MPa, surpassing the 2 MPa minimum required for single-story buildings according to NF P 15-471. Although still below handcrafted brick (31 kg/cm^2), these findings indicate that combining natural fibers with cement reinforcement can make adobe more resilient against load and moisture in modern construction. Within this framework, the adobe studied in Pastaza achieves a strategic balance: sufficient strength for load-bearing walls in low-rise housing, combined with thermal and acoustic advantages derived from its internal porosity and modular thickness. This makes adobe not only a technically viable material but also a sustainable and culturally appropriate option for communities that prioritize self-managed construction and the use of local resources.

5 Conclusion

This study provides tangible evidence that adobe stabilized with fine sand and wild straw can meet the mechanical and environmental requirements for sustainable construction. The experimental blocks achieved an average compressive strength of 9.63 kg/cm^2, placing them within the international range for stabilized earth materials and confirming their structural viability for load-bearing walls in low-rise buildings. Beyond numerical performance, the research highlights three key contributions: (1) the establishment of reproducible fabrication and curing parameters, particularly a 30-day natural curing protocol that ensured dimensional stability and homogeneity; (2) the identification of wild straw as an effective, low-cost reinforcement that increased ductility and cohesion without external stabilizers; and (3) the formulation of a baseline for mechanical characterization and standardization of adobe production under Ecuadorian climatic conditions.

These results demonstrate that artisanal production, when guided by controlled dosage, compacting, and curing processes, can achieve predictable structural performance with minimal industrial inputs. Furthermore, the documented relationship between micro-cracking patterns, fiber anchorage, and cohesive fracture behavior provides insight for future guidelines on quality control and scalability, especially in community-based building contexts. Future work should focus on scaling production through modular molds and eco-stabilizers such as lime or bio-polymers to enhance long-term durability. Integrating these findings into local standards could strengthen the case for adobe as a standardized, low-carbon, and socio-technically adaptable material, bridging traditional knowledge with modern sustainable construction practices.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

CP-A: Writing – review and editing, Methodology, Conceptualization, Resources, Visualization, Funding acquisition, Formal Analysis, Writing – original draft, Validation, Project administration. NJ-B: Validation, Project administration, Data curation, Writing – original draft. NA-R: Writing – original draft, Investigation. BC: Investigation, Writing – original draft. JC-C: Investigation, Writing – original draft. RM-M: Writing – original draft, Investigation. JB: Validation, Methodology, Formal Analysis, Writing – review and editing, Supervision, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. The authors declare that the Article Processing Charge for this publication was funded by the Universidad Tecnológica Indoamérica.

Acknowledgments

We extend our gratitude to Universidad Tecnológica Indoamérica for its support in the dissemination of results.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. During the preparation of this manuscript, the authors used ChatGPT (GPT-5, OpenAI) for the sole purpose of revising English grammar and syntax. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Bailou, O., Aboubakar, C., Tubreoumya, G. C., Ouedraogo, E., Tiendrebeogo, E. S., Dissa, A. O., et al. (2025). Thermal and energy performance analysis of solar dryers with adobe walls: an experimental study in semi-arid regions. *Curr. J. Appl. Sci. Technol.* 44, 163–175. doi:10.9734/cjast/2025/v44i84597

Banaba, G., Murer, S., Rousse, C., Beaumont, F., Bliard, C., Chatelet, É., et al. (2025). Effect of rice husk addition on the hygrothermal, mechanical, and acoustic properties of lightened adobe bricks. *Materials* 18, 3364. doi:10.3390/ma18143364

Bhatt, A., Khanchandani, M., Rana, M. S., and Prajapati, S. K. (2022). Techno-economic analysis of microalgae cultivation for commercial sustainability: a state-of-the-art review. *J. Clean. Prod.* 370, 133456. doi:10.1016/j.jclepro.2022.133456

Brito, M. R., Marvila, M. T., Linhares, J. A. T., and Azevedo, A. R. G. de (2023). Evaluation of the properties of adobe blocks with clay and manure. *Buildings* 13, 657. doi:10.3390/buildings13030657

Bustán-Gaona, D., Ayala-Chauvin, M., Buele, J., Jara-Garzón, P., and Riba-Sanmartí, G. (2023). Natural lighting performance of vernacular architecture, case study oldtown pasa, Ecuador. *Energy Convers. Manag. X* 20, 100494. doi:10.1016/j.ecmx.2023.100494

Carbone, C., Ferrario, D., Lanzini, A., Stendardo, S., and Agostini, A. (2022). Evaluating the carbon footprint of cement plants integrated with the calcium looping CO2 capture process. *Front. Sustain.* 3, 809231. doi:10.3389/frsus.2022.809231

Cassundé, C. C., de Araújo, T., Yuba, A. N., and Pinto, J. O. P. (2022). *Evaluation of the hygrothermal behavior of a full-scale adobe evaporative cooler*. Geneva, Switzerland: Zenodo. doi:10.5281/zenodo.6846522

Cheng, D., Reiner, D. M., Yang, F., Cui, C., Meng, J., Shan, Y., et al. (2023). Projecting future carbon emissions from cement production in developing countries. *Nat. Commun.* 14, 8213. doi:10.1038/s41467-023-43660-x

Chettri, N., Leki, P., Dorji, T. K., Dorji, K., and Gautam, D. (2025). Mechanical characterization and numerical modeling of adobe walls with additives in normal and interlocking configurations. *J. Build. Eng.* 111, 113454. doi:10.1016/j.jobe.2025.113454

Combey, A., Audin, L., Gandreau, D., Benavente, C., Rosell, L., and Marconato, L. (2022). Reassessing the seismic hazard in the Cusco area, Peru: new contribution coming from an archaeoseismological survey on inca remains. *Quat. Int.* 634, 81–98. doi:10.1016/j.quaint.2022.07.003

Costa, E. (2024). Industry 5.0 and SDG 9: a symbiotic dance towards sustainable transformation. *Sustain. Earth Rev.* 7, 4. doi:10.1186/s42055-024-00073-y

Da Conceição Gomes, C., De Avila Delucis, R., and Machado Theisen, K. (2024). Valorization of piassava fiber by its incorporation in adobe bricks. *An. Acad. Bras. Ciênc.* 96, e20240210. doi:10.1590/0001-3765202420240210

Dawood, A. O., Mussa, F. I., Khazraji, H. A., Ulsada, H. A. A., and Yasser, M. M. (2021). Investigation of compressive strength of straw reinforced unfired clay bricks for sustainable building construction. *Civ. Environ. Eng.* 17, 150–163. doi:10.2478/cee-2021-0016

Gandia, R. M., Corrêa, A. A. R., Gomes, F. C., Marin, D. B., and Santana, L. S. (2019). Physical, mechanical and thermal behavior of adobe stabilized with "synthetic termite saliva." *Eng. Agríc.* 39, 139–149. doi:10.1590/1809-4430-Eng.Agric.v39n2p139-149/2019

Gonidakis, D. N., Frangedaki, E. I., and Lagaros, N. D. (2024). Optimizing daylight performance of digital fabricated adobe walls. *Architecture* 4, 515–540. doi:10.3390/architecture4030028

Guo, Y., Luo, L., Liu, T., Hao, L., Li, Y., Liu, P., et al. (2024). A review of low-carbon technologies and projects for the global cement industry. *J. Environ. Sci.* 136, 682–697. doi:10.1016/j.jes.2023.01.021

Hamza, B., and Abdulmuminu, I. (2021). Thermo physical properties of a sun dried clay brick moulded with cement and neem leaves ash as additives. *Int. J. Adv. Sci. Res. Eng.* 7, 60–69. doi:10.31695/IJASRE.2021.34011

Hejazi, B., Luz, C., Grüner, F., Frick, J., and Garrecht, H. (2024). Characterisation of adobe and mud–straw for the restoration and rehabilitation of Persian historical adobe buildings. *Materials* 17, 1764. doi:10.3390/ma17081764

Kanagaraj, B., Anand, N., Johnson Alengaram, U., Samuvel Raj, R., and Karthick, S. (2024). Limestone calcined clay cement (LC3): a sustainable solution for mitigating environmental impact in the construction sector. *Resour. Conservation and Recycl. Adv.* 21, 200197. doi:10.1016/j.rcradv.2023.200197

Kennedy, J. F., Smith, M. G., and Wanek, C. (2014). *The art of natural building-second edition-completely revised, expanded and updated: design, construction, resources*. Gabriola, British Columbia: New Society Publishers.

