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Original Article

Evaluation of the Mechanical Properties of Adobe with the Addition of Rice Husk Ash and Opuntia Ficus-Indica

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Abstract *- Raw Earth continues to be a widely used material in rural construction due to its accessibility and low cost; however, Adobe has significant limitations, such as its low mechanical strength and high vulnerability to moisture, which negatively affect its durability and structural safety. In view of this problem, this research aimed to evaluate the effect of incorporating Rice Husk Ash (RHA) and Prickly Pear Juice (Opuntia ficus-indica, PPJ) on the mechanical, physical, and thermal properties of Adobe, with a view to developing a more sustainable and environmentally friendly alternative. To this end, soil extracted from the Cullpa Alta quarry, located in the district of El Tambo, was used and classified according to the SUCS system. As for the additives, RHA was obtained through a process of controlled calcination and subsequent sieving of rice husks, while PPJ was prepared from the collection, washing, cleaning, and blending of prickly pear cactus pads. Next, six dosage levels were tested for both additives (RHA: 0%, 2%, 4%, 6%, 8% and 10%; PPJ: 0%, 10%, 11.5%, 13%, 14.5% and 16%), resulting in 210 samples that were subjected to compressive strength, tensile strength and flexural strength tests, as well as tests on adobe walls, water absorption and thermal conductivity. As a result, the combination of 6% RHA with 13% PPJ proved to be the most effective, achieving increases of 65.85% in compression, 294.37% in traction, 98.73% in flexion, and 159% in walls, as well as reductions of 47.46% in water absorption and 43.44% in thermal conductivity. Finally, an ANOVA analysis verified that these improvements were statistically significant ($p < 0.05$), demonstrating that the incorporation of these natural additives allows for a comprehensive improvement of traditional Adobe, positioning this alternative as a viable, durable, and environmentally friendly construction solution.*

Keywords *- Ficus-Indica, Rice Husk Ash, Adobe, Thermal Conductivity.*

1. Introduction

Earthen construction remains one of the oldest and most sustainable building systems, and currently, nearly 33% of the global population resides in dwellings made from earth-based materials [1]. Among these, Adobe stands out for its low cost, local availability, and low environmental impact, especially in rural areas of developing countries [2, 3]. However, Adobe presents major structural and durability limitations due to its low mechanical strength, brittleness, and high susceptibility to moisture, leading to degradation through cracking, erosion, and material detachment [4-6]. Moisture exposure also promotes the growth of fungi and mold, affecting both indoor air quality and the health of occupants [7].

Although chemical stabilizers such as cement or bituminous emulsions can improve Adobe's performance, their use in rural contexts is limited by cost, availability, and environmental footprint. Therefore, there is an urgent need for sustainable, low-cost, and eco-efficient alternatives that strengthen Adobe while addressing agro-industrial waste management issues [8].

In Peru, the rice industry produces approximately 220,000 tons of rice husks annually, which are often openly burned or discarded, generating pollution and greenhouse gases due to their high silica content and slow biodegradation [9]. Meanwhile, the prickly pear cactus Opuntia Ficus-Indica (OFI), cultivated extensively in central and southern Andean zones for cochineal production, generates tons of organic residues after harvest, rich in mucilage and carbohydrates that decompose rapidly, releasing gases and odors [10, 11].

To address both challenges, this research proposes the combined use of Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ) as natural stabilizers in adobe production. RHA, rich in amorphous silica, acts as a pozzolanic additive, reacting with calcium hydroxide to form Calcium Silicate Hydrates (C–S–H), which densify the matrix, reduce porosity, and increase compressive strength [12-14]. In turn, the mucilage present in Opuntia juice behaves as a biopolymeric binder, generating a viscous gel that coats soil particles, reducing capillary suction and water absorption, and enhancing internal cohesion [15].

Despite promising individual results, the synergistic effect of combining a pozzolanic agent (RHA) with a natural mucilage-based biopolymer (PPJ) has not been comprehensively studied. Therefore, this research evaluates the mechanical, physical, and thermal properties of Adobe stabilized with both materials, aiming to develop a bio-sustainable construction material suited for rural housing under humid and seismic conditions.

2. Literature Review

2.1. Rice Husk Ash (RHA) as a Pozzolanic Stabilizer

The performance of Rice Husk Ash (RHA) as a stabilizing agent primarily depends on its high amorphous silica content, ranging between 85% and 95%, its particle fineness below 45 μm, and controlled calcination between 500 and 700 °C. These conditions maximize pozzolanic reactivity and micro-filling effects within the adobe matrix. During the pozzolanic reaction, RHA consumes Calcium Hydroxide [$Ca(OH)_2$] released by the hydration of lime compounds present in the clay, forming secondary Calcium Silicate Hydrates (C–S–H). These reaction products act as an additional cementitious agent, enhancing the internal cohesion of the clay–aggregate skeleton, reducing effective porosity and critical pore size, and consequently lowering permeability and sorptivity.

In Burkina Faso, partial replacement of cement by RHA at levels between 2% and 12% was studied, finding that a 10% substitution achieved a compressive strength of approximately 2.0 MPa— the minimum value required for one-story adobe units. Moreover, reductions in porosity and surface erosion confirmed the micro-filling effect of the ash within the matrix [16, 17]. In the United Kingdom, the combination of 0.25–1% RHA with 10% lime produced a 62% increase in compressive strength and a 95% increase in tensile strength, along with a reduction of 13–60% in water absorption and up to 75% in production costs, confirming its technical and economic viability [18, 19]. Similarly, in Egypt, the addition of 5–20% rice straw ash improved both mechanical and thermal properties. At a 20% dosage, results showed significant increases in compressive strength, a density of 1.46 g/cm³, reduced water absorption of 8.3%, and thermal conductivity of 0.46 W/m·K [20].

In Myanmar, the incorporation of 3–15% RHA revealed that 3% provided optimal compressive strength (32 kg/cm²) while reducing unit weight and linear shrinkage, leading to greater dimensional stability [21]. Likewise, in Cameroon, 1–2.5% RHA improved mechanical strength by 5–6% and reduced capillary absorption and shrinkage, with the best results obtained for curing periods of 7–14 days [22]. In Thailand, comparative tests indicated that raw husk sometimes outperformed calcined ash in erosion resistance, highlighting the influence of combustion temperature on silica crystallinity and pozzolanic reactivity [23, 24]. Finally, in Salaya, the addition of 4.5% RHA significantly improved compressive, flexural, and erosion resistance, confirming its potential for use in low-cost rural housing [25].

In summary, RHA provides substantial benefits across three dimensions: mechanical, durability, and hygrothermal. Mechanically, the formation of secondary C–S–H and granular Compaction Increases Compressive (fc) and Flexural (MOR) strength. In terms of durability, pore refinement reduces sorptivity, capillary rise, and degradation caused by wet–dry cycles. Thermally, stable micro-porosity decreases thermal conductivity (λ), improving indoor passive comfort. However, the magnitude of these benefits depends on the ash fineness, calcination temperature, and duration, and the calcium content in the soil, all of which influence the extent of the pozzolanic reaction and the development of the cementitious microstructure.

2.2. Opuntia Mucilage as a Natural Polymeric Binder

Opuntia Ficus-Indica mucilage is a natural biopolymer composed of hydrophilic polysaccharides (arabinose, galactose, xylose, and rhamnose) with high viscosity, film-forming capacity, and strong affinity for mineral surfaces through hydrogen bonds and polar interactions. In earthen mixtures, the mucilage acts as a binding and stabilizing agent, improving particle cohesion, reducing capillary absorption, and increasing flexural and tensile strength. Its colloidal nature also promotes uniform drying, mitigating shrinkage-induced cracking.

In Italy, experimental studies demonstrated that the incorporation of prickly pear mucilage increased internal cohesion, compressive strength, and moisture resistance of Adobe, while significantly reducing surface cracking and mass loss from erosion [26]. In Peru, the Civil Engineering School at the National University of Engineering reported that adding 15% prickly pear gum (partially replacing water) and reinforcing with palm fibers resulted in 98% higher flexural strength, 24.39% higher compressive strength, and 73.4% greater diagonal shear resistance, while deformation and suction decreased by 27% and capillary absorption was reduced [27].

Beyond the use of Opuntia mucilage, various Peruvian studies have investigated other natural or agro-industrial additives with comparable effects. At the National University of the Center of Peru, the combination of 0.5–1.5% sugarcane bagasse and rice husk improved compressive strength by 30.8%, wear resistance by 37%, and reduced capillary absorption by 26% [28]. Similarly, the joint addition of 0.75% RHA and 0.5–2% cabuya fiber increased compressive strength by 52% and tensile strength by 50%, demonstrating the synergistic potential between pozzolanic mineral additives and plant-based fiber reinforcements [29].

These findings confirm a growing trend toward the development of bio-based construction materials that incorporate natural reinforcements to enhance both structural performance and durability of traditional materials. However, to date, there are no studies evaluating the simultaneous performance of the pozzolanic (RHA) and biopolymeric (Prickly Pear Mucilage) systems within a unified experimental framework, representing a significant gap in the scientific literature.

2.3. Research Gap and Novelty

Despite significant progress reported in previous studies on the individual use of Rice Husk Ash (RHA) and Opuntia Ficus-Indica mucilage as natural stabilizing agents in earthen materials, scientific literature still lacks comprehensive analyses that evaluate their combined effect and the possible synergy between both additives on the mechanical, physical, and thermal behavior of Adobe. Most existing research focuses on the isolated performance of each component, without addressing the chemical and microstructural interactions that may occur when a siliceous pozzolanic agent and a biopolymeric gel are integrated simultaneously. This gap in knowledge prevents identifying the optimal combined dosage that maximizes compressive strength, moisture resistance, and thermal efficiency while maintaining volumetric stability and compatibility with traditional construction methods.

In this context, the novelty of the present research lies in the joint evaluation and optimization of RHA and Prickly Pear Juice (PPJ) as a hybrid stabilization system. The proposed approach does not analyze the additives separately; instead, it focuses on identifying the synergistic balance between them—determining how the pozzolanic reactions of RHA interact with the colloidal behavior of PPJ to improve adobe performance. A structured experimental program consisting of six combined dosages and one control mixture, for a total of 210 specimens, was designed to assess the effects of these natural stabilizers on compressive, tensile, and flexural strength, as well as pillar compression, water absorption, and thermal conductivity. This methodological design allows for quantifying the combined influence of the additives and defining the range of optimal performance for both structural and hygrothermal behavior.

The primary purpose of this research is to establish technical guidelines and optimal dosage ranges that can serve as a foundation for developing sustainable formulations suitable for rural housing in humid-seismic regions. Unlike prior studies [16-29], this investigation does not aim to evaluate each material independently but rather to optimize their combined interaction, generating a balanced material that is mechanically strong, moisture-resistant, and thermally efficient. The proposed approach contributes to the field of sustainable construction by providing a scientific basis for bio-based hybrid stabilization systems, reducing environmental impact while enhancing the resilience and durability of earthen structures.

3. Materials and Methods

3.1. Adobe

Adobe is a building material made from a mixture of clay soil, water, and sometimes organic fibres, which is moulded by hand or using moulds to form blocks. These blocks are left to dry in the open air for several days, allowing them to harden without the need for firing. Its use is common in areas where industrial resources are limited, and it has historically been used in the construction of houses, walls, and other structures in different parts of the world [30]. Its mechanical behaviour depends largely on the type of soil used, the proportion of its components, and the curing conditions.

There are various methods of earth construction, including Adobe, each with its own particular characteristics. Figure 1 shows seven notable techniques. The first is cob, which consists of accumulating moist Earth without formwork [31]; the second, daub and wattle, combines interwoven wooden structures with mud as filler [32]; the third, Poured Earth, uses a mixture of Earth, gypsum and aggregates that is poured into moulds [33]; the fourth is Adobe, composed of a mixture of clay, sand and water, moulded and dried in the sun [34].

Fifthly, there are Rammed Earth Walls, where the Earth is compacted in layers within formwork to form solid structures [35]. Finally, Compressed Earth Blocks (CEBs) are made by compacting Earth in moulds, functioning in a similar way to conventional bricks [36]. Each of these techniques has advantages and limitations that must be considered according to the construction context, climate, and available resources.

Tests were carried out on compressed earth blocks because, in the city of Huancayo, it is common to see houses built with this material, taking advantage of its low cost and local availability. This type of construction is mainly used in rural and peri-urban areas, which makes it relevant to evaluate its properties to ensure its efficiency and durability in these contexts. As shown in Figure 2, construction with compressed earth blocks remains a viable option in the region. The process followed in conducting the tests will be detailed below, providing a clearer picture of their practical application.

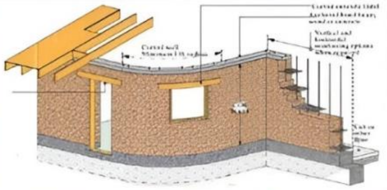
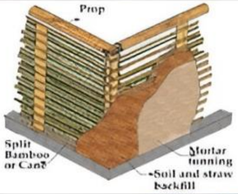
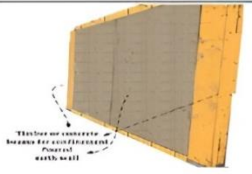
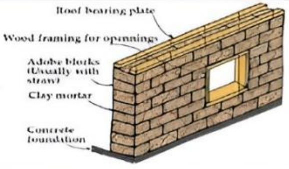
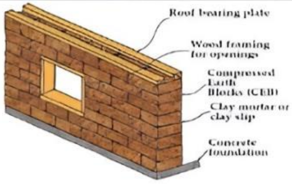
Earth-Based Construction Systems	Description	Advantages	Disadvantages
	A method that uses the accumulation of moist earth without the need for formwork. The mixture of clay and straw is compacted in successive layers directly on the construction site, forming solid walls with high thermal mass.	• Excellent thermal capacity, which improves the energy efficiency of buildings. • Ideal for extreme climates, as it maintains more stable temperatures inside buildings.	• Slow process requiring considerable manual effort. • Construction can be laborious and time-consuming, especially without the right machinery.
	A traditional method that combines woven wood as a structure and mud as a filling, providing an economical construction that can be quickly implemented in rural areas.	• Its low cost and ease of construction make it an efficient option for housing development in rural areas with economic constraints.	• Low durability without proper maintenance. • Requires regular care to prevent deterioration due to environmental factors.
	A recent method that uses moist earth mixed with aggregates and gypsum, with a consistency similar to concrete. This mixture is poured into moulds and, once dry, forms monolithic walls. The technique is fast and versatile, although its use in modern construction is less common.	• A fast technique that can be adapted to different shapes. • It allows structures to be built quickly, making it efficient for certain projects.	• Less availability of specialised technical knowledge and specific materials. • The process is not as well documented or widespread in today's industry.
	Blocks made from a mixture of clay, sand and water, dried in the sun. This method is ideal for dry climates, as it offers a flexible and environmentally friendly construction system.	• Low cost and easy access to materials. • Simple manufacturing process with no need for complex machinery.	• Limited moisture resistance without treatment. • Low compressive strength in dry conditions and vulnerable to water if not properly treated.
	A construction technique that involves compacting successive layers of soil within formwork, forming dense and solid structures. This method produces walls with high strength and durability, ideal for permanent buildings.	• High resistance to compression. • Excellent structural durability. • Suitable for stable load-bearing constructions.	• Requires the use of specific machinery or equipment to achieve adequate compaction. • The process may be slower if the appropriate technical resources are not available.
	Blocks manufactured by sun-drying a mixture of clay, sand and water. This traditional technique is particularly suitable for arid climates, as it promotes a sustainable construction system that can be adapted to various local needs.	• Low production cost. • Locally available materials. • Simple technique with low environmental impact.	• Low moisture resistance if no treatment is applied. • Limited compression resistance in dry conditions. • May deteriorate rapidly in humid environments without adequate protection.

Fig. 1 Construction systems [37]

Fig. 2 Traditional adobe building in Huancayo [38]

3.2. Rice

Rice is one of the most important and widely consumed crops worldwide, serving as a staple food for millions of people [39]. It originated in Asia, although today it is grown in many regions of the world due to its adaptability to different climates and soils [40]. There are two main varieties of rice: long-grain rice, which is more common in the West, and short-grain rice, which is more common in Asia. In addition to being an essential source of carbohydrates, rice is also a good source of B vitamins and minerals such as iron, although its nutrients vary depending on how it is processed [41]. In this context, rice husks, generated as waste during threshing, represent an abundant and accessible material in many producing regions. Previous research has shown that this waste has pozzolanic properties attributable to its high amorphous silica content, especially when subjected to controlled thermal processes. These characteristics make it a viable candidate for incorporation into alternative building materials, such as adobe bricks, thus promoting sustainable production approaches through the use of agro-industrial waste.

3.2.1. Third-Order Heading

Figure 3 illustrates the procedure employed to obtain Rice Husk Ash (RHA) through a controlled combustion process. In the first stage, shown in item (a), dry rice husks were manually collected, ensuring the absence of moisture to guarantee uniform combustion. In the subsequent phase, indicated in item (b), the material was placed in a furnace and subjected to progressive heating at a controlled rate of approximately 5 to 10 °C per minute until reaching a temperature range between 500 °C and 700 °C. This thermal range was maintained for several hours to ensure complete calcination of the residue.

During the combustion process, the air flow was carefully regulated to prevent the accumulation of harmful gases and to promote efficient oxidation. This controlled atmosphere favoured the formation of silica in its amorphous phase, characterised by high pozzolanic reactivity. Once the thermal process was completed, the resulting ash was allowed to cool naturally for a period of three hours, ensuring material stability. Finally, as shown in item (c), the cooled ash was crushed and sieved to obtain a fine particle size, with particles smaller than 1 mm, suitable for subsequent incorporation into adobe mixtures.

(a) Rice husks **(b) Calcination** **(c) Ash screening**

Fig. 3 Process for obtaining Rice Husk Ash

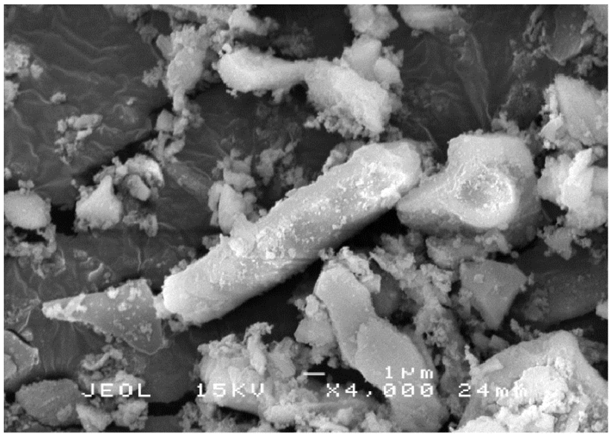


Fig. 4 SEM of the structure of Rice Husk Ash [42]

Figure 4 shows the microstructure of Rice Husk Ash (RHA) observed using Scanning Electron Microscopy (SEM), a technique that allows the morphology and surface composition of materials to be analysed at high resolution. After the grinding process, the particles obtained have a high silica content, predominantly in its amorphous form. This amorphous form has a structure similar to cristobalite, a polymorphic phase of silicon dioxide. In addition, small proportions of silica in its crystalline phase are identified, specifically in the form of quartz. This combination of phases can significantly influence the pozzolanic properties of the material.

Table 1 shows that Rice Husk ash (RHA) has a significantly high Silicon Dioxide (SiO_2) content, with a value of 82.13%, its most notable characteristic and important pozzolanic properties for use in construction materials. In addition, smaller proportions of oxides such as Aluminium (Al_2O_3) with 4.27% and Magnesium (MgO) with 1.65% are identified, which can also influence the reactivity of the material.

Together, these components highlight the potential of RHA as a sustainable and functional alternative in the manufacture of products such as adobe blocks or concrete with mineral additives.

Table 1. Composition of rice husks [43]

Rice Husk Ash (RHA)	
Composition	**Value**
SiO_2	82.13
AL_2O_3	4.27
Fe_2O_3	0.38
Na_2O	0.14
K_2O	1.23
CaO	0.16
MgO	1.65
P_2O_3	1.44

3.3. Prickly Pear Stalk

The Prickly Pear pad comes from the nopal (Opuntia spp.), a genus of cactus native to America, especially the regions of Mexico and Central America [44, 45]. The pads are the flat, fleshy leaves of the nopal, which contain nutritional properties such as fibre, vitamin C, calcium, and magnesium, and are used both in cooking and in traditional medicine. They are eaten fresh, cooked, or in salads, and are known for their digestive and anti-inflammatory benefits. In addition, the gel from the pads has soothing and healing properties, which are useful for treating burns and wounds. In some regions, Prickly Pear pads are used in roof construction and as filler material due to their strength and ability to withstand extreme conditions [16].

