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Analysis of the Mechanical Properties of Adobe with Chillihua Fibre and Recycled LDPE for Sustainable Construction in the Andes

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Abstract In the Andean regions of Peru, Andean house construction in Peru relies heavily on adobe as the main material, characterized by an entrenched self-construction system. This method faces significant challenges in terms of durability and structural strength, especially in areas exposed to flooding and seismic movements, due to the inherent low mechanical properties of adobe. In response to these limitations, research has explored the improvement of the mechanical properties of adobe by incorporating readily available fibers, such as chillihua fiber (CF), a plant that grows in the high Andean zone. At the same time, efforts have been made to reduce environmental pollution by reusing plastic waste, such as low-density polyethylene (LDPE), due to its slow decomposition process. This research work evaluates the mechanical properties of adobe modified by incorporating CF fiber and recycled LDPE in the Andean region of Huancayo. Evaluations of the physical properties of the soil in situ were carried out to verify its suitability, followed by tests of granulometry, moisture content and plasticity index (PI). Subsequently, compressive strength and absorption strength tests were developed to evaluate the mechanical properties of the stabilized adobes. The study was divided into control and experimental groups with varying concentrations of CF fiber and recycled LDPE (0%, 1%, 2%, 3%, 4%, 5% and 6%). The results showed that adobes stabilized with CF and recycled LDPE exhibit significant improvement in their compressive, indirect tensile, flexural and absorption strength, increasing load-bearing capacity and improving water absorption resistance. These improvements potentially contribute positively to the durability and structural stability of buildings with a variation of the cost of a conventional wall per m^2 versus a stabilized wall of only 6.86%.

Keywords Chillihua Fibre, LDPE Fibre, Compressive Strength, Absorption Strength, Adobe, Durability

1. Introduction

Adobe, according to the report of the National Institute of Statistics and Informatics (INEI) in 2017, is the predominant material in the construction of approximately 2,148,494 houses in the Andean and high Andean region of Peru [1]. Adobe is the result of deep-rooted self-construction systems, This traditional material is manufactured in situ by mixing soils with potable water and vegetable fiber, such as ichu, and is used to construct one- or two-story buildings with tin, tile or calamine roofs

[2], [3]. However, these structures present significant challenges in terms of durability and structural resistance, especially in the face of emergencies such as floods and seismic movements, due to the inherent fragility of adobe [4], [5]. Faced with this problem, there is an urgent need to strengthen the mechanical characteristics of adobe in order to increase its strength and durability under adverse conditions. In this context, the research focuses on two innovative materials: CF and recycled (LDPE). Chillihua, a plant native to the Andes, has shown promising mechanical properties that can improve the cohesion and strength of adobe. Its local availability and low cost make it a viable and sustainable option for Andean communities. On the other hand, the inclusion of recycled LDPE fiber not only contributes to improving the insulating qualities of adobe [6], but also addresses the environmental problem of plastic waste accumulation, providing an ecological solution by reusing plