

Effect of Coconut Fiber and Expired Cement on the Physical-Mechanical and Thermal Properties of Adobe Blocks

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ABSTRACT Adobe remains an essential construction material for rural housing in the Andean highlands, yet its performance is limited by high water absorption, insufficient durability, and moderate mechanical strength. This study systematically evaluated the effect of combined coconut fiber and expired cement additions on the mechanical, hygrothermal, and economic properties of adobe blocks and walls. Soil was characterized, and blocks were reinforced with coconut fiber (0.6%, 0.9%, 1.2%, 1.5% by weight) and expired cement (3%, 6%, 9%), both by weight of dry soil. A total of 135 samples underwent tests for compressive, tensile, and flexural strength, water absorption, thermal conductivity, and wall compressive performance. Statistical analysis using ANOVA confirmed highly significant improvements ($p < 0.0001$) across all evaluated properties. The optimal mixture, comprising 0.9% coconut fiber and 9% expired cement, achieved a compressive strength of 37.86 kg.cm^{-2} , nearly double that of the control sample (adobe without additives), which reached 17.69 kg.cm^{-2} , while wall compressive strength reached 33.9 kg.cm^{-2} . Tensile and flexural strengths increased to 11.43 kg.cm^{-2} and 19.78 kg.cm^{-2} , respectively; water absorption decreased to 7.82%, and thermal conductivity was reduced to $0.52 \text{ W.m}^{-1}.\text{K}^{-1}$. Economically, the improved adobe presented a unit cost of $\$/ 154.14$ per m^2 (Peruvian soles), 27% higher than the control sample, although offset by notable gains in durability and overall performance. In summary, the combined use of coconut fiber and expired cement in adobe yields statistically validated improvements in structural, hygrothermal, and economic behavior, offering a practical and sustainable alternative for resilient rural housing in high altitude regions.

KEYWORDS Adobe; Coconut fiber; Expired cement; Thermal conductivity; Water absorption; Mechanical strength.

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1 INTRODUCTION

Earthen construction remains a fundamental pillar of global architecture, as more than 33 per cent of the world's population live in houses made of adobe or other soil-based materials. This reality is particularly evident in rural communities and in regions with limited access to modern construction technologies (Sanou, Bamogo, Sory, Gansoré and Millogo, 2024). In Peru, adobe is the second most widely used material for external walls, representing 27.9 per cent of the national housing stock and reaching as high as 82.4 per cent in regions such as Huancavelica (Baquedano Juliá et al., 2024; Instituto Nacional de Estadística e Informática, 2017). Its widespread use is explained by local availability, low cost and the cultural heritage linked to traditional earthen architecture.

Nevertheless, despite these advantages, conventional adobe presents critical weaknesses, most notably its high susceptibility to moisture and its relatively low mechanical strength. In the Peruvian Andes, where relative humidity can reach 87.95 per cent, these shortcomings result in structural vulnerability, accelerated deterioration and public health risks associated with

mould and fungi growth (Gallipoli et al., 2022; RPP, 2025; SENAMHI, 2025, n.d.).

In response, various studies have sought to improve the safety, durability and habitability of adobe dwellings through the use of natural fibers and mineral stabilisers. At the Federal University of Paraíba, for example, adobe blocks with cement additions of 6 per cent, 9 per cent and 12 per cent were tested. After 28 days of curing, blocks with 8 per cent cement showed a 25.55 per cent increase in compressive strength compared to those without cement, while a dosage of 9 per cent was sufficient to meet the minimum standards required by the regulations (Goutsaya et al., 2021; Santos et al., 2020).

In Burkina Faso, the Laboratory of Chemistry and Renewable Energies investigated the effect of coconut fiber on the water absorption and strength of adobe blocks. The study found that contents greater than 8 per cent reduced water absorption significantly, while compressive and flexural strengths were optimised at 0.4 per cent to 0.6 per cent of fiber (Boukaré et al., 2024;

Ramakrishnan et al., 2021). In Brazil, the publication of Standard NBR 16814 in 2020 encouraged new studies on coconut fiber in adobe. Blocks measuring 7 cm in height, 15 cm in width and 31 cm in length were reinforced with 1 per cent and 2 per cent fiber. With 1 per cent fiber, bulk density decreased by 4.20 per cent and compressive strength reached 22.33 kg.cm^{-2} , exceeding the minimum requirement of 15.30 kg.cm^{-2} . With 2 per cent fiber, density decreased by 6.40 per cent and compressive strength reached 19.88 kg.cm^{-2} (da Silva et al., 2024).

At the University of Jaffna, the combined use of coconut fiber and cement in adobe was examined. With 0.2 per cent fiber, compressive strength increased from 33.86 kg.cm^{-2} to 35.18 kg.cm^{-2} . However, higher proportions reduced strength, falling to below 38.55 kg.cm^{-2} at 0.6 per cent. In flexural tension, adobe without fiber achieved 18.15 kg.cm^{-2} , while higher proportions reduced this value progressively to below 10.20 kg.cm^{-2} at 0.6 per cent. These findings confirm that small additions of coconut fiber improve mechanical properties, but excessive content negatively affects structural performance (Thanushan et al., 2021).

In Thailand, the Faculties of Industrial Technology and Arts and Sciences of Chanthaburi Province investigated the incorporation of rubber latex and coconut fiber in adobe to promote sustainable development. A water to soil ratio of 0.4 was used, latex was added in proportions of 5 per cent, 10 per cent, 15 per cent and 20 per cent relative to water weight, and 1 per cent coconut fiber was incorporated. Results showed that blocks with latex and coconut fiber resisted 28 days of immersion without disintegration, whereas traditional blocks dissolved within 24 hours. In compression, blocks with 15 per cent latex achieved 16.11 kg.cm^{-2} and those with coconut fiber 12.14 kg.cm^{-2} , compared to 9.38 kg.cm^{-2} for untreated blocks. Volumetric change was also significantly reduced, evidencing improved dimensional stability (Jakrapan and Pailyn, 2019; Rajapakse et al., 2022).

In the United States, the Department of Civil Engineering studied soil blocks stabilised with cement, banana fiber and coconut fiber, motivated by waste management. Compressive and flexural tests, freeze-thaw cycles and exposure to chemicals were conducted. Results were positive, with banana fiber showing better performance in compression and coconut fiber in flexion. Both fibers also showed resistance to acidic and alkaline attack as well as weathering. Coconut fiber provided greater durability than banana fiber (Danso, 2017; Jesudass et al., 2021; Thanushan and Sathiparan, 2022).

In Mexico, the Autonomous University of Tamaulipas examined adobe made with silty and clayey soils reinforced with coconut fiber and aloe vera, compar-

ing them with lime-stabilised adobe. Mechanical, morphological and thermal properties were evaluated. The study reported a 12 per cent increase in flexural strength with only 0.5 per cent fiber, a 34 per cent increase in compressive strength, a 2 per cent reduction in water swelling, a 12 per cent improvement in thermal conductivity and a 30 per cent increase in abrasion resistance (Velasco-Aquino et al., 2020).

Other fibers have also demonstrated positive results, such as kenaf. In Burkina Faso, kenaf fibers of 1.5 to 3 cm were incorporated into adobe, resulting in improved thermal and fracture performance. Blocks with 3 cm fibers performed better than those stabilised with cement, mainly due to the cellulose content that reduced thermal conductivity (Laibi et al., 2018; Sanou et al., 2024; Serebe et al., 2024). In Peru, the University of Applied Sciences reported increases of 12 per cent in flexural strength and 40 per cent in compressive strength with 1.75 per cent additions of cabuya and straw fibers (Lopez et al., 2019; Ouedraogo et al., 2019). Similarly, in Mexico, the National Polytechnic Institute achieved improvements of 7.01 per cent in flexion and 33 per cent in compression with agave fibers, complying with the national standard N-CMT-2-01-001/02, Class C (Abdulla et al., 2021; Araya-Letelier et al., 2021; Caballero-Caballero et al., 2018).

Regarding alternative binders, the use of discarded materials such as expired cement has gained attention within a circular economy framework. In Algeria, the addition of lime to adobe increased mechanical and thermal performance, with compressive strength improving by up to 25 per cent (Laid et al., 2023). In China, fly ash combined with high modulus potassium silicate enhanced adobe resistance to freeze-thaw cycles and environmental variations (Zhang et al., 2017). In Algeria, expired cement used in conventional cement production was found to retain compliance with regulatory standards (Meddah et al., 2022). In Ethiopia, expired cement combined with ground granulated blast furnace slag improved compressive, tensile and flexural strengths by up to 20 per cent (Abbas and Ibrahim, 2023). Expired cement, defined as Portland cement Type I that has exceeded its shelf life or aged during storage, loses part of its reactivity through early hydration and clinker carbonation. However, it retains a non-negligible cementing capacity that, when dosed correctly, promotes microstructural densification, reduces interconnected porosity, strengthens interparticle bonding and decreases moisture transport, thereby improving compressive and flexural strengths of adobe matrices (Abbas and Ibrahim, 2023; Chofore et al., 2022; Meddah et al., 2022).

In summary, the literature consistently supports the technical feasibility and sustainability of reinforcing adobe with natural fibers, particularly coconut fiber, and to a lesser extent with industrial by-products such

as expired cement. However, a significant research gap remains concerning their combined effects on mechanical, hygrothermal and economic performance, especially under the climatic conditions of the Peruvian Andes.

Within this framework, the present study seeks to address this gap by systematically evaluating the combined influence of coconut fiber and expired cement on adobe blocks and walls. The research analyses compressive, tensile and flexural strength, quantifies reductions in water absorption and thermal conductivity, and includes a detailed cost analysis of improved mixtures. In doing so, it aims to propose a sustainable and technically robust solution for adobe construction in vulnerable regions, contributing to scientific knowledge as well as to the development of resilient, energy-efficient and affordable rural housing.

2 METHODS

2.1 Adobe

Adobe is a traditional building material composed of clay soil, sand, and water, often supplemented with natural fibers such as straw. It is characterized by its low cost, thermal inertia, and ease of construction, although its use has decreased due to its low seismic resistance and high water absorption (Baquedano Juliá et al., 2024). Importantly, cement is not a fundamental component of adobe; rather, in contemporary studies, different stabilizers have been incorporated experimentally to enhance its performance. For instance, investigations report that the addition of cement and corn straw fiber improves strength and overall thermal behavior (Kidari and Tilioua, 2024), while other fibers, such as palm and glass fibers, optimize mechanical strength and specific thermal properties such as conductivity and diffusivity (Fidjah et al., 2024).

In this context, it is relevant to distinguish between thermal properties and thermal behavior. Thermal properties refer to the intrinsic characteristics of the material such as thermal conductivity, specific heat capacity, and density that determine how it interacts with heat at the microscopic level. Thermal behavior, on the other hand, describes the macroscopic response of adobe structures under real environmental conditions, including their ability to provide thermal inertia, delay heat transfer, and stabilize indoor temperatures.

Building on this framework, the present research analyzes the addition of coconut fiber and expired cement in adobe mixtures, with the objective of improving their mechanical, physical, and thermal performance through the combined modification of intrinsic properties and observable thermal behavior.



Figure 1 Expired Cement

Table 1. Chemical, Physical and Mechanical Composition of Expired Cement.

Item	Expired Cement	Unexpired cement
CaO	60.51%	65.04%
SiO ₂	20.00%	17.11%
Al ₂ O ₃	4.44%	3.82%
Fe ₂ O ₃	5.26%	2.80%
SO ₃	2.45%	2.75%
MgO	2.65%	1.25%
Na ₂ O	0.34%	0.36%
K ₂ O	0.98%	0.84%
Specific gravity	3.15%	3.25%
Autoclave expansion	0.17%	0.13%
Compressive strength (28 days)	236.57 (kg.cm ⁻²)	348.74 (kg.cm ⁻²)

Note. Data adapted from Ibrahim and Abbas (2024)

2.2 Expired Cement

Cement is one of the most fundamental construction materials in the building and civil works industry due to its versatility and ability to form strong and durable structures (Suarez-Riera et al., 2024). Its addition to concrete contributes significantly to improve its mechanical properties, such as compressive, tensile, and flexural strength, making it a key component in the manufacture of high-strength building materials (Dao et al., 2018; Javier et al., 2017). In the framework of this research, 42.5 kg Type I Portland cement, whose expiration period is 6 months, was used (Figure 1) (Abbas and Ibrahim, 2023). This type of cement is a pozzolanic cement, made by combining clinker and pozzolans, which gives it specific characteristics that improve the durability and strength of concrete (Balasubramanian and Sarangapani, 2024). Table 1 presents the chemical, physical and mechanical characteristics of Type I Portland cement, both expired and unexpired. Its chemical composition highlights a high CaO content, followed by SiO₂, both fundamental for cement hardening and strength. In addition, silicon dioxide favors the formation of silica gels. The table also includes the 28-day compressive strength values for both cement conditions, allowing an assessment of how expiry affects the mechanical performance of the cement.



Figure 2 Obtaining coconut fiber

Table 2. Mechanical and physical properties of coconut fiber.

Properties	Value	Unit
Density	0.25	g.cm^{-3}
Moisture content	20	%
Water absorption	30	%
Compressive strength	101.97	kg.cm^{-2}
Tensile strength	2039.44	kg.cm^{-2}
Flexural strength	407.89	kg.cm^{-2}
Modulus of elasticity	203.944	kg.cm^{-2}

Note. Data adapted from Inegbedion and Osasona (2024)

2.3 Coconut Fiber

Coconut fiber, an agricultural by-product derived from the coconut husk, has gained attention as a sustainable reinforcement material due to its low cost, broad availability, and potential contribution to reducing the environmental footprint of construction (Balador, 2024). Previous studies have reported that its incorporation into earthen materials can enhance durability by increasing resistance to alkaline environments, weathering, and thermal fluctuations, while simultaneously improving key mechanical properties such as compressive, tensile, and flexural strength (da Silva et al., 2024; Thanushan and Sathiparan, 2022). In this study, coconut fiber was incorporated into adobe mixtures at dosages of 0.6%, 0.9%, 1.2%, and 1.5% by weight, with the objective of systematically evaluating its influence on the physical and mechanical performance of reinforced adobe.

To obtain coconut fibre (CF), coconut waste (CW) was used, from which the external fibres were manually separated from the mesocarp in the form of small threads. Subsequently, these fibres were dried in an industrial oven at a constant temperature of 65 °C for 12 hours, and once dry, they were cut to a uniform size of 2 cm, thus obtaining coconut fibre (CF), as shown in Figure 2.

According to the results presented in Table 2, coconut has physical and mechanical properties that make it a

material with high potential for reinforcing adobe mixtures. Its fibrous and lightweight structure, evidenced by its low density and high porosity, contributes to improving the cohesion and hygrothermal control of the material. In turn, its tensile strength and flexibility allow it to dissipate stresses and reduce the propagation of cracks under loads or humidity variations. These qualities demonstrate that coconut fibre not only provides structural stability, but also durability and sustainability to the construction system.

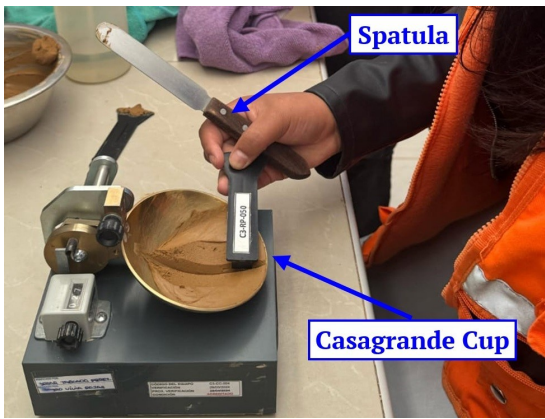
2.4 Measuring indicators for soil classification

2.4.1 Soil Sample

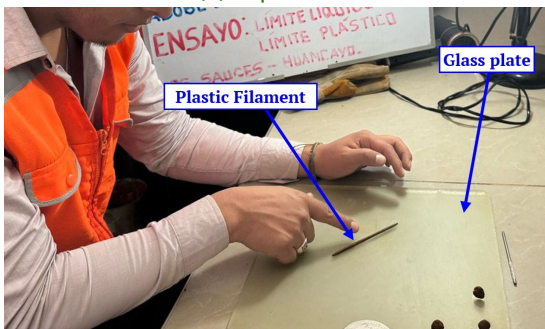
Soil samples were collected from the Uñas quarry, located in the province of Huancayo, which was selected for being representative of the regional soil conditions and for its strategic geographical location. Sampling was carried out using a manual auger to ensure homogeneous extraction and to avoid any contamination that could alter the natural properties of the material. The samples were then transported to the laboratory, where they were subjected to detailed physical and chemical characterisation, including grain size distribution, moisture content and plasticity, with the purpose of assessing their suitability for subsequent testing.

2.4.2 Grain Size Distribution

The grain size distribution of the soil was determined in accordance with the MTC E 107 procedure (Ministerio de Transportes y Comunicaciones, 2014), for which the material extracted from the trial pit was quartered to obtain a representative subsample of approximately 500 g. This subsample was oven-dried for 24 hours at 110 ± 5 °C in order to establish its initial dry weight and was subsequently washed through a No. 200 sieve until the water ran clear, thereby separating the fine fraction, consisting of silts and clays that passed through the sieve, from the coarse fraction, composed of sands and gravels that remained retained. The coarse fraction was then oven-dried again for a further 24 hours at 110 ± 5 °C, and by comparing its weight with the initial dry weight of the subsample, the fine content was determined. Finally, the dried coarse fraction was subjected to manual sieving using a stack of sieves ranging from 3 inches to No. 200, with the set being shaken for approximately 15 minutes until no appreciable additional material passed through. The material retained on each sieve was weighed to construct the particle size distribution curve, the results of which showed that 99.7% of the material passed the No. 4 sieve (4.75 mm), 95.9% passed the No. 40 sieve (0.425 mm) and 87.8% passed the No. 200 sieve (0.075 mm), thereby confirming the predominance of fine particles in the analysed sample.