Figure 5 shows the process carried out to obtain Prickly Pear Juice (PPJ). Firstly, in item (a), the manual collection of fresh cladodes was performed, selecting mature, healthy specimens free from physical or biological damage. Next, in item (b), the cladodes were washed with potable water to remove impurities. Then, the spines were carefully removed using a stainless-steel knife, and the outer skin was peeled to expose the internal pulp. Subsequently, in item (c), the pulp was cut into small pieces of approximately 2 to 3 centimetres and placed in a blender. Afterwards, 500 millilitres of distilled water were added, and the mixture was processed for 2 to 3 minutes until a homogeneous consistency was obtained. Finally, in item (d), the mixture was filtered through a fine mesh, resulting in a clean, uniform juice free of impurities, suitable for use in the subsequent stages of the process.

(a) Prickly pear stalk **(b) Peeling** **(c) Cutting** **(d) Juice**

Fig. 5 Process for obtaining juice from prickly pear cactus pads

Table 2 shows that Prickly Pear Juice (PPJ) has a high moisture content (94–96%) and low thermal conductivity (0.19–0.22 W/m·K), making it an interesting material for applications requiring water retention or insulating properties. In addition, it contains between 1.2 and 2.5% mucilage, compounds with thickening and stabilising properties, while its viscosity, which varies between 30 and 65 cP, reinforces its potential use in food, pharmaceutical, or cosmetic products. Its density is between 0.98 and 1.05 g/cm³, close to that of water, which facilitates its handling and integration into liquid mixtures.

Table 2. Properties of prickly pear juice

Physical and Mechanical properties	
Composition	**Value**
Mucilages	1.2-2.5%
Viscosity	30-65cP
Density	0.98-1.05 g/cm3
Humidity	94-96%
Thermal Conductivity	0.19-0.22 W/m.k

Table 3 shows the different dosages of Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ) used in this study. These natural materials were incorporated with the aim of evaluating their influence on the Physical and Mechanical properties of Adobe.

Six dosage levels were considered for Rice Husk Ash: 0%, 2%, 4%, 6%, 8% and 10%. In the case of prickly pear juice, the dosages applied were 0%, 10%, 11.5%, 13%, 14.5% and 16%. These combinations made it possible to analyse the behaviour of the material in response to different sustainable addition ratios, seeking to optimise its characteristics without resorting to industrial inputs.

Table 3. Dosage

Materials	Dosage
Rice Husk Ash (RHA)	0%, 2%, 4%, 6%, 8%, 10%.
Prickly Pear Juice (PPJ)	0%, 10%, 11.5%, 13%, 14.5%, 16%.

3.4. Soil Study

3.4.1. Soil Classification

In order to properly classify soil, a series of preliminary tests must be carried out, with the grain size test being one of the most important, as it allows the distribution of the size of the particles that compose it to be determined, which is essential information for understanding the characteristics of the material and its suitability for use in construction processes. This analysis was carried out in accordance with Technical Standard MTC E-402 [46], which governs procedures for granular soils. First, the material was collected from the Cullpa Alta quarry, located in the district of El Tambo, and then transported to the laboratory under appropriate handling and transport conditions to avoid altering its physical properties. Once in the laboratory, the corresponding stages of the test were carried out. First, the material was quartered in the appropriate position in order to obtain a representative sample. The sample was then washed to remove fine particles smaller than 0.075 mm that could alter the results of the granulometric analysis. After washing, the sample was dried in an oven at a temperature of 105 ± 5 °C for 24 hours. Finally, the dry sample was sieved using a series of meshes from No. 2 to No. 200, which allowed the particle size distribution to be obtained, essential information for identifying the soil type.

After performing the particle size analysis, the complementary tests essential for the correct classification of the soil were carried out, namely: moisture content, liquid limit, and plastic limit. The moisture content test, carried out in accordance with standard MTC E-108 [46], consisted of weighing a wet soil sample, drying it in an oven at 110 ± 5 °C for 24 hours, and reweighing it to determine the amount of water it contained. The result obtained was 6.19%, which indicates that the soil has a low moisture content, typical of granular soils or soils with low water retention capacity. Next, the liquid limit test was performed, in accordance with standard MTC E-110 [46], using the Casagrande apparatus. To do this, a homogeneous soil paste was prepared with water and placed in the cup of the device; a groove was made in the centre, and controlled blows were applied until the groove closed. This procedure was repeated with different moisture contents to plot the characteristic curve, from which the moisture content corresponding to 25 blows was obtained. Next, the plastic limit test was carried out, following standard MTC E-111 [46], in which thin strands of soil (up to 3 mm in diameter) were moulded to identify the moisture content at which the soil changes from a plastic to a semi-solid state. The data obtained from both tests were used to calculate the Plasticity Index (PI), which was 18.79. This value reflects medium plasticity, which means that the soil has a certain capacity to deform without cracking, making it suitable for compaction and the formation of construction elements such as blocks. Finally, considering the results of the granulometry, moisture content, and Atterberg limits, the soil was classified as SC - clayey sand, according to the Unified Soil Classification System (USCS). This category represents a soil composed mainly of sand with a significant plastic fine fraction, which gives it good compaction and cohesion capacity, making it suitable for use in construction techniques such as Compressed Earth Blocks (CEB), provided that the moisture content is controlled during the process.

3.4.2. Mechanical Tests

In order to evaluate the mechanical behaviour of the improved Adobe, various tests were carried out in accordance with current technical regulations. In all cases, the samples were prepared by incorporating rice husk ash and prickly pear juice as stabilising additives, following the proportions established in Table 3. Likewise, a specific number of specimens were prepared for each dosage, which ensured the repeatability of the results and their statistical validity.

Firstly, a uniaxial compressive strength test was carried out to evaluate the material's capacity to withstand axial loads without exhibiting plastic deformations or fractures. The procedure was conducted in accordance with the MTC E-704 [46] standard, using cubic specimens measuring 10 × 10 × 10 cm, prepared in steel moulds that ensured precise geometry and flat surfaces for uniform load distribution. Six mix combinations were prepared, producing three specimens for each, resulting in a total of eighteen samples. The specimens were cured for 28 days in a controlled and ventilated environment, protected from direct sunlight and extreme temperature variations, allowing for gradual and uniform drying of the material until the hardening process was complete. Afterwards, the specimens were tested in a calibrated hydraulic compression machine, ensuring axial alignment and parallel contact surfaces to avoid eccentric loading. The axial load was applied continuously and uniformly, with a stress increase rate between 0.20 and 0.30 MPa/s, until failure occurred. The individual compressive strength was determined from the maximum stress recorded in each specimen, and the mean representative value for each mix was obtained as the arithmetic average of the three corresponding specimens.

Subsequently, the indirect tensile strength test, also known as the diametral compression test, was carried out to evaluate Adobe's capacity to withstand tensile stresses before fracturing. For this purpose, six mix combinations were considered, and for each, six cylindrical specimens measuring 10 cm in diameter and 20 cm in height were prepared, resulting in a total of 36 specimens, which were left to dry for 28 days under controlled environmental conditions. Once dried, the specimens were carefully prepared: the diameters were marked at both ends to ensure that the load was applied along the same axial plane, thereby guaranteeing a uniform stress distribution; likewise, the diameter was measured at three points (both ends and the centre) with a precision of ±0.25 mm, while the length was measured at least twice, averaging the values to obtain reliable dimensions for strength calculation. Finally, the specimens were subjected to an increasing axial load applied at controlled rates between 689 kPa/min and 1380 kPa/min, in accordance with the MTC E-708 [46] standard, until failure occurred, with the maximum load sustained in each case recorded as an indicator of the material's tensile strength capacity.

Next, the flexural strength test was carried out with the objective of evaluating the behaviour of the material under the tensile and compressive stresses generated along the section as a result of bending. This procedure was conducted in accordance with standard MTC E-711 [46], using prismatic specimens measuring 40 cm in length, 20 cm in width, and 12 cm in height. Six mix combinations were considered and, for each of them, three specimens were prepared, resulting in a total of 18 specimens tested. In addition, the specimens were left to dry for 28 days under controlled environmental conditions prior to testing, in order to ensure proper strength development and moisture equilibrium. Subsequently, each specimen was rotated from its moulding position and carefully centred on the supporting blocks, while the loading blocks were placed at the third points of the span to guarantee precise alignment and a uniform distribution of stresses. The load was applied continuously and without shocks, at a rate of stress increase in the extreme fibre, corresponding to the area farthest from the neutral axis of the section, where the maximum tensile and compressive stresses occur, maintained between 0.9 MPa/min and 1.2 MPa/min until the specimen fractured. During this process, both the maximum load sustained and the corresponding deformation were recorded. Finally, to ensure accuracy in the calculation of flexural strength, the width and height of each specimen were measured at three points, two at the edges and one at the centre, with a precision of 1.3 mm, and the average values obtained were used in the modulus of rupture formula, thereby providing more reliable and representative results of the material's actual behaviour at the moment of failure.

Finally, the compression test on small walls was carried out with the purpose of analysing the structural behaviour of masonry units subjected to vertical loads, simulating real building conditions. This procedure was performed in accordance with the Peruvian Building Code, Technical Standard E.080: Adobe, constructing walls composed of three adobe blocks (13 cm × 24 cm × 9 cm) joined by 1 cm thick mortar joints. Six mix combinations were considered and, for each of them, six walls were produced, giving a total of 36 specimens tested. Each wall was placed in a compression testing machine and subjected to an axial load applied uniformly and continuously until failure, recording in each case the maximum strength achieved. This value was then used to assess the performance of the walls under vertical loading and to compare it with the minimum required by Standard E.080, which specifies a compressive strength of approximately 1.0 MPa, thereby ensuring that the results obtained were representative of the actual behaviour of adobe walls under vertical loads.

3.4.3. Physical Tests

In order to evaluate the physical properties of the improved Adobe, water absorption and thermal conductivity tests were carried out, which allow its behaviour in relation to humidity and heat transfer to be analysed, respectively. For both tests, the samples were prepared with the addition of Rice Husk Ash and Prickly Pear Juice, following the proportions indicated in Table 3.

First, in order to determine the porosity of the adobe blocks, the water absorption test was carried out in accordance with the Peruvian Technical Standard NTP 399.613. For this purpose, eighteen prismatic samples measuring 40 cm in length, 20 cm in width, and 12 cm in height were prepared, corresponding to six different mix combinations with three replicas for each, ensuring uniformity in dosage, compaction, and curing. After fabrication, the blocks were cured for 28 days under controlled conditions to allow the proper development of their physical properties. Subsequently, the samples were oven-dried at a temperature between 105 °C and 115 °C until a constant mass was achieved, after which they were allowed to cool to room temperature, and their dry weight was recorded. Then, each block was immersed in water for 24 hours at a controlled temperature to ensure uniform saturation. Finally, the surface of each sample was gently dried to remove excess water, and the wet weight was determined, allowing the calculation of the percentage of water absorption as a direct indicator of the material's porosity.