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

Kıpçak, F., and Erdil, B. (2025). Experimental evaluation of multi-layer brick and adobe materials. *Adıyaman Üniversitesi Mühendislik Bilim. Derg.* 12, 266–280. doi:10.54365/adyumbd.1702071

Kwakye, J. M., Ekechukwu, D. E., and Ogundipe, O. B. (2024). Systematic review of the economic impacts of bioenergy on agricultural markets. *Int. J. Adv. Econ.* 6, 306–318. doi:10.51594/ijae.v6i7.1342

Lind, J., Malmqvist, T., and Wangel, J. (2019). Key considerations when designing certification systems for urban sustainability and implications for the Swedish post-construction system citylab. *Sustainability* 11, 2673. doi:10.3390/su11092673

Loli Gutierrez, R. H., Yanac Toledo, L. M., Samamé Zegarra, E. K., and Pulido Cavada, A. M. (2025). Compressive strength of ichu-reinforced adobe: a comparative analysis. *Herança* 8, 128–134.

Moon, S.-W., Vinoth, G., Subramanian, S., Kim, J., and Ku, T. (2019). Effect of fine particles on strength and stiffness of cement treated sand. *Granul. Matter* 22, 9. doi:10.1007/s10035-019-0975-6

Morsy, M. I., Zain Eldin, A. M., El-Maghawry, H. A. M., Abdel Hamied, R. G., and Youssef, R. M. (2024). Impact of nanoscale polyaniline and fly ash on engineering properties of adobe bricks for north Coast region of Egypt. *Misr J. Agric. Eng.* 41, 0–184. doi:10.21608/mjae.2024.274204.1133

Nochebuena-Mora, E., Mendes, N., Salvalaggio, M., and Lourenço, P. B. (2025). The Seismic Performance of Earthen Historical Buildings in Seismic-Prone Regions: the Church of Santo Tomás de Aquino in Rondocan as a Complex Example. *Appl. Sci.* 15, 7624. doi:10.3390/app15137624

Peraza-Gongora, J., Rios-Soberanis, C. R., Verriest, A. J. E. D., and Rodriguez-Laviada, J. (2023). Geomechanical Characterization of Experimental Mud Bricks from La Joya Archaeological Site: effect of the Addition of Additives on Their Mechanical Properties. *Int. J. Archit. Herit.* 17, 1525–1541. doi:10.1080/15583058.2022.2043953

Price, S. R., Donohoe, J. P., Price, S. R., Fairley, J., and Robert, S. (2024). Complex permittivity of adobe verses frequency and water content. *Remote Sens.* 16, 3445. doi:10.3390/rs16183445

Purton, M. (2024). *4 ways to make the cement industry more sustainable*. Cologny, Geneva: World Economic Forum. Available online at: https://www.weforum.org/stories/2024/09/cement-production-sustainable-concrete-co2-emissions/ (Accessed August 25, 2025).

Puy-Alquiza, M. J., Miranda-Avilés, R., Puy, M. Y. M., Salazar-Hernández, M. C., and Sánchez, C. D. M. (2025). Adobes recycled with polystyrene: an alternative for the conservation and restoration of monuments and historical sites. *Mater. Construcción* 75, e369. doi:10.3989/mc.2025.386524

Ramos, H., and Viera, P. (2025). Caracterización de Paneles de Paja y su Evaluación Estructural en una Edificación de Tres Pisos. *Rev. Politécnica* 55, 29–40. doi:10.33333/rp.vol55n1.03

Rios-Soberanis, C. R., Daneels Verriest, A. J. E., Peraza-Gongora, J., Borges-Palomo, D. S., and Rodriguez-Laviada, J. (2025). Experimental characterization of flexural strength and water absorption properties of mud-bricks manufactured under prehispanic technique and the addition of asphalt additives. *Int. J. Archit. Herit.* 19, 2190–2200. doi:10.1080/15583058.2024.2402314

Rocco, A., Vicente, R., Rodrigues, H., and Ferreira, V. (2024). Adobe blocks reinforced with vegetal fibres: mechanical and thermal characterisation. *Buildings* 14, 2582. doi:10.3390/buildings14082582

Rocha, R. R. da, Barros, G. H. V., Silva, R. J. da, and Delatore, R. S. (2021). *Resistência mecânica de tijolos "adobe" reforçados com resíduos industriais*. Brazil: Colloquium Exactarum. p. 30–37.