(a) Liquid limit



(b) Plastic limit

Figure 3 Atterberg limit tests

2.4.3 Moisture Content

We experimentally determined the moisture content of the soil following the procedure of MTC E 108 (Ministerio de Transportes y Comunicaciones, 2014). We started by obtaining a representative sample of soil, formed a cone and flattened it until a uniform circle was obtained. We divide this sample into four equal parts and select two to perform the initial weighing in wet state. From this, we took three samples of 100 grams each and dried them in an oven at $105 \pm 5^\circ\text{C}$ for 16 hours. After drying, the samples were reweighed to obtain their dry mass. Moisture content was calculated from the difference between wet and dry weights, resulting in an overall moisture content of 22.2%.

2.4.4 Atterberg Limits

The Atterberg limits were determined as a fundamental tool for classifying soil consistency based on its water content (O'Kelly et al., 2018). For the determination of the liquid limit (Figure 3a), the MTC E 110 procedure was followed (Ministerio de Transportes y Comunicaciones, 2014). Approximately 100 g of soil, previously sieved through a No. 40 sieve, was mixed with distilled water until a homogeneous paste was obtained. Subsequently, the Casagrande cup method was applied, al-

lowing the cup to fall from a height of 1 cm and repeating the procedure until a 13 mm-long groove was closed after 25 blows. For the determination of the plastic limit (Figure 3b), the procedure established in MTC E 111 (Ministerio de Transportes y Comunicaciones, 2014) was employed, which involved manually forming cylinders 3 mm in diameter and 25–30 mm in length. The plastic limit was identified when the cylinders fragmented into 6 mm segments. The results showed a liquid limit of 32% and a plastic limit of 18%, corresponding to a plasticity index of 14%. These values indicate that the soil exhibits low plasticity, making it suitable for stabilized adobe mixtures due to its good workability and cohesion.

2.4.5 Soil Classification

According to Standard E.080 (Ministerio de Vivienda, Construcción y Saneamiento, 2017), a soil is considered suitable for adobe production when it contains an adequate proportion of clay. In this case, the analysed material presented 87.8% clay, which allowed it to be classified as a sandy clay of low plasticity, thereby meeting the requirements established for adobe manufacture.

2.5 Indicators for Measuring Adobe Mechanical Properties

2.5.1 Compressive Strength

The compressive strength test, performed according to MTC Standard E 704 (Ministerio de Transportes y Comunicaciones, 2014), was aimed at evaluating the capacity of adobe to withstand loads under compressive stresses. Adobe cubes measuring $10 \times 10 \times 10$ cm (Figure 4) were prepared with varying proportions of coconut fiber (0.6%, 0.9%, 1.2%, and 1.5%) and cement (3%, 6%, and 9%), calculated based on the dry weight of the soil. For each combination of coconut fiber and cement, three samples were produced and subjected to a 28-day drying process prior to testing. After curing, the specimens were tested using a compressive strength testing machine until failure. The minimum strength of $10.2 \text{ kg}\cdot\text{cm}^{-2}$ was considered as a reference value, as specified by Standard E.080 (Ministerio de Vivienda, Construcción y Saneamiento, 2017).

2.5.2 Compression Test on Walls

The compressive strength test on walls was carried out in accordance with Standard E.080 (Ministerio de Vivienda, Construcción y Saneamiento, 2017), with the purpose of determining the structural capacity of reinforced adobe under vertical loads, simulating the real stress conditions to which a load-bearing wall in traditional constructions is subjected. For this purpose,

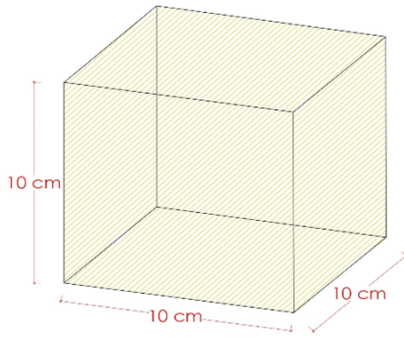


Figure 4 The dimension of the cubic samples used in the compression test

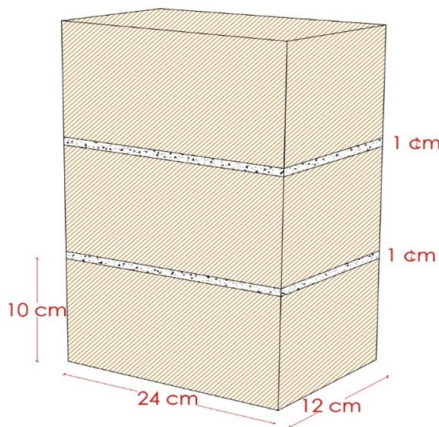


Figure 5 The dimension of the wall sample used in the experiment

adobe piles composed of three stacked blocks were tested, representing a wall segment under compressive stress. The blocks, measuring $24 \times 12 \times 10$ cm with 1 cm mortar joints (Figure 5), were produced with varying proportions of coconut fiber (0.6%, 0.9%, 1.2%, and 1.5%) and cement (3%, 6%, and 9%), and were left to dry for 28 days prior to testing. Subsequently, the piles were subjected to compressive loading in a strength testing machine until structural failure occurred, thereby allowing a realistic evaluation of the combined effect of coconut fiber and cement on the mechanical performance of adobe masonry.

2.5.3 Flexural Strength

The flexural strength test assesses a material's ability to withstand bending stresses, determining the maximum load it can resist before fracture occurs (Al-Osta et al., 2017). This test was carried out in accordance with the specifications established in standard MTC E 711 (Ministerio de Transportes y Comunicaciones, 2014). For this purpose, prismatic adobe beams measuring $40 \times 20 \times 12$ cm ($L \times h \times b$) were fabricated (Figure 6), incorporating varying proportions of coconut fiber (0.6%, 0.9%, 1.2%, and 1.5%) and cement (3%, 6%, and 9%). The specimens were cured for 28 days and

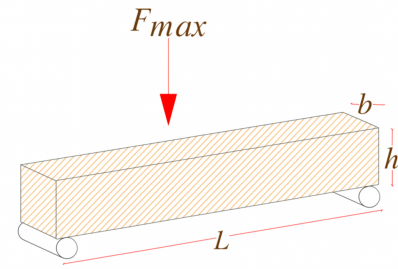


Figure 6 Dimensions of the prismatic adobe specimens used in the flexural strength test

subsequently tested using a universal testing machine, where a point load was applied at constant rates of $0.9 \text{ MPa}\cdot\text{min}^{-1}$ and $1.2 \text{ MPa}\cdot\text{min}^{-1}$ until deformation or failure of the material occurred.

2.5.4 Indirect Tensile Strength

The indirect tensile strength test allows determining the capacity of a material to resist tensile stresses applied in an indirect manner, that is, along a direction not coincident with its principal axis, until failure occurs (Bertelsen et al., 2021). The tensile strength of the soil was evaluated according to MTC E 708 (Ministerio de Transportes y Comunicaciones, 2014), performed on cylinders of $10 \text{ cm} \times 20 \text{ cm}$ in diameter and length. These cylinders were prepared with different combinations of coconut fiber (0.6%, 0.9%, 1.2% and 1.5%) and cement (3%, 6% and 9%). For each combination, three samples were produced and, after a curing period of 28 days, they were subjected to testing in an indirect tensile testing machine until failure occurred, as illustrated in Figure 7, applying a loading rate of approximately $1000 \text{ kPa}\cdot\text{min}^{-1}$. Finally, the maximum load (P) recorded just before failure was used in Equation 1 to calculate the indirect tensile strength of the material.

$$T = \frac{2P}{\pi A} \quad (1)$$

Where:

T : Maximum Tensile Stress

P : Maximum Load

A : Area of the Load Area

2.6 Indicators for Measuring The Physical Properties of Adobe

2.6.1 Water Absorption

The water absorption test on adobe blocks is a critical indicator of their ability to resist moisture penetration, which directly affects their durability and weather resistance (Rocco et al., 2024). For this test, adobe blocks



Figure 7 Indirect tension test

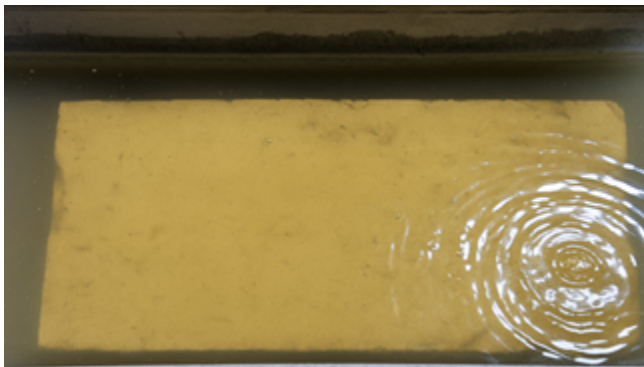


Figure 8 Complete immersion of adobe blocks during the water absorption test

were prepared with different combinations of coconut fiber (0.6%, 0.9%, 1.2% and 1.5%) and cement (3%, 6% and 9%) with dimensions of 40 x 20 x 12 cm. According to NTP 399.613 (Instituto Nacional de Calidad (IN-ACAL), 2025), the process consisted of choosing adobe blocks that were dry before starting the test. Once chosen, each sample was weighed and the value was recorded as the dry weight (W_d). Subsequently, the samples were completely immersed in water at room temperature for a period of 24 hours, making sure that the entire sample was covered by water (Figure 8). At the end of the immersion period, the samples were removed and excess surface water was removed with a damp cloth to avoid adding extra weight. Finally, each sample was weighed after removing the water and this value was recorded as the saturated weight (W_s) (Morsy et al., 2022). The calculation of water absorption was performed as a percentage using Equation 2.

$$A = \frac{W_s - W_d}{W_d} \times 100 \quad (2)$$

Where:

W_s : Weight of the saturated sample

W_d : Weight of the dry sample

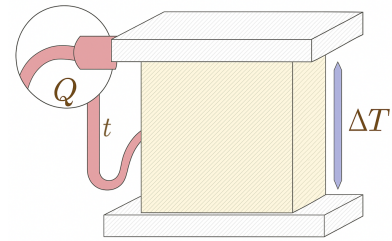


Figure 9 Thermal Conductivity

2.7 Thermal Conductivity

We determined the thermal conductivity of adobe blocks, since it is fundamental to evaluate their insulating capacity in construction (Laid et al., 2023). We used 10 × 10 × 10 cm blocks, previously dried, with different combinations of coconut fiber (0.6%, 0.9%, 1.2% and 1.5%) and cement (3%, 6% and 9%). Following ASTM C518 (ASTM International, 2021; Vaca et al., 2021). We subjected the blocks to a temperature difference between two plates, as shown in Figure 9, maintaining an average temperature of 47.5 °C and measuring the heat flow through each sample (Morsy et al., 2022). Finally, the thermal conductivity was calculated using Equation 3.

$$\lambda = \frac{Qt}{\Delta T} \quad (3)$$

Where:

Q : heat flux

t : thickness of the sample

ΔT : temperature difference between the plates

We observed that the combination of expired cement and coconut fiber formed a more compact matrix, with fewer voids, which reduced heat transfer through the adobe. Thus, we achieved that the adobe retains the interior temperature better, increasing its performance as an insulating material in extreme environments.

3 RESULTS

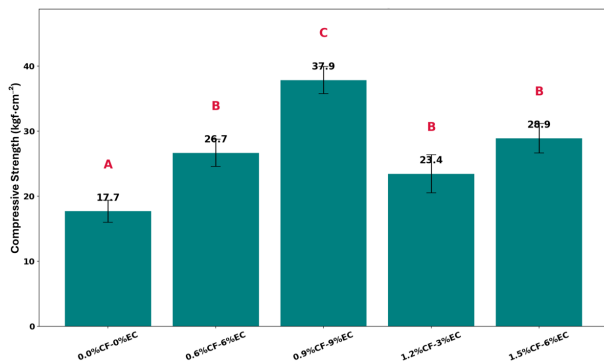
3.1 Static Mechanical Behavior of Reinforced Adobe

3.1.1 Compressive Strength

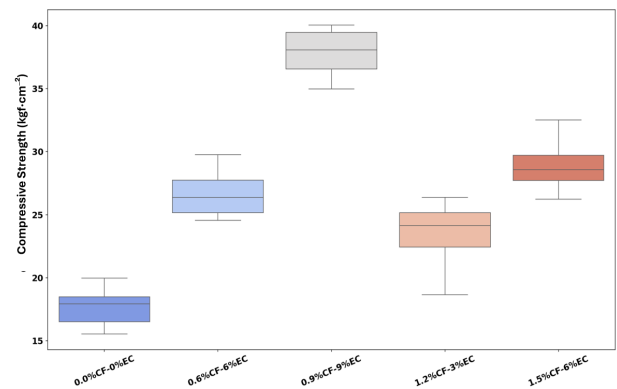
The experimental results (Figure 10) demonstrated a statistically significant effect of the combined addition of coconut fiber and expired cement on the compressive strength of adobe blocks (ANOVA, $p < 0.0001$). Tukey's post hoc analysis (Table 3) identified three statistical groups of mechanical performance: Group A, corresponding to the control mix without coconut fiber or expired cement; Group B, which includes the mixes with 0.6%, 1.2%, and 1.5% coconut fiber combined with

Table 3. Statistical analysis of compressive strength

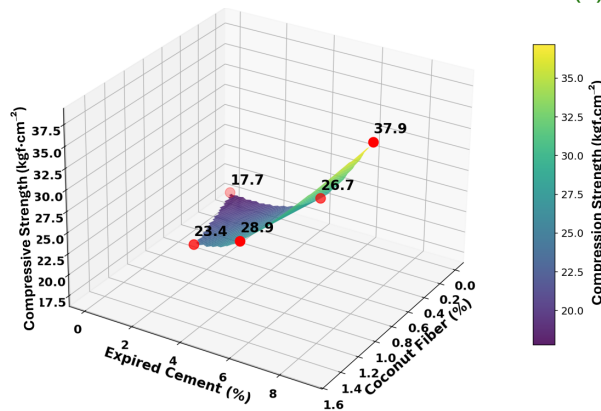
Coconut fibers	Expired cement	Average (kgf.cm ⁻²)	Standard error	Confidence interval 95 %	Tukey Lyrics
0%	0%	17.69	0.67	1.71	A
0.60%	6%	26.67	0.81	2.09	B
0.90%	9%	37.86	0.81	2.09	C
1.20%	3%	23.45	1.14	2.93	B
1.50%	6%	28.91	0.89	2.28	B



(a) Bar chart with 95% confidence interval



(b) Box diagram



(c) Surface graph of compressive strength

Figure 10 Compressive strength of reinforced adobe blocks: statistical analysis and response surface

6% or 3% expired cement; and Group C, represented by the mix containing 0.9% coconut fiber and 9% expired cement. The bar chart with 95% confidence intervals and Tukey letters (Figure 10a) shows that the mix with 0.9% coconut fiber and 9% expired cement achieved the highest mean compressive strength, with a value of 37.9 kgf.cm⁻², being statistically superior to all other mixes in Group C. The mixes containing 0.6%, 1.2%, and 1.5% fiber combined with 6% or 3% expired cement formed Group B, exhibiting significant improvements compared to the control (Group A). The control mix (0% CF–0% EC) displayed the lowest strength, with a value of 17.7 kgf.cm⁻².

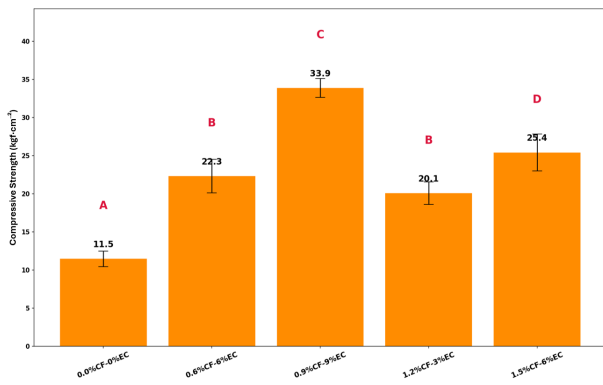
The box plot, item b) highlights the dispersion and symmetry of the results for each dosage, showing less variability in the optimum combination and greater

homogeneity of the data in the dosages incorporating additives. The 3D response surface item c) visualizes the joint and non-linear effect of both additives on strength. A local maximum was observed around 0.9% CF–9% EC, indicating that additional increases in fiber or cement do not generate proportional improvements and, in some cases, may even negatively affect strength.

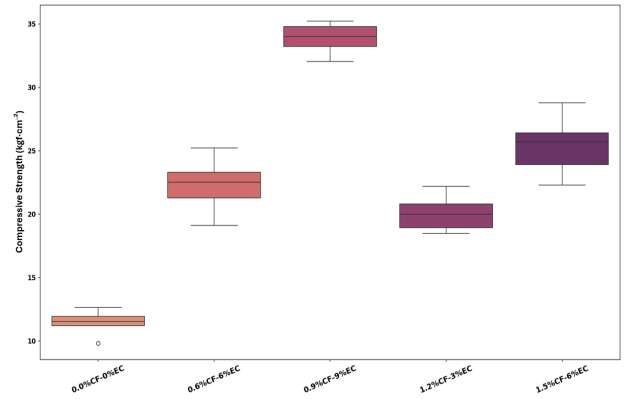
The statistical analysis shown in Table 3 showed significant differences in compressive strength according to the dosage ANOVA $F = 71.74, p = 0.00001$. The mixture with 0.9% coconut fiber and 9% expired cement obtained the highest average value of 37.86 kgf.cm⁻², 95% CI 2.09 and was statistically superior to the others Tukey C. The dosages with 0.6%, 1.2% and 1.5% fiber combined with 3 to 6% cement formed an intermedi-

Table 4. Statistical analysis of adobe piles

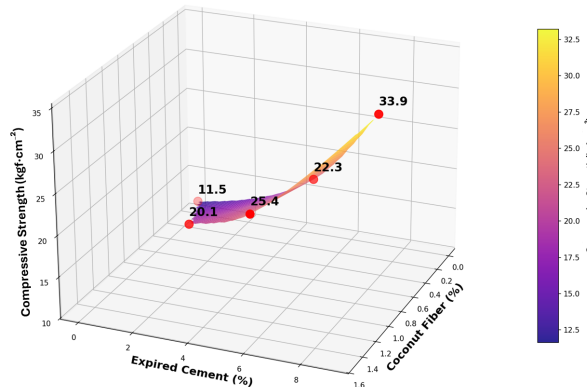
Coconut fibers	Expired cement	Average (kgf.cm ⁻²)	Standard error	Confidence interval 95 %	Tukey Lyrics
0%	0%	11.47	0.97	1.01	A
0.60%	6%	22.31	2.1	2.2	B
0.90%	9%	33.89	1.2	1.26	C
1.20%	3%	20.07	1.41	1.48	B
1.50%	6%	25.42	2.31	2.42	D



(a) Bar chart with 95% confidence interval



(b) Box diagram



(c) Pile surface graph

Figure 11 Compressive strength of reinforced adobe piles: statistical analysis and response surface

ate group B, while control A showed the lowest strength of 17.69 kgf.cm⁻². The low standard errors and narrow confidence intervals demonstrate the reliability of the results.

The highest compressive strength was achieved with 0.9% CF–9% EC because this dosage achieves a balance between the matrix and the fibrous reinforcement. Expired cement, although less reactive, still provides microstructural densification and additional bonding points that increase the cohesion of the mixture. At the same time, coconut fiber acts as a stress bridge, controlling the propagation of microcracks and delaying brittle failure. When the fiber exceeds 1.2–1.5%, the continuity of the matrix is reduced and areas of weak paste–fiber contact appear, which explains the relative loss of strength in these dosages.

3.1.2 Compressive Strength of Walls

The wall compression test results (Figure 11) revealed a significant effect of the combined addition of coconut fiber and expired cement on the compressive strength (ANOVA, $p < 0.0001$). Tukey’s post hoc analysis identified four statistically distinct groups. The bar graph with 95% confidence intervals and Tukey letters (Figure 11a) shows that the 0.9% CF–9% EC mixture achieved the highest mean compressive strength of 33.9 kgf.cm⁻², classifying it as group C and statistically outperforming the other mixtures. The 1.5% CF–6% EC mixture formed group D, reflecting intermediate strength, while mixtures with 0.6–1.2% fiber combined with 3–6% cement formed group B. The control (0% CF–0% EC) showed the lowest resistance, 11.5 kgf.cm⁻², classified as group A.

Table 5. Statistical analysis of indirect adobe traction

Coconut fibers	Expired cement	Average (kgf.cm ⁻²)	Standard error	Confidence interval 95 %	Tukey Lyrics
0%	0%	2.86	0.25	0.26	A
0.60%	6%	6.31	0.22	0.23	B
0.90%	9%	11.43	0.86	0.91	C
1.20%	3%	8.76	0.71	0.74	D
1.50%	6%	10.85	0.51	0.54	C

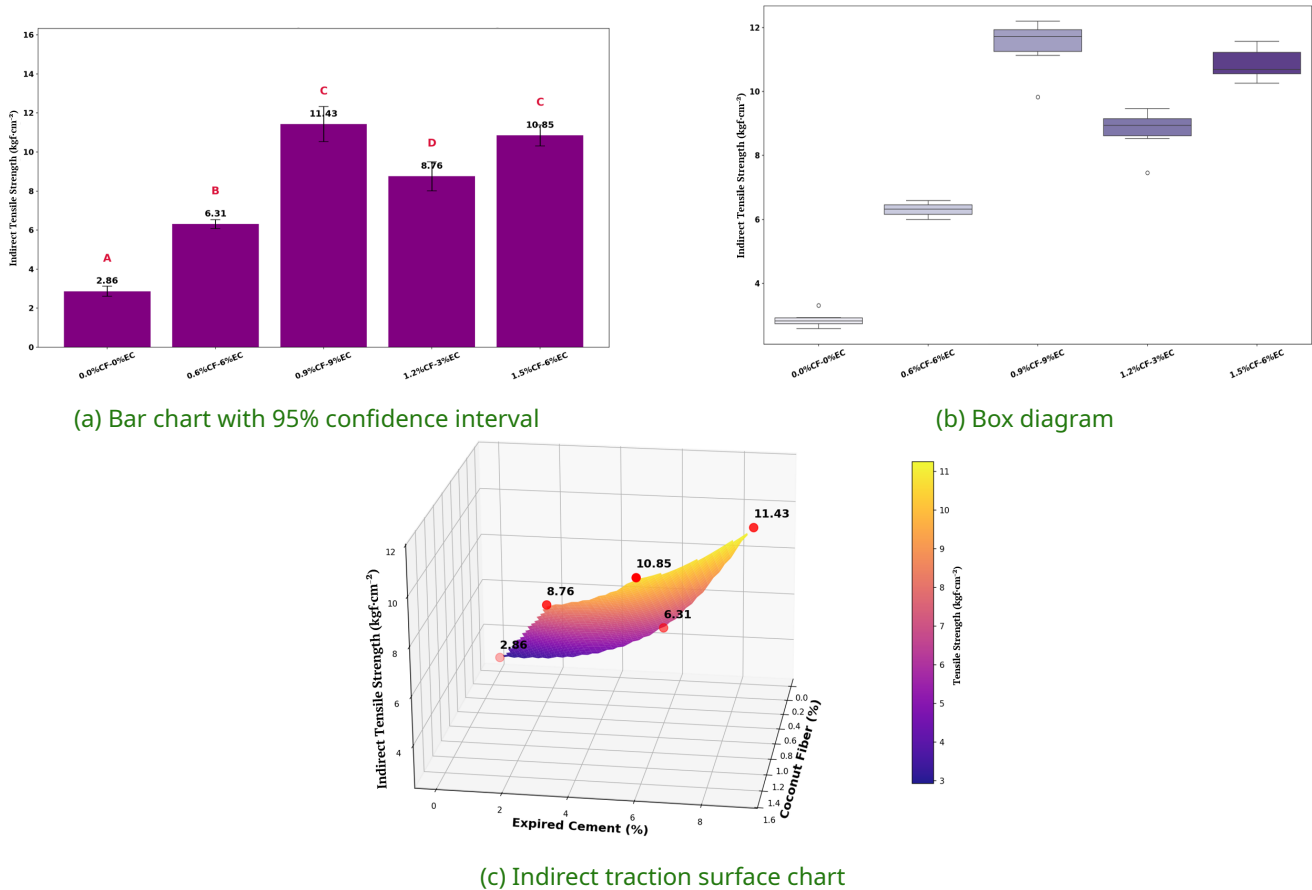


Figure 12 Indirect tensile strength of reinforced adobe: statistical analysis and response surface

The box plot (Figure 11b) highlights the dispersion and symmetry of the results, showing greater homogeneity in the optimum mixture (0.9% CF–9% EC) and moderate variability in the other mixtures. The 3D response surface (Figure 11c) illustrates the joint and nonlinear effects of fiber and cement, revealing a local maximum around 0.9% CF–9% EC. Beyond this point, additional fiber or cement did not produce proportional improvements and, in some cases, reduced performance.

Statistical analysis (Table 4) confirmed significant differences among mixtures (ANOVA, $F = 141.45$, $p = 0.0000$). The 0.9% CF–9% EC mixture achieved the highest mean compressive strength of 33.89 kgf.cm⁻² (95% CI: ± 1.26) and was statistically superior to the other groups. Group D (1.5% CF–6% EC) and group B (0.6–1.2% fiber with 3–6% cement) showed interme-

diated values, while the control remained the lowest. The low standard errors and narrow confidence intervals demonstrate the robustness and reliability of the results.

From a mechanical perspective, the superior performance of the 0.9% CF–9% EC mixture is attributed to improved transfer of vertical loads and enhanced local confinement capacity of the matrix. Expired cement increased the stiffness of joints and strengthened particle bonding, while the fibers redistributed stresses and delayed progressive failure. Higher fiber contents (1.5%) resulted in intermediate strength, as the fibers-controlled cracking but simultaneously reduced the effective cement content in the matrix, thereby limiting overall load-bearing capacity.