Subsequently, the thermal conductivity test was carried out with the aim of evaluating Adobe's ability to transfer heat, a fundamental aspect of its performance as a construction material in applications where insulation is critical. For this purpose, cubic specimens measuring 10 cm × 10 cm × 10 cm were prepared, considering six mixture combinations and three units for each, resulting in a total of 18 specimens. After a curing period of 28 days, all samples were oven-dried at 105 °C until reaching constant mass, in order to eliminate the effect of moisture on the results and to ensure homogeneous testing conditions, in accordance with the ASTM C518 standard for determining thermal conductivity. Subsequently, the samples were tested using specialised equipment, in which sensors were inserted to record the heat flow through the material. Finally, the thermal conductivity value was obtained by considering the amount of heat transferred, the temperature difference, and the dimensions of each specimen, ensuring accurate and representative results for each condition studied.

Figure 6 presents a general summary of the study, detailing the main materials used, such as Rice Husk Ash, Prickly Pear Juice, and soil, along with the experimental combinations that were prepared with different percentages of these components. It also shows the tests carried out after 28 days of curing, such as compressive strength, tensile strength, flexural strength, water absorption, and thermal conductivity. The diagram includes reference images that allow the materials and procedures used to be visualised, facilitating a better understanding of the experimental approach developed.

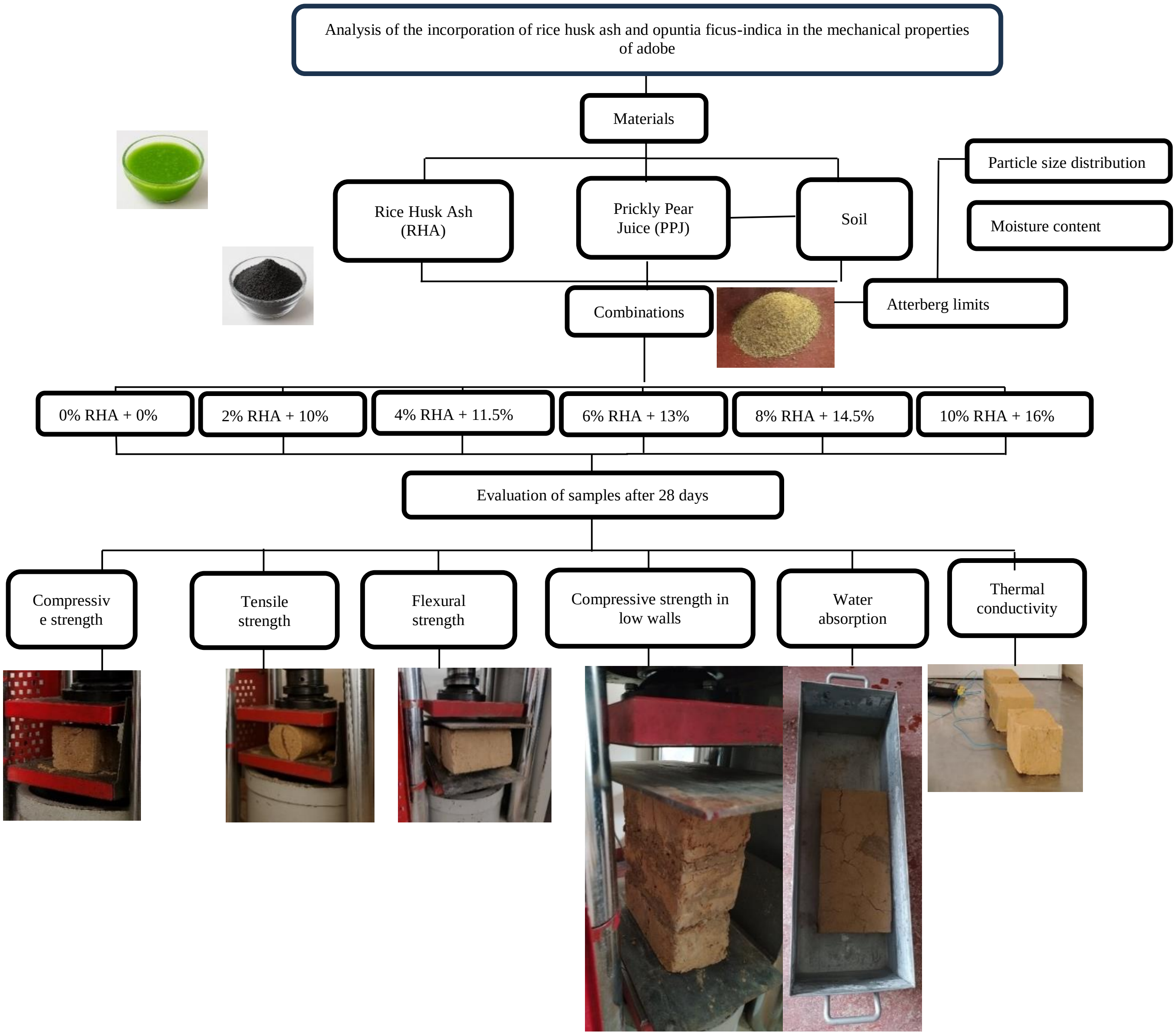


Fig. 6 Flow chart of the tests carried out at Adobe

4. Results

4.1. Compressive Strength

Figure 7 shows the compressive strength results of adobe blocks after 28 days of curing, made with different proportions of Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ). Compared to blocks without additives, there was a significant improvement in load-bearing capacity when these substances were incorporated. With a dosage of 2% RHA and 10% PPJ, the strength reached 21.45 kg/cm², increasing progressively to a maximum value of 29.87 kg/cm² with 6% RHA and 13% PPJ. However, when the proportions were increased to 8% RHA and 14.5% PPJ, the strength decreased slightly to 27.08 kg/cm², and with 10% RHA and 16% PPJ, it decreased further to 25.43 kg/cm². These results reveal that the controlled use of RHA and PPJ can significantly strengthen the mechanical properties of Adobe, making it crucial to identify an optimal dosage-in this case, 6% RHA and 13% PPJ-as higher proportions could lead to saturation or an imbalance in the mixture, negatively affecting its structural performance. This finding highlights the potential of these natural additives as a sustainable alternative for improving traditional materials. Their application is especially relevant in green building projects, rural housing, low-cost infrastructure, and other initiatives that promote the use of renewable and local resources while reducing dependence on industrial inputs.

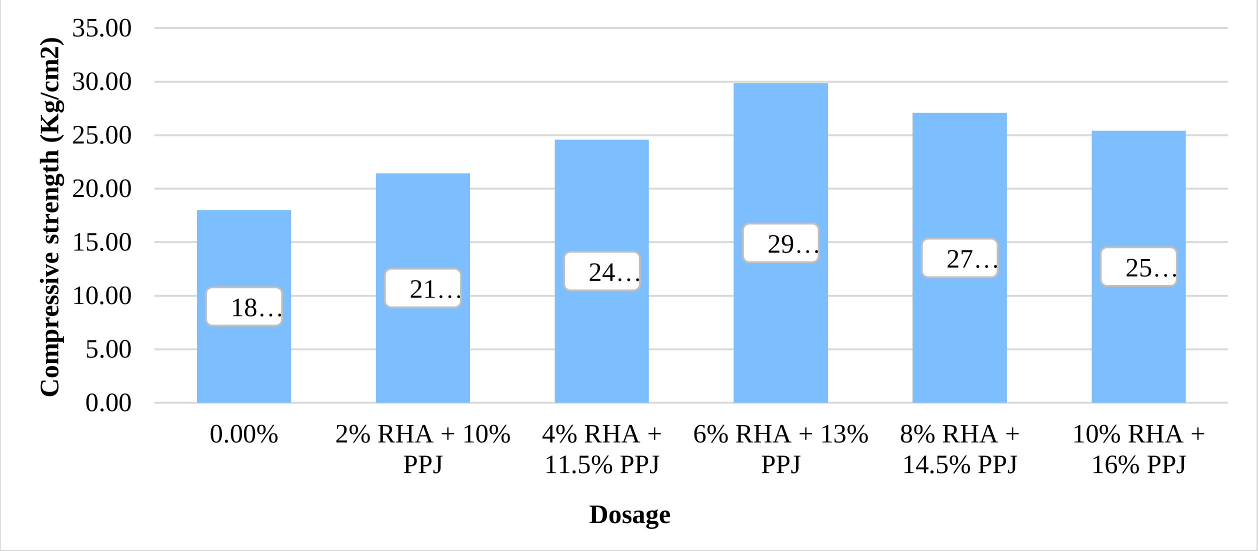


Fig. 7 Compressive strength

4.2. Tensile Strength

Figure 8 shows the tensile strength results of adobe blocks at 28 days, using different proportions of Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ). Compared to the sample without additives, which reached 2.31 kg/cm², the modified blocks showed a significant improvement. By incorporating 2% RHA and 10% PPJ, the strength increased to 3.99 kg/cm²; with 4% RHA and 11.5% PPJ, it rose to 5.06 kg/cm²; while applying 6% RHA and 13% PPJ resulted in the maximum value of 9.11 kg/cm². However, with a dosage of 8% RHA and 14.5% PPJ, the strength decreased to 7.58 kg/cm², and with 10% RHA and 16% PPJ, it fell to 5.12 kg/cm². These results demonstrate that the inclusion of these additives can significantly optimise the mechanical behaviour of Adobe under tensile stress. Furthermore, they highlight the importance of proper dosage to avoid counterproductive effects. Such improvements offer new possibilities for the development of more efficient construction technologies, especially in areas where innovation with alternative, accessible, and low-cost materials is sought.