Romero Huaman, J. P., Flores Rojas, D. A., Nizama Mallqui, J. L., Valenzuela Inga, A. J., Benito Zuñiga, J. G., and Estrada Porras, F. E. (2023). Self-built houses in a Peruvian andean city: seismic vulnerability and seismic behavior. *Civ. Eng. Archit.* 11, 3488–3504. doi:10.13189/cea.2023.110619

Rothenberg, G. (2023). A realistic look at CO2 emissions, climate change and the role of sustainable chemistry. *Sustain. Chem. Clim. Action* 2, 100012. doi:10.1016/j.scca.2023.100012

Ruiz, D. M., Reyes, J. C., Alvarado, Y. A., Vacca, H., Tarque, N., and Jerez, S. (2025). Investigating scale effects on experimental shear strength of earthen walls (adobe and rammed-earth). *Buildings* 15, 689. doi:10.3390/buildings15050689

Sanchez-Calvillo, A., Alonso-Guzman, E. M., Martinez-Molina, W., Navarrete-Seras, M. A., Ruvalcaba-Sil, J. L., Navarro-Ezquerra, A., et al. (2021). Characterization of adobe blocks: point-load assessment as a complementary study of damaged buildings and samples. *Heritage* 4, 864–888. doi:10.3390/heritage4020047

Sanou, I., Bamogo, H., Sory, N., Gansoré, A., and Millogo, Y. (2024). Effect of the coconut fibers and cement on the physico-mechanical and thermal properties of adobe blocks. *Heliyon* 10, e38752. doi:10.1016/j.heliyon.2024.e38752

Savary, M., Sazedj, S., Pinto, J. F. G., and Reis, L. F. G. (2025). *Improving the adobe structures by bio friendly materials*. doi:10.21203/rs.3.rs-6939709/v1

Sedes, F. (2025). The culture of adobe usage in Anatolia. *Motif Acad.* 18, 888–898. doi:10.12981/mahder.1557177

SENCICO (2020). *Norma E.080 Diseño y construcción con tierra reforzada*. San Borja: SENCICO.

Servicio Ecuatoriano de Normalización (2015). NTE INEN 296. In: *Ladrillos cerámicos. Determinación de absorción de humedad*. Pichincha, Ecuador: Servicio Ecuatoriano de Normalización. Available online at: https://es.scribd.com/document/378644078/nte-inen-296-1 (Accessed October 6, 2025).

Surdu, E., Farcaş-Flamaropol, C., Cârdei, P., Durbacă, I., and Sporea, N. (2023). Research on the recovery of some agricultural waste for the manufacture of composite materials with clay matrices. *J. Eng. Stud. Res.* 29, 57–68. doi:10.29081/jesr.v29i4.008

Swart, D., Dippenaar, M. A., and Van Rooy, J. L. (2023). Field tests for the identification of silts. *Bull. Eng. Geol. Environ.* 82, 425. doi:10.1007/s10064-023-03442-7

Tarek, S., Mansour, Y., Abdelmohsen, S., Kohail, M., and Assem, A. (2025). Evaluating the role of additive manufacturing in adobe brick enhancement: a comparative study. *Ain Shams Eng. J.* 16, 103298. doi:10.1016/j.asej.2025.103298

Tauta Camacho, J., Uribe-Kaffure, C., and Ramos-Cañón, A. (2023). Mechanical deterioration by weathering of the adobe from the tausa chapel (Colombia). *TecnoLógicas* 26, e2733. doi:10.22430/22565337.2733

Vasić, M. V., Pezo, L. L., and Radojević, Z. (2020). Optimization of adobe clay bricks based on the raw material properties (mathematical analysis). *Constr. Build. Mater.* 244, 118342. doi:10.1016/j.conbuildmat.2020.118342

Vidales, J. M. M., Hernández, L. N., and Fraga, J. I. M. (2022). Valoración inicial de las propiedades de la goma de nopal como posible aditivo en la conservación de edificaciones de adobe. *Interv. Rev. Int. Conserv. Restauración Museol.* 1, 159–199. doi:10.30763/Intervencion.264.v1n25.43.2022

Wang, W., and Wang, H. (2025). Evaluating the physical properties and thermal comfort of vetiver adobe brick: a decade-long study on sustainable granary construction in Northeast Thailand. *Discov. Civ. Eng.* 2, 157. doi:10.1007/s44290-025-00322-9