Table 6. Statistical flexural analysis of adobe beams

Coconut fibers	Expired cement	Average (kgf.cm ⁻²)	Standard error	Confidence interval 95 %	Tukey Lyrics
0%	0%	10.73	0.5	2.15	A
0.60%	6%	14.98	0.62	2.65	B
0.90%	9%	19.78	0.32	1.36	C
1.20%	3%	15.05	0.38	1.62	B
1.50%	6%	17.34	0.34	1.48	D

3.1.3 Tensile Strength

Figure 12 shows the analysis of the indirect tensile strength of reinforced adobe blocks, with the results organized in: a) bar graph with 95% confidence intervals and Tukey grouping letters, b) box plot showing the dispersion of the data, and c) 3D response surface modeling the joint behavior of the factors. Statistical processing showed that the combined addition of coconut fiber and expired cement significantly increased the indirect tensile strength (ANOVA $F = 229.54$, $p < 0.0001$). Through Tukey's test, it was identified that the dosages 0.9% CF–9% EC and 1.5% CF–6% EC reached the highest average values of 11.43 and 10.85 kgf.cm⁻², group C), while 1.2% CF–3% EC corresponded to an intermediate group D and the control of 0% CF–0% EC resulted statistically lower 2.86 kgf.cm⁻², group A. It was also observed that the dispersion of the results was minimal in the optimum combinations, which reflects high experimental repeatability and reliability. The response surface model evidenced a local maximum, suggesting that further increases in additives do not necessarily lead to continuous improvements and may even reduce the tensile strength. The low standard errors and narrow confidence intervals consolidate the statistical robustness of the results, supporting the potential of these formulations for structural applications in adobe.

Table 5 shows the mean values, standard errors, 95% confidence intervals and the statistical grouping according to Tukey's test, as well as the overall F and p values of the analysis of variance, allowing a comprehensive and rigorous interpretation of the significance between the dosages studied.

The optimum (0.9% CF–9% EC) significantly increased tensile strength because the fibers act as direct tensile reinforcement, absorbing stresses where adobe alone is weak. Expired cement improves fiber-matrix adhesion, allowing the fibers to better transmit the load before being torn out. However, at higher fiber percentages, the matrix loses continuity and voids are generated, reducing the effectiveness of the anchorage and explaining the decrease in values.

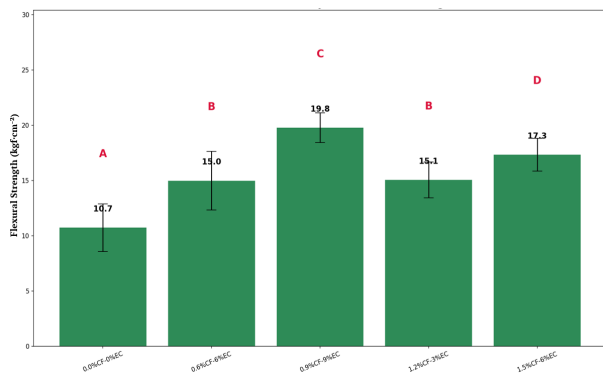
3.1.4 Bending Strength

We analyzed the experimental flexural results using Figure 13, employing a rigorous statistical methodology. The bar graph with 95% confidence interval and Tukey letters item a) showed that the dosage 0.9% CF–9% EC achieved the highest average flexural strength 19.8 kgf.cm⁻², integrating the statistically superior group C, while the mixture 1.5% CF–6% EC formed an intermediate group D. The combinations with 0.6% and 1.2% fiber together with 6% and 3% cement formed group B, and the 0% CF–0% EC control was placed in group A with the lowest strength of 10.7 kgf.cm⁻². The box plot, item b), showed less dispersion in the optimum mix and good homogeneity in the dosages with additives. The 3D response surface, item c), illustrated the non-linear behavior of both factors, showing a local maximum of flexural strength for 0.9% CF–9% EC and a decreasing or stagnating trend as the amount of admixture was further increased. The statistical analysis summarized in Table 6 revealed highly significant differences between dosages (ANOVA: $F = 56.85$, $p = 0.0000$). The low standard errors and relatively narrow confidence intervals support the reliability of the data obtained in the flexural test.

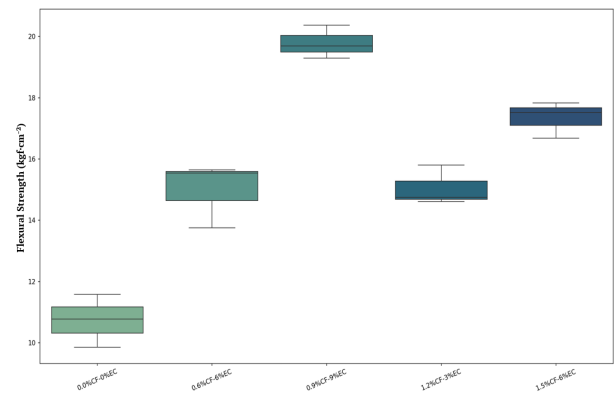
Flexure is where the synergistic effect is most evident. The 0.9% CF–9% EC reached the maximum because expired cement contributes to the compressive stiffness of the compression zone, while the fibers act in the tension zone, delaying the appearance and propagation of cracks. With higher fiber content, the reduction in cement volume and the generation of discontinuities prevent an upward trend from being maintained, showing a plateau or even a decrease in values.

3.1.5 Water Absorption

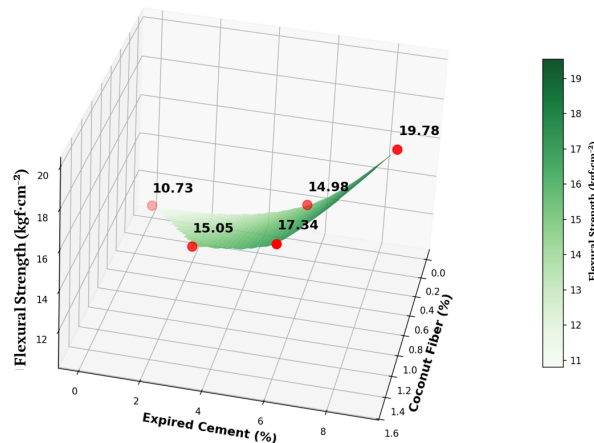
Figure 14 shows the results obtained from the absorption test, in which a significant decrease in the water absorption of the adobe blocks was noted. In the bar graph item a), with 95% confidence interval and Tukey letters, we identified that the dosage 0.9% CF–9% EC obtained the lowest average absorption of 7.82%, forming a statistically distinct group C with respect to the rest. The combinations including between 0.6%, 1.2%



(a) Bar chart with 95% confidence interval



(b) Box diagram



(c) Flexural surface graph of beams

Figure 13 Bending strength of reinforced adobe: statistical analysis and response surface

and 1.5% of coconut fiber with 3–6% of expired cement formed an intermediate group B, while the control presented the highest absorption 21.59%, located in group A. The box plot item b), allowed visualizing the low dispersion and homogeneity of the experimental results, especially in the mixtures with additives, which reinforces the reliability of the data obtained. On the other hand, the 3D response surface item c), showed that the reduction in absorption was not linear, presenting a local minimum around the optimum combination, and demonstrating that additional doses of additives do not always result in an additional improvement.

In Table 7 we summarize the statistical parameters of the absorption test, including the analysis of variance (ANOVA), where we obtained a value of $F = 309.72$ and $p < 0.0001$, confirming the existence of highly significant differences between the dosages analyzed. Likewise, we report the averages, standard errors, 95% confidence intervals and the statistical grouping by Tukey’s test, which allowed us to identify that the 0.9% CF–9% EC mixture was statistically the most efficient in reducing water absorption compared to the rest of the formulations.

The lowest absorption was achieved with 0.9% CF–9%

EC because expired cement helps to seal capillary pores with residual hydration products, reducing permeability. At the same time, coconut fiber, in this proportion, generates a uniform network that limits the development of microcracks due to shrinkage. At higher fiber dosages, the increased porosity generated around the fibers increases the absorption pathways, reducing the benefit obtained.

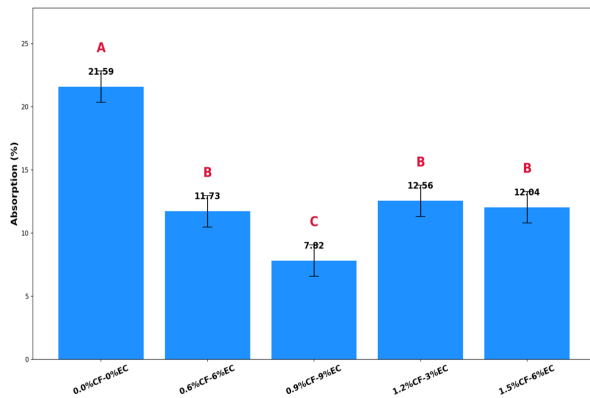
3.1.6 Thermal Conductivity

The experimental results for the thermal conductivity of adobe blocks (Figures 15) showed a highly significant effect of the joint addition of coconut fiber and expired cement on conductivity, according to the analysis of variance (ANOVA, $p < 0.0001$). Tukey’s post hoc test allowed distinguishing three statistically distinct groups.