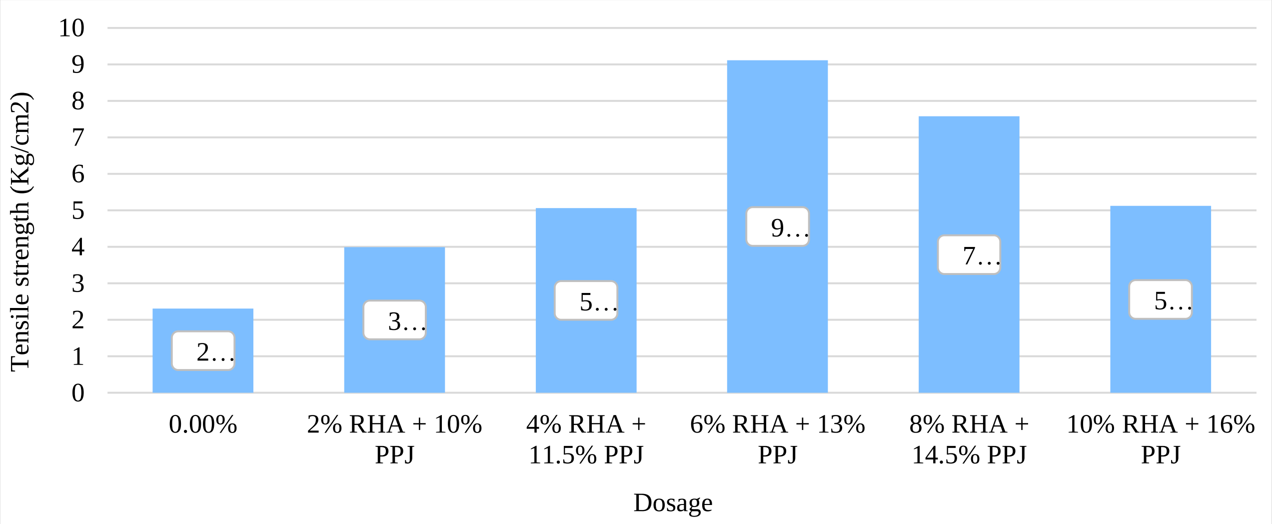


Fig. 8 Tensile strength

4.3. Flexural Strength

The flexural test is essential, as it evaluates the resistance of adobe blocks to flexural stresses, which are common in walls and structures exposed to lateral or inclined loads. Figure 9 shows the results of the flexural strength of adobe blocks at 28 days, made with different proportions of Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ). The blocks without additives recorded a strength of 8.71 kg/cm², while adding 2% RHA with 10% PPJ increased the strength to 10.03 kg/cm². This trend continued with 13.45 kg/cm² when using 4% RHA and 11.5% PPJ, and reached a maximum value of 17.31 kg/cm² with a dosage of 6% RHA and 13% PPJ. Subsequently, when the addition was increased to 8% RHA with 14.5% PPJ, the strength decreased to 15.98 kg/cm², and with 10% RHA and 16% PPJ, it decreased to 12.72 kg/cm². These results show that there is an optimum point in the combination of RHA and PPJ that maximises flexural strength, which is relevant for structures exposed to lateral or inclined loads. Furthermore, excessive addition negatively affects the mechanical properties of Adobe, implying that more is not always better. The increase in strength with moderate proportions indicates a positive interaction between RHA and the organic compounds in PPJ, which improves the internal cohesion of the material. However, when certain levels are exceeded, excess organic matter or ash interferes with the structure of the Adobe, making it less homogeneous and more fragile. This highlights the importance of maintaining a balance between the amount of additives used and the mechanical properties of the Adobe to ensure good performance in its structural use.

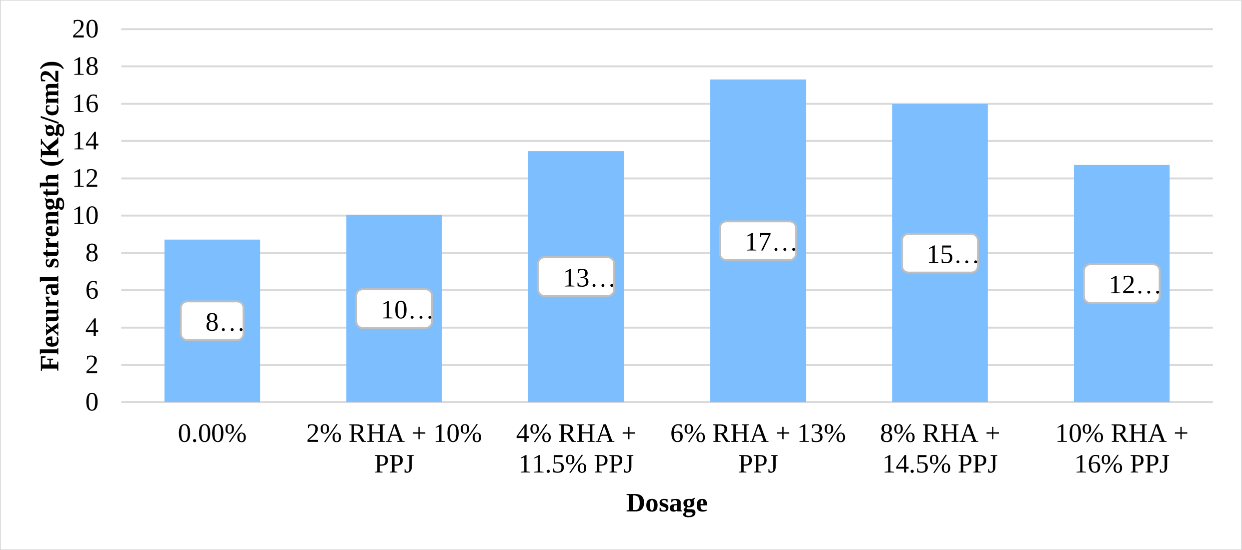


Fig. 9 Flexural strength

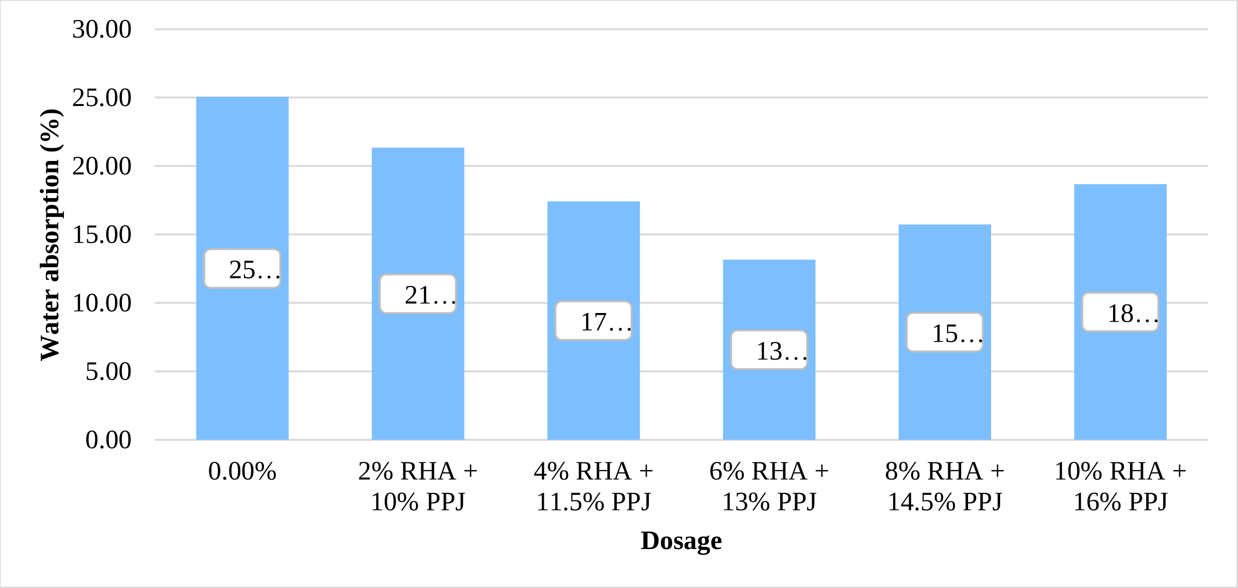


Fig. 10 Water absorption

4.4. Water Absorption

Figure 10 shows the water absorption results in adobe blocks after 28 days, where the effect of incorporating Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ) was evaluated. The standard sample without additives had the highest absorption at 25.05%. With the addition of additives, a progressive decrease was observed: sample 2, with 1% RHA and 5% PPJ, had 21.35%; sample 3, with 2% RHA and 10% PPJ, 17.42%; sample 4, with 3% RHA and 15% PPJ, 13.16%; and sample 5, with 4% RHA and 5% PPJ, reached the lowest value with 15.74%. In sample 6, with 5% RHA and 10% PPJ, a slight increase to 18.67% was observed, still remaining below the standard. These results indicate that the addition of RHA and PPJ improves the impermeability of Adobe, significantly reducing water absorption, which is crucial for increasing the durability of the material in humid conditions.

4.5. Compression Test on Low Walls

In this study, low walls were used that more realistically replicate the construction conditions of adobe walls, which allowed for more representative results, considering that compressive strength is a fundamental parameter for ensuring structural stability and durability, as it determines the material's ability to withstand loads without deforming. Figure 11 shows the results obtained when evaluating different dosages of Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ), with a progressive increase in strength as the proportions of both additions increase. The mixture without addition (0.00%) achieved a strength of 9.98 kg/cm², while the combinations with 2% RHA + 10% PPJ and 4% RHA + 11.5% PPJ achieved 14.34 kg/cm² and 19.07 kg/cm², respectively. The maximum strength was obtained with the dosage of 6% RHA + 13% PPJ, with a value of 25.87 kg/cm²; However, mixtures with higher proportions, such as 8% RHA + 14.5% PPJ and 10% RHA + 16% PPJ, showed a slight decrease, reaching 19.80 kg/cm² and 17.65 kg/cm², respectively. These results show that the controlled incorporation of RHA and PPJ significantly improves the compressive strength of adobe walls, thus optimising their structural performance and durability in real construction contexts.

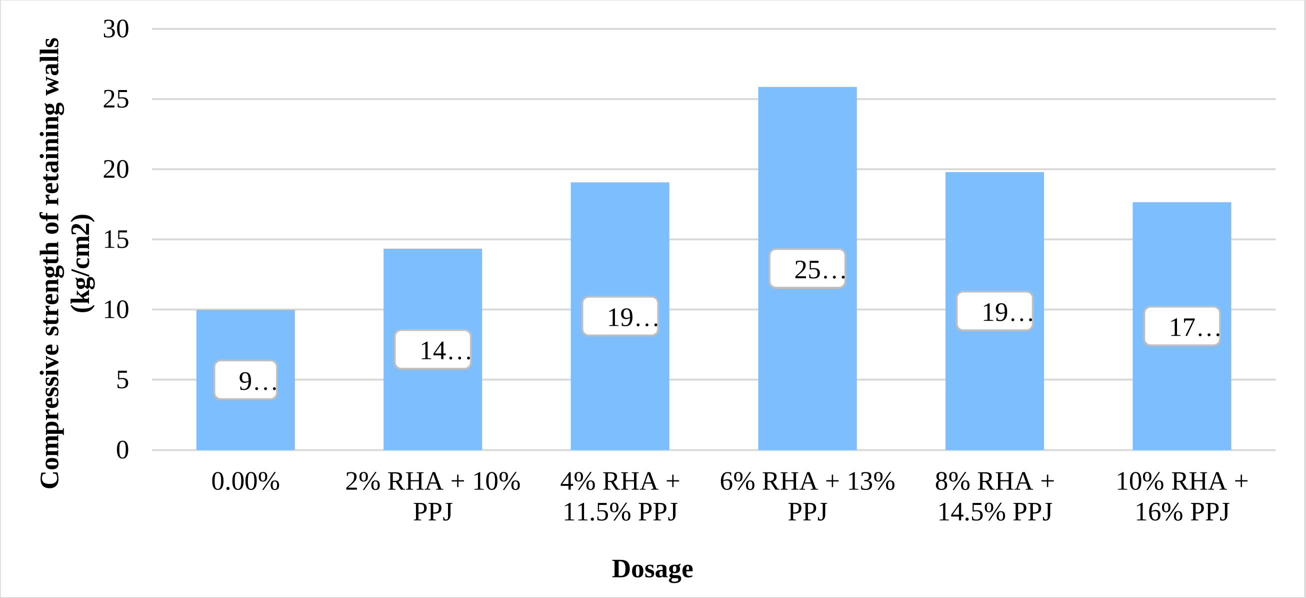


Fig. 11 Compressive strength in retaining walls

4.6. Thermal Conductivity Test

Figure 12 shows the results of the thermal conductivity evaluation based on different dosages of Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ). It can be seen that the mixture without addition (0.00%) had the highest thermal conductivity, with a value of 1.809 W/m·K, indicating greater ease of heat transfer through the material. When the addition was added, the thermal conductivity decreased progressively, suggesting an improvement in the thermal insulation capacity of the material. For example, with the combination of 2% RHA + 10% PPJ, the thermal conductivity was reduced to 1.472 W/m·K, representing a significant improvement over the mixture without addition. With a higher content of RHA and PPJ, as in the mixture of 4% RHA + 11.5% PPJ, the thermal conductivity was further reduced to 1.023 W/m·K, indicating a greater ability to resist heat transfer. The lowest thermal conductivity was achieved with the 6% RHA + 13% PPJ mixture, which had a value of 0.985 W/m·K, reflecting remarkable thermal insulation, especially advantageous in cold climates, as it helps to keep heat inside spaces, improving energy efficiency and thermal comfort in buildings. However, by further increasing the proportions of RHA and PPJ, as in the mixtures of 8% RHA + 14.5% PPJ and 10% RHA + 16% PPJ, a slight increase in thermal conductivity was observed, reaching values of 1.167 W/m·K and 1.348 W/m·K, respectively, which could be attributed to the higher presence of RHA that altered the thermal properties of the material in a less favourable way. Despite this, the mixtures with additives continue to offer better thermal performance than the mixture without additives, especially at higher proportions of RHA and PPJ. In summary, the results indicate that the controlled incorporation of RHA and PPJ significantly improves the thermal insulation of the material, which is essential for maintaining warmer environments in cold climates and reducing dependence on heating systems, with mixtures containing 6% RHA and 13% PPJ offering the best performance in terms of thermal conductivity, optimising energy efficiency in buildings.

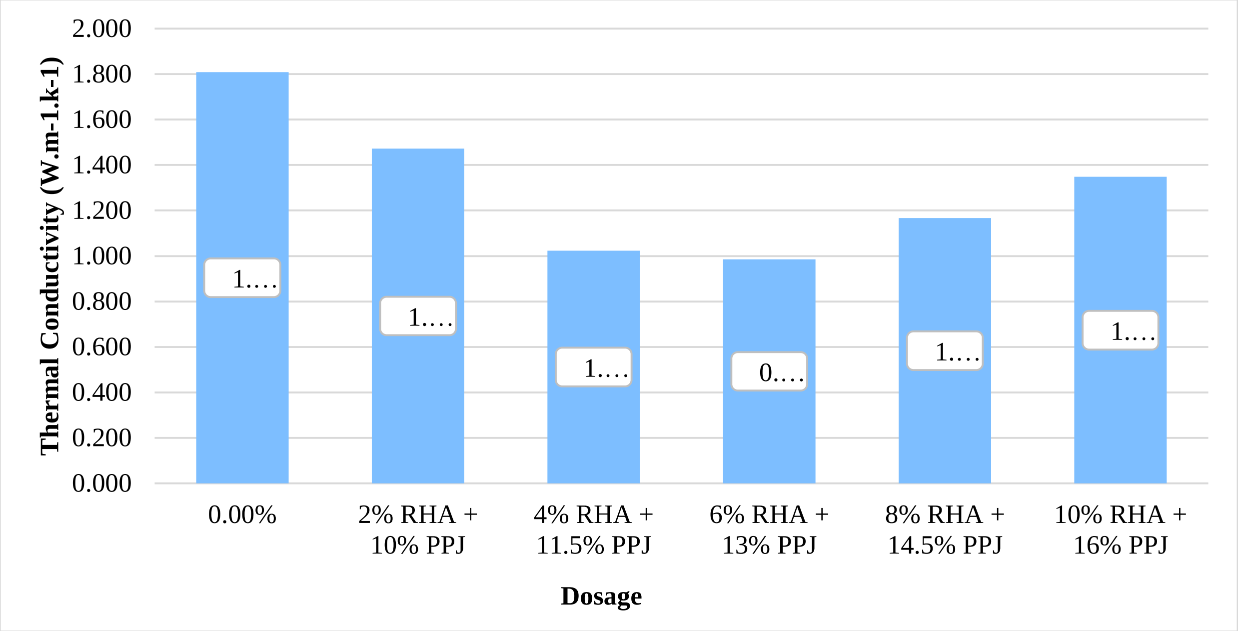


Fig. 12 Thermal conductivity

4.7. Statistical Analysis

Table 4 presents the results of the ANOVA statistical analysis applied to the different mechanical and physical tests performed, including compressive strength, tensile strength, flexural strength, compression on low walls, water absorption, and thermal conductivity.

The analysis considered the different dosages of Rice Husk Ash and Prickly Pear Juice incorporated into the mixture as the independent variable.

In all cases, the significance values obtained were below 0.05, confirming the existence of statistically significant differences between the mean values of the groups evaluated. This demonstrates that the variations observed in the physical and mechanical properties of the Adobe are not the result of random factors but are directly related to the proportion of the natural additions incorporated.

In greater detail, the compressive strength test recorded a p-value (PR(>F)) of 1.31×10^{-18}, while the tensile strength test showed a p-value of 1.40×10^{-18}, both indicating a highly significant effect of the natural additions on the load-bearing capacity of the material. The flexural strength test presented a p-value of 2.36×10^{-15}, confirming a notable improvement in Adobe's ability to resist bending loads, where compressive and tensile stresses act simultaneously.

The compression test on low walls obtained a p-value of 7.18×10^{-19}, indicating a considerable increase in the structural integrity of the material under load. Regarding water absorption, the p-value of 1.48×10^{-6} reveals a significant reduction in absorption capacity, suggesting greater impermeability and resistance to moisture. Finally, the thermal conductivity test recorded a p-value of 6.28×10^{-25}, demonstrating a marked decrease in heat transfer and confirming that the natural additions contribute to improved thermal performance and energy efficiency of the Adobe.

Overall, the ANOVA results show that incorporating natural additions of Rice Husk Ash and Prickly Pear Juice has a direct and positive influence on both the physical and mechanical properties of the material. These combined effects optimise its structural and thermal behaviour, increasing its strength, durability, and insulation capacity. Consequently, the use of such natural additions emerges as a sustainable, cost-effective, and efficient alternative for enhancing traditional construction materials without compromising their ecological character.

Table 4. ANOVA

Compressive strength				
Source	sum_sq	df	F	PR(>F)
C (Dosage)	526.064	5	114.533	1.31E-18
Residual	27.559	30	nan	nan
Tensile strength				
Source	sum_sq	df	F	PR(>F)
C (Dosage)	180.912	5	113.974	1.40E-18
Residual	9.524	30	nan	nan
Flexural strength				
Source	sum_sq	df	F	PR(>F)
C (Dosage)	329.415	5	66.888	2.36E-15
Residual	29.55	30	nan	nan
Compression test on low walls				
Source	sum_sq	df	F	PR(>F)
C (Dosage)	863.572	5	119.488	7.18E-19
Residual	43.363	30	nan	nan
Water absorption				
Source	sum_sq	df	F	PR(>F)
C (Dosage)	264.878	5	32.227	1.48E-06
Residual	19.726	12	nan	nan
Thermal conductivity				
Source	sum_sq	df	F	PR(>F)
C (Dosage)	1.454	5	40571.944	6.28E-25
Residual	8.599	12	nan	nan

4.8. Environmental Impact: Sustainability Benefits

The use of Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ) as natural additives in the manufacture of adobe blocks not only enhances their mechanical and physical performance but also represents an environmentally sustainable alternative to the use of industrial stabilisers. In the case of RHA, its utilisation adds value to an agro-industrial residue generated in large quantities, whose inadequate disposal often leads to air and soil pollution issues [9, 40]. Studies have shown that incorporating RHA into construction materials helps reduce the carbon footprint, as it partially or completely replaces cement, thereby lowering the emissions associated with cement production [12, 14, 17]. Furthermore, the use of RHA promotes material circularity by transforming an agricultural waste product into a high-value input for construction [18, 19].

On the other hand, the use of PPJ as an additive offers additional sustainability-related benefits. The mucilage present in the pads of Opuntia Ficus-Indica possesses binding and water-retention properties that improve internal cohesion and reduce moisture absorption in adobe blocks, thus extending their service life and reducing the need for frequent maintenance [10, 11, 15, 26]. Recent research has shown that incorporating derivatives of prickly pear into adobe mixtures enhances their mechanical strength and optimises their performance under load and environmental exposure [27]. In this way, PPJ makes use of an abundant and locally available resource, traditionally underutilised, aligning with the principles of the circular economy by preventing waste and promoting the use of renewable inputs.

Overall, the use of RHA and PPJ in adobe blocks provides a dual benefit: on one hand, it increases the material's strength and durability, and on the other, it contributes to environmental sustainability through the reduction of agricultural waste, the mitigation of emissions by partially substituting cement, and the valorisation of low-cost local resources [12, 14, 17, 27]. These findings support the potential of both additives as key components in sustainable and resilient construction projects, particularly in rural contexts and social housing initiatives.