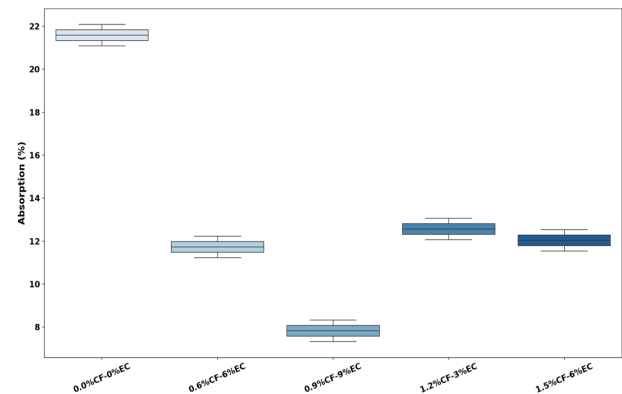
The bar graph with 95% confidence intervals and Tukey letters, item a), shows that the dosage 0.9% CF–9% EC presented the lowest average value of thermal conductivity $0.52 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, group C, being statistically lower than the rest of the combinations. The mixtures with 0.6%, 1.2% and 1.5% fiber, in combination with 3% to 6% expired cement, formed an intermediate group let-

Table 7. Statistical analysis of adobe absorption

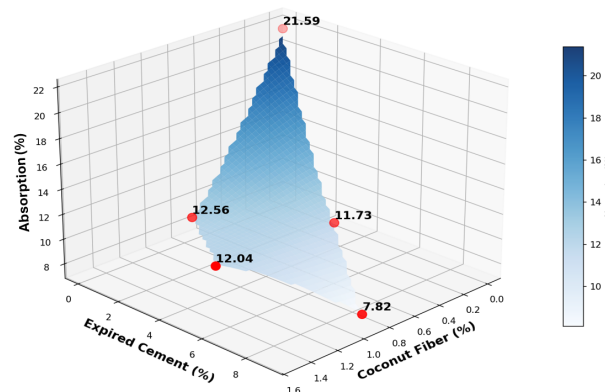
Coconut fibers	Expired cement	Average (kgf.cm ⁻²)	Standard error	Confidence interval 95 %	Tukey Lyrics
0%	0%	21.59	0.29	1.24	A
0.60%	6%	11.73	0.29	1.24	B
0.90%	9%	7.82	0.29	1.24	C
1.20%	3%	12.56	0.29	1.24	B
1.50%	6%	12.04	0.29	1.24	B



(a) Bar chart with 95% confidence interval



(b) Box diagram



(c) Absorption surface graph

Figure 14 Absorption of reinforced adobe: statistical analysis and response surface

ter B, showing a significant reduction compared to the control. The 0% CF–0% EC control showed the highest conductivity $1.67 \text{ W.m}^{-1}.\text{K}^{-1}$, group A.

The box plot, item b), shows the low dispersion and symmetry of the experimental data by dosage, which indicates a high reproducibility and reliability in the measurements for each group analyzed.

The 3D response surface, item c), illustrates the joint and non-linear behavior of the factors, where a localized minimum is observed around 0.9% CF–9% EC, confirming that the optimum combination of both additives produces blocks with lower thermal transmission. Additional increases in fiber or cement did not generate substantial improvements and, in some cases,

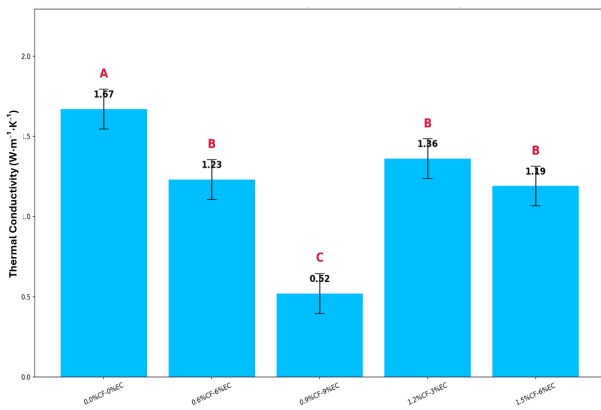
tended to increase conductivity.

The summary statistics in Table 8 confirm significant differences between dosages (ANOVA $F = 212.92$, $p = 0.00001$). The 0.9% CF–9% EC combination reached the lowest average $0.52 \text{ W.m}^{-1}.\text{K}^{-1}$, 95%CI: 0.12 and was statistically lower than the rest (Tukey: C). Group B (0.6%, 1.2%, 1.5% fiber) presented intermediate values, and the control remained the highest. The low standard errors and narrow confidence intervals demonstrate the reliability and robustness of the results obtained for thermal conductivity.

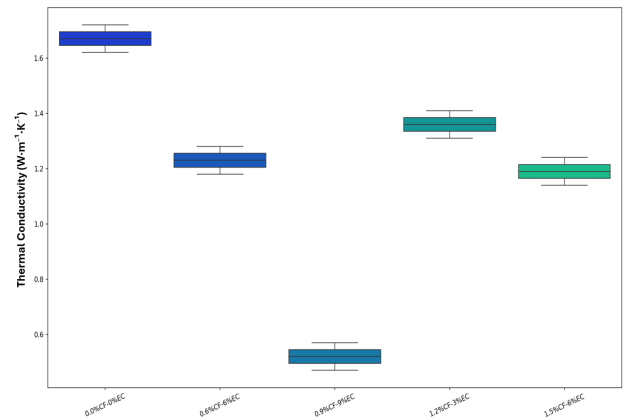
The 0.9% CF–9% EC dosage had the lowest conductivity because it achieves a balance: expired cement provides compaction (reducing large voids), while coconut

Table 8. Statistical analysis of adobe thermal conductivity

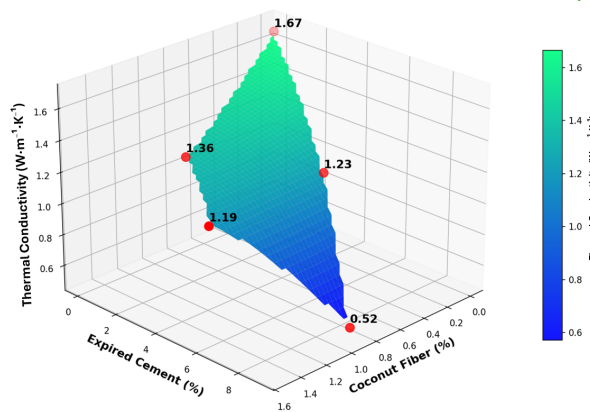
Coconut fibers	Expired cement	Average (kgf.cm^{-2})	Standard error	Confidence interval 95 %	Tukey Lyrics
0%	0%	1.67	0.03	0.12	A
0.60%	6%	1.23	0.03	0.12	B
0.90%	9%	0.52	0.03	0.12	C
1.20%	3%	1.36	0.03	0.12	B
1.50%	6%	1.19	0.03	0.12	B



(a) Bar chart with 95% confidence interval



(b) Box diagram



(c) Thermal conductivity surface graph

Figure 15 Thermal Conductivity of reinforced adobe: statistical analysis and response surface

fiber introduces micro air cavities that act as insulators. At higher fiber dosages, excess interconnected voids can The 0.9% CF--9% EC dosage had the lowest conductivity because it achieves a balance: expired cement provides compaction (reducing large voids), while coconut fiber introduces micro air cavities that act as insulators. At higher fiber dosages, excess interconnected voids can promote heat transfer by internal convection, slightly increasing conductivity and reducing thermal efficiency.