5. Discussion

According to Sanou et al. [16], in their research on Rice Husk Ash, they observed that by incorporating 10% of this material, the mechanical strength of Adobe increased significantly, reaching values above 2 MPa. This increase in strength was attributed to the chemical and physical properties of Rice Husk Ash, which acts as a stabiliser by improving the cohesion and compaction of the material. On the other hand, in the study by Mohamed et al. [20] on Rice Straw Ash, the good results obtained in terms of physical, mechanical, and thermal properties when 20% rice ash was used in the mixture were highlighted. In their research, the physical parameters evaluated included the minimum bulk density, which was 1.463 g/cm³, water absorption, which reached 8.3%, and thermal conductivity, with a value of 0.46 W/(m·K). In addition, the maximum Compressive Strength (CS) was 2.1 MPa after 28 days of curing, indicating a substantial improvement in the mechanical properties of the material, making it more suitable for construction applications, especially in areas with high humidity. According to this research, the results obtained in the present study are in line with previous findings, as a significant improvement in the mechanical properties of the material was also observed. In particular, flexural strength showed an increase of 98.73%, suggesting a notable improvement in Adobe's ability to resist deformation under load, increasing its durability and structural performance. In terms of water absorption, a reduction of 47.46% was achieved, indicating that the mixture with rice husk ash and PolyPropylene (PP) has a greater ability to resist moisture, which is crucial for the durability of the material in high-humidity environments. In addition, thermal conductivity was reduced by 45.55%, implying an improvement in the insulating properties of the material, contributing to greater thermal efficiency and, therefore, better performance in terms of thermal comfort. The improvement is explained by the synergistic effect of

Rice Husk Ash and Prickly Pear Juice on the adobe matrix. The high silica content in rice husk ash promotes pozzolanic reactions that strengthen particle bonding and densify the microstructure, while the organic compounds in prickly pear juice, mainly pectins and mucilages, act as natural binders that enhance adhesion between clay particles and reduce porosity [16, 20]. This combination generates a more compact and homogeneous structure, which explains the observed increases in mechanical strength and the reductions in both water absorption and thermal conductivity. These results were achieved by adding 6% Rice Husk Ash (RHA) and 13% Prickly Pear Juice (PPJ) to the adobe mixture, demonstrating the potential of these materials to improve the physical and mechanical properties of Adobe without resorting to industrial additives.

According to García Chumacero [27], in his research on the use of prickly pear gum reinforced with palm fibre in the physical and mechanical properties of Adobe, the most effective combination was 15% prickly pear gum and 0.5% palm fibre. This mixture reduced suction by 27% and deformation by 3.4%, although there was a 68% increase in water absorption, which represents a disadvantage in terms of durability against moisture. In terms of mechanical performance, notable improvements were recorded: compressive strength increased by 24.47%, flexural strength by 98%, prism compression by 24.39% and diagonal shear strength in walls by 73.4%, compared to the design without additives. In accordance with these findings, it is confirmed that the incorporation of prickly pear gum and rice husk ash, even in the absence of palm fibre, significantly enhances the mechanical properties of Adobe, achieving a 159.22% increase in structural strength. This remarkable improvement is explained by the synergistic interaction between both natural additives: the rice husk ash, rich in amorphous silica, initiates pozzolanic reactions that generate secondary cementitious compounds (such as calcium silicate and aluminate hydrates), resulting in a denser and more stable microstructure [12, 15, 20]; while the prickly pear gum, composed mainly of pectins and mucilages, acts as a colloidal binder that reinforces particle cohesion, reduces capillary porosity, and improves the distribution of internal stresses [27]. Together, these physicochemical processes optimise the structural performance of Adobe and demonstrate the potential of natural materials as sustainable alternatives for the improvement of traditional construction techniques.

In this regard, the results demonstrate that Adobe modified with rice husk ash and prickly pear juice exhibits superior technical performance, with significant improvements in compressive, tensile, and flexural strength, confirming greater structural capacity and durability under typical construction loads. This performance is attributed to a more compact and homogeneous microstructure generated by the combined action of the siliceous compounds from the ash and the natural mucilage of the prickly pear juice, which enhances internal cohesion and reduces material porosity. Consequently, the Adobe shows lower water absorption, higher stability against moisture–drying cycles, and a notable reduction in thermal conductivity, improving its insulating capacity and maintaining comfortable indoor thermal conditions. These combined properties extend its practical applications to rural housing, social projects, and sustainable buildings that demand resistant, thermally efficient, and environmentally friendly materials.

From an economic perspective, the proposal proves to be both viable and sustainable, as Rice Husk Ash and Prickly Pear Juice are abundant, low-cost agricultural by-products. Their use reduces production and transportation costs compared with industrial stabilisers, while promoting the reuse of agro-industrial residues and fostering a circular economy within the construction sector. The enhanced thermal performance of the Adobe also contributes to significant energy savings throughout the building's life cycle by reducing the energy required for heating and cooling, thus generating long-term economic and environmental benefits.

Beyond its technical and economic merits, the incorporation of these natural additions provides valuable social and environmental benefits by facilitating integration into local production chains that encourage artisanal manufacturing, technical training, and employment generation in rural communities. This approach strengthens local autonomy and regional development while reducing the carbon footprint of the construction process through the substitution of industrial materials with renewable, low-impact resources. Overall, the results confirm that the combination of rice husk ash and prickly pear juice not only enhances the physical and mechanical properties of Adobe but also redefines it as an ecological, affordable, and socially responsible material capable of meeting contemporary demands for sustainable construction without losing its traditional identity.

6. Conclusion

In conclusion, the addition of Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ) significantly improves the mechanical, physical, and thermal properties of Adobe. In terms of mechanical properties, the combination of 6% RHA and 13% PPJ resulted in a 65.85% improvement in the compressive strength of Adobe. This increase indicates that Adobe treated with this dosage can withstand higher loads without failure, making it more suitable for the construction of adobe structures that require high compressive strength. In addition, the tensile strength of the Adobe increased by 294.37%, reflecting a significant improvement in the material's ability to resist stretching or tension, which broadens its applications in adobe constructions that are subject to tensile forces. Flexural strength also showed an improvement of 98.73%, suggesting that Adobe treated with this dosage has a greater ability to resist deformation when a lateral load is applied, which is key in the construction of adobe walls and other flexible structures. A 159.21% improvement in compressive strength was achieved in adobe walls, highlighting the benefit of this dosage in vertical structural applications, such as adobe walls.

In terms of physical properties, the same dosage of 6% RHA and 13% PPJ showed a 47.46% reduction in adobe water absorption. This is critical for the durability of the material, as lower water absorption means greater resistance to moisture, preventing problems such as degradation, expansion, or decomposition of Adobe in humid environments. The reduction in water absorption also helps to maintain the structural stability of Adobe throughout its useful life.

With regard to thermal properties, the dosage of 6% RHA and 13% PPJ showed a 45.42% improvement in Adobe's ability to resist heat transfer. This improves the material's thermal insulation, resulting in greater energy efficiency in construction. Better thermal insulation allows buildings to maintain a more stable internal temperature, reducing the need for heating or cooling and improving thermal comfort in indoor environments. This aspect is especially valuable for constructing homes in areas with extreme climates, as it contributes to greater sustainability and reduced energy consumption.

In summary, the combination of 6% RHA and 13% PPJ comprehensively improves the mechanical, physical, and thermal properties of Adobe, making it a more resistant, durable, and efficient material. This dosage optimises the performance of Adobe in terms of structural strength, water absorption, and thermal insulation, making it a more suitable and sustainable option for building construction, especially in regions with variable climates. It should be noted that the results were validated by ANOVA statistical analysis, which showed significant differences between the different dosages analysed ($p < 0.05$), thus confirming the positive effect of the addition of RHA and PPJ on the properties evaluated. This statistical support strengthens the validity of the conclusions obtained and supports the recommendation to use this mixture as a viable ecological alternative for adobe construction.

There are some limitations that should be considered for future studies: the variability of the materials, since the results may be affected by the quality of the materials used, such as rice husk ash and prickly pear juice, which may vary depending on their origin, extraction process and storage, requiring further research into the homogeneity of these materials and their impact on the final properties of the Adobe; curing conditions, since, although in this study the blocks were cured for 28 days under controlled conditions, the curing process in field conditions may differ considerably due to factors such as humidity and ambient temperature, affecting the strength and other properties of the material, so future studies should evaluate the impact of various curing conditions, including extreme climatic conditions, on the performance of the modified Adobe; the impact of long-term durability, given that the long-term durability of adobe blocks with RHA and PPJ has not been thoroughly evaluated, so it would be useful to conduct accelerated ageing tests, simulating extreme climatic conditions, to evaluate the behaviour of these materials over time and their resistance to erosion, humidity and other environmental factors; and the effects on sustainability, since although the incorporation of RHA and PPJ may represent a sustainable alternative, further studies should be carried out on the full environmental impact of these materials, considering their carbon footprint, consumption of natural resources and recyclability.

Future research should focus on evaluating the long-term durability of adobe blocks modified with Rice Husk Ash (RHA) and Prickly Pear Juice (PPJ), considering cycles of wetting and drying, freeze–thaw action, and prolonged solar exposure, as well as assessing the seismic behaviour of complete walls through dynamic testing and shake table experiments. It is also pertinent to deepen the microstructural analysis using techniques such as SEM or XRD to understand the internal reinforcement mechanisms and verify whether the optimal proportions identified are maintained under different climatic and environmental conditions. Another line of work involves scaling up to real construction prototypes, evaluating not only wall strength but also the overall performance of dwellings. At the same time, the comparison with other natural additives or hybrid combinations could provide further synergies. Finally, life cycle and sustainability studies are required to quantify the environmental and social benefits of using RHA and PPJ compared to industrial additives, thereby consolidating their application in sustainable, resilient, and low-cost construction projects.

References

[1] Issiaka Sanou et al., “Effect of the Coconut Fibers and Cement on the Physico-Mechanical and Thermal Properties of Adobe Blocks,” *Heliyon*, vol. 10, no. 19, pp. 1-15, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[2] Yask Kulshreshtha et al., “The Potential and Current Status of Earthen Material for Low-Cost Housing in Rural India,” *Construction and Building Materials*, vol. 247, pp. 1-14, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[3] Ginés A. Abanto et al., "Thermal Properties of Adobe Employed in Peruvian Rural Areas: Experimental Results and Numerical Simulation of a Traditional Bio-Composite Material," *Case Studies in Construction Materials*, vol. 6, pp. 177-191, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[4] T. Li Piani, J. Weerheijm, and L.J. Sluys, "Critical Review on the Material Characterization of Adobe Elements," *Journal of Green Building*, vol. 17, no. 3, pp. 203-226, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[5] Julio Vargas-Neumann et al., "Seismic Retrofit of Adobe Constructions," *Strengthening and Retrofitting of Existing Structures*, vol. 9, pp. 85-111, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[6] Luis Fernando Guerrero Baca, "The Use of Cob in the Intervention of Adobe Construction Components," *Intervención*, vol. 11, no. 22, pp. 133-187, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[7] Javier Camacho Tauta, Claudia Uribe-Kaffure, and Alfonso Ramos-Cañón, "Mechanical Deterioration due to Weathering of the Adobe of the Tausa Chapel (Colombia)," *TecnoLógicas*, vol. 26, no. 58, pp. 1-16, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[8] G. Araya-Letelier et al., "Waste-Based Natural Fiber Reinforcement of Adobe Mixtures: Physical, Mechanical, Damage and Durability Performance Assessment," *Journal of Cleaner Production*, vol. 273, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[9] National Institute of Statistics and Informatics, 2025. [Online]. Available: https://m.inei.gob.pe/prensa/noticias/produccion-de-arroz-cascara-alcanzo-220-mil-toneladas-y-aumento-en-50-durante-enero-de-2023-14320/

[10] Kamlesh Kumar, Dhurendra Singh Rama, and R.S. Singh, *Cactus Pear: Cultivation and Uses*, Technical Bulletin, pp. 1-38, 2018. [Google Scholar]

[11] José Amador Honorato-Salazar, Jorge Aburto, and Myriam Adela Amezcua-Allieri, "Agave and Opuntia Species as Sustainable Feedstocks for Bioenergy and Byproducts," *Sustainability*, vol. 13, no. 21, pp. 1-18, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[12] Mugahed Amran et al., "Rice Husk Ash-Based Concrete Composites: A Critical Review of Their Properties and Applications," *Crystals*, vol. 11, no. 2, pp. 1-30, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[13] D.M. Gomez Mejia et al., "Effect of the Addition of Silica Obtained from Rice Husk on Physicochemical and Mechanical Properties of Fibercement," *Heliyon*, vol. 9, no. 2, pp. 1-13, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[14] V. Jittin, A. Bahurudeen, and S.D. Ajinkya, "Utilisation of Rice Husk Ash for Cleaner Production of Different Construction Products," *Journal of Cleaner Production*, vol. 263, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[15] Juan Carlos Guevara-Arauza, "Industrial Uses of Opuntia Spp. By-Products," *Opuntia Spp.: Chemistry, Bioactivity and Industrial Applications*, pp. 707-752, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[16] Issiaka Sanou et al., "Mineralogy, Physical and Mechanical Properties of Adobes Stabilized with Cement and Rice Husk Ash," *Science Journal of Chemistry*, vol. 7, no. 1, pp. 1-10, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[17] Shantanu Paul, Mohammad Shariful Islam, and Tausif E. Elahi, "Potential of Waste Rice Husk Ash and Cement in Making Compressed Stabilized Earth Blocks: Strength, Durability and Life Cycle Assessment," *Journal of Building Engineering*, vol. 73, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[18] Olubisi Ige, and Humphrey Danso, "Experimental Characterization of Adobe Bricks Stabilized with Rice Husk and Lime for Sustainable Construction," *Journal of Materials in Civil Engineering*, vol. 34, no. 2, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[19] Moussa Ouedraogo et al., "Microstructure, Physical and Mechanical Properties of Adobes Stabilized with Rice Husks," *International Journal of Architectural Heritage*, vol. 17, no. 8, pp. 1348-1363, 2023. [CrossRef] [Google Scholar] [Publisher Link]

[20] Mohamed I. Morsy et al., "Recycling Rice Straw Ash to Produce Low Thermal Conductivity and Moisture-Resistant Geopolymer Adobe Bricks," *Saudi Journal of Biological Sciences*, vol. 29, no. 5, pp. 3759-3771, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[21] Magdy F. Abadir et al., "Preparation of Adobe Brick by Mixing with Rice Hush Ash," *International Journal of Technical Research & Science*, vol. 3, no. 6, pp. 206-221, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[22] S. Mbairangone et al., "Effects of Rice Husk on Adobes in Clay Soils," *Research Journal of Engineering Sciences*, vol. 11, no. 3, pp. 12-21, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[23] Sasui Sasui, Watcharin Jinwuth, and Sirimas Hengrasmee, "The Effects of Raw Rice Husk and Rice Husk Ash on the Strength and Durability of Adobe Bricks," *Civil Engineering Journal*, vol. 4, no. 4, pp. 732-742, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[24] Sasui et al., "A Study on Improving the Strength Properties of Adobe Brick with the use of Agriculture Waste Stabilizer," *Proceedings of the Korean Institute of Building Construction Conference*, pp. 25-26, 2019. [Google Scholar] [Publisher Link]

[25] Sutham Rotchanameka, Attapole Malai, and Prachoom Khamput, "The Effect of Natural Fibers and Para Rubber Latex on Adobe Bricks," *Rattanakosin Journal of Science and Technology*, vol. 6, no. 2, pp. 99-109, 2024. [Google Scholar] [Publisher Link]

[26] F. Fernandez et al., "Use of Prickly Pear (Nopal) Mucilage in Construction Applications: Research and Results," *Life Safety and Security*, vol. 12, no. 1, pp. 1-11, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[27] Socrates Pedro Muñoz Pérez et al., "Influence of Prickly Pear Gum on the Physical and Mechanical Properties of Adobe Reinforced with Palm Fiber," *Engineering and Applied Science Research*, vol. 51, no. 4, pp. 495-504, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[28] Flavia Cristina Castillo Bacalla, Juan Martín García Chumacero, and Luis Mariano Villegas Granados, "Improvement of Adobe Brick Reinforced with Sugarcane Bagasse Fiber, Rice Husk, and Metal Mesh: Study in Peru," *Innovative Infrastructure Solutions*, vol. 10, no. 5, pp. 1-13, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[29] Danilo Servando Carrasco Pacheco et al., "Influence of Rice Husk and Cabuya Fiber on the Physical and Mechanical Properties of Adobe," *Engineering and Applied Science Research*, vol. 52, no. 1, pp. 112-124, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[30] S. Ramakrishnan et al., "Adobe Blocks Reinforced with Natural Fibres: A Review," *Materials Today Proceedings*, vol. 45, pp. 6493-6499, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[31] Lola Ben-Alon et al., "Cradle to Site Life Cycle Assessment (LCA) of Natural vs Conventional Building Materials: A Case Study on Cob Earthen Material," *Building and Environment*, vol. 160, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[32] M. Lenin Lara, and Rosa Bustamante, "Characterization and Pathology of Earthen Building Walls in the Ecuadorian Andean Area," *Polytechnic Magazine*, vol. 49, no. 2, pp. 37-46, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[33] Lily Walter et al., "Design of Poured Earth Construction Materials from the Elementary Characteristics of Tropical Soils," *Case Studies in Construction Materials*, vol. 20, pp. 1-16, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[34] Brya Aldawoodi, Salaheddin Sabri, and Abdulmounem Alchekh Wis, "Optimum Calcination Condition of Waste Stabilized Adobe for Alkali Activated High Volume Adobe-Slag Binder Cured at Room Temperature," *Journal of Renewable Materials*, vol. 10, no. 5, pp. 1269-1285, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[35] Álvaro R. Serrano-Chacón et al., "Multi-Criteria Parametric Verifications for Stability Diagnosis of Rammed-Earth Historic Urban Ramparts Working as Retaining Walls," *Applied Sciences*, vol. 11, no. 6, pp. 1-22, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[36] María Isabel Mota-López et al., "Analytical Characterization of the Almohad Rammed-Earth Wall of Cáceres, Spain," *Construction and Building Materials*, vol. 273, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[37] Viviana Mora-Ruiz et al., "Sustainable Earthen Construction: A Meta-Analytical Review of Environmental, Mechanical, and Thermal Performance," *Buildings*, vol. 15, no. 6, pp. 1-47, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[38] Nataly Cecilia Perez Curi et al., "Analysis of the Mechanical Properties of Adobe with Chillihua Fibre and Recycled LDPE for Sustainable Construction in the Andes," *Civil Engineering and Architecture*, vol. 13, no. 1, pp. 193-209, 2025. [CrossRef] [Google Scholar] [Publisher Link]

[39] Nirmal Gadal, "A Review on Production Status and Growing Environments of Rice in Nepal and in the World," *Agriculture and Environmental Science*, vol. 4, no. 1, pp. 83-87, 2019. [CrossRef] [Google Scholar] [Publisher Link]

[40] Rajendra Prasad, Yashbir Singh Shivay, and Dinesh Kumar, "Current Status, Challenges, and Opportunities in Rice Production," *Rice Production Worldwide*, pp. 1-32, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[41] Mingchao Zhao, Yongjun Lin, and Hao Chen, "Improving Nutritional Quality of Rice for Human Health," *Theoretical and Applied Genetics*, vol. 133, no. 5, pp. 1397-1413, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[42] Mohd Salahuddin Mohd Basri et al., "Rice-Husk-Ash-Based Geopolymer Coating: Fire-Retardant, Optimize Composition, Microstructural, Thermal and Element Characteristics Analysis," *Polymers*, vol. 13, no. 21, pp. 1-30, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[43] Bhupinder Singh, "Rice Husk Ash," *Waste and Supplementary Cementitious Materials in Concrete*, pp. 417-460, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[44] Mouaad Amine Mazri, "Cactus Pear (Opuntia Spp.) Species and Cultivars," *Opuntia Spp.: Chemistry, Bioactivity and Industrial Applications*, pp. 83-107, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[45] Perla Tenorio-Escandón et al., "A Systematic Review on Opuntia (Cactaceae; Opuntioideae) Flower-Visiting Insects in the World with Emphasis on Mexico: Implications for Biodiversity Conservation," *Plants*, vol. 11, no. 1, pp. 1-17, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[46] Enhanced Reader, RD N° 18_2014_MTC_14 Original_Approves Materials Testing Manual. [Online]. Available: https://www.scribd.com/document/769012517/RD-N-18-2014-MTC-14-Original-Aprueba-Manual-de-Ensayo-de-Materiales