3.1.7 Reinforced Adobe Unit Production Costs

For the analysis of unit costs per square meter of adobe wall, we considered the main components: labor, materials and equipment. In the dosages that included coconut fiber, we increased the man-hours (hh) of operator and laborer by 1.50 hh and 0.50 hh per m^2 , respectively, reflecting the greater time required for mixing and placing the natural reinforcement. The amount of expired cement was determined according to the percentage in weight with respect to the volume of adobe manufactured, using local market prices for this input, while coconut fiber did not generate additional cost since it is a locally available by-product. The base yields, conventional materials and the fixed percentage

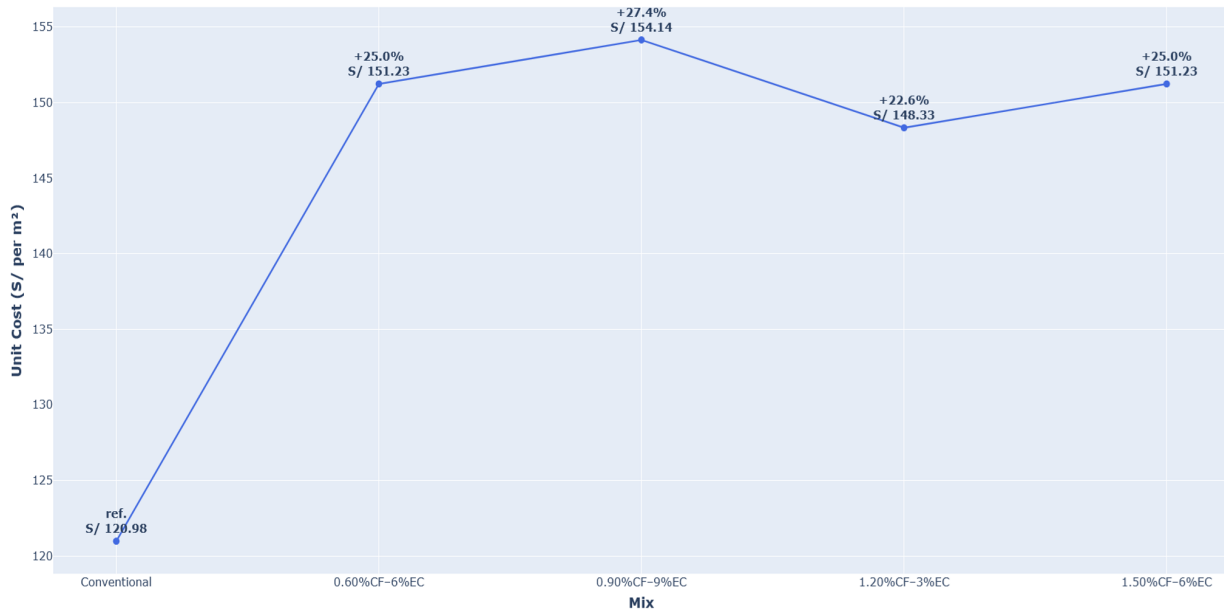


Figure 16 Unit cost analysis for reinforced adobe bricks

for hand tools, 5% of labor, were kept constant to ensure comparability between alternatives.

Figure 16 shows that the unit cost of reinforced adobe increased between 22% and 27% compared to conventional adobe, with the optimum 0.9% CF–9% EC mixture reaching S/ 154.14 per m² (Peruvian soles, PEN). This additional cost is justified by the technical improvements observed: there was a significant reduction in water absorption, a decrease in thermal conductivity, and a substantial increase in compressive, tensile and flexural strength in the formulations with additives. For example, the 0.9% CF–9% EC combination not only showed the highest indirect compressive and tensile strength, but also the lowest absorption and the best thermal insulation capacity, conditions that favor the durability, energy efficiency and useful life of the material on site. In sum, the higher initial cost is offset by the added value in mechanical performance and durability, as well as by the sustainability benefits associated with the use of waste in the manufacture of adobe.

3.1.8 CO₂e emissions (A1–A3) from cement and modeling criteria

The carbon dioxide equivalent (CO₂e) incorporated into cement in adobe mixtures is estimated. The scope adopted is “cradle to gate” (A1–A3), in accordance with EN 15804 (raw materials, transport to plant, and manufacturing) and the principles of ISO 14040/14044 for defining the objective/scope (Circular Ecology, 2025; International Organization for Standardization (ISO), 2006). Emissions factor used (EPD): a representative Environmental Product Declaration (EPD) for CEM I in

Europe was adopted as a reference, reporting GWP A1–A3 = 803 kg CO₂e/t cement (Preve, n.d.). This value includes raw materials, fuels, and electricity. Based on this data, we can indicate that for every kilogram of cement, 0.803 kg of CO₂e is produced. Modeling criteria for “expired cement.” Given that the input used in this study is expired cement that would have been discarded and replaces fresh cement, a “cut-off”/consequential approach is adopted:

- A1–A3 of expired cement: no upstream loads are reattributed (only transport/handling are calculated, if applicable).
- Substitution benefit: a credit for avoided fresh cement production is reported as Module D, quantified as $-m_{\text{cement}} \times 0.803 \text{ kg CO}_2\text{e/kg}$. This treatment is consistent with the role of Module D in EN 15804 for benefits and charges beyond the boundary of the by-product/waste recovery system (International Organization for Standardization (ISO), 2006).

This approach shows that, in addition to the previously demonstrated economic viability, reinforcement with expired cement can represent a net environmental benefit by avoiding emissions from the production of new cement in rural Andean areas.

4 DISCUSSION

Our experimental results corroborate and extend previous findings, demonstrating that the combined incorporation of coconut fiber and expired cement substantially improves the mechanical, hygrothermal, and economic properties of adobe. The remarkable increase in compressive strength observed (114% higher than the control) with the optimal dosage (0.9% co-

conut fiber and 9% expired cement) coincides with the results of Santos et al. (2020). That study attributes similar improvements to the formation of additional cementitious phases during cement hydration. Although we used expired cement with reduced reactivity, our results indicate that the remaining active components contribute to densifying the matrix and decreasing porosity. As mentioned by Ouedraogo et al. (2019), coconut fiber acts efficiently as microstructural reinforcement, controlling crack propagation and improving load transfer, which also explains the considerable increase in flexural (84%) and indirect tensile (298%) strength observed.

In the area of thermal conductivity, our results extend the findings of Velasco-Aquino et al. (2020), achieving a significant reduction of 69%. This can be attributed not only to the intrinsic insulating effect of the fiber, but also to the combined effect generated by the expired cement in the matrix, where the interfacial zones between fiber and matrix operate as additional thermal barriers. The microstructure becomes less dense and more efficient at retaining air, which is a considerable advantage for climates requiring thermally efficient envelopes.

The reduction in water absorption observed (from 21.59% to 7.82%) is in agreement with that reported by Cecilia et al. (2025), who explain how natural fibers reduce capillarity and increase moisture resistance. In our study, such reduction is produced by the effective interruption of the capillary pathways by the fibers and by the partial pozzolanic reaction of the expired cement, which refined the porous structure and increased the impermeability.

The economic analysis showed a 27% increase in direct costs per square meter with respect to conventional adobe. This cost overrun is fully justified technically, given the significant benefits in structural strength, lower water absorption, higher thermal insulation, and potentially lower maintenance costs and longer life of the material. This comprehensive economic approach is crucial to argue the technical and economic feasibility of adopting modified adobe in sustainable and social housing projects.

These results highlight not only the technical feasibility and environmental sustainability of the combined use of agro-industrial waste and expired cement in adobe, but also its potential to significantly improve the structural and economic performance of earthen constructions, actively contributing to a circular economy and to the sustainable development of the construction sector.

5 CONCLUSION

The simultaneous incorporation of 0.9% coconut fiber and 9% expired cement allowed achieving an average compressive strength of $37.86 \text{ kgf.cm}^{-2}$ in adobe blocks, exceeding the conventional adobe, which presented $17.69 \text{ kgf.cm}^{-2}$, by $20.17 \text{ kgf.cm}^{-2}$. In the pile test, the average resistance reached $33.89 \text{ kgf.cm}^{-2}$ compared to $11.47 \text{ kgf.cm}^{-2}$ in the control, confirming a substantial increase in bearing capacity. Likewise, the indirect tensile strength increased from 2.86 kgf.cm^{-2} (control) to $11.43 \text{ kgf.cm}^{-2}$ in the optimum mix, and the flexural strength increased from $10.73 \text{ kgf.cm}^{-2}$ to $19.78 \text{ kgf.cm}^{-2}$. These improvements show a comprehensive optimization of mechanical performance, statistically validated by ANOVA ($p < 0.0001$) and Tukey's post hoc tests.

From the hygrothermal perspective, water absorption decreased from 21.59% in the traditional adobe to 7.82% in the reinforced adobe, while thermal conductivity decreased from $1.67 \text{ W.m}^{-1}.\text{K}^{-1}$ to $0.52 \text{ W.m}^{-1}.\text{K}^{-1}$. This decrease reflects a denser and less permeable internal structure, improving the durability and energy efficiency of the earth construction.

The economic analysis showed that the direct cost per square meter of conventional adobe wall is S/ 120.98, while the reinforced mix reached S/ 154.14 per m^2 . Although this represents an increase of S/ 33.16 per square meter, the improvement in structural performance and durability technically supports this cost overrun, reducing maintenance costs and extending the useful life of the building.

In summary, the proposed strategy of agroindustrial waste valorization and the use of expired cement enabled the development of adobe with superior mechanical and thermal performance, validating its viability as a sustainable solution for rural and social housing. Its adoption and the performance of complementary studies on long-term durability and life cycle assessment are recommended to consolidate its application on a real scale.

DISCLAIMER

The authors declare no conflict of interest regarding the funding, authorship, or publication of this research.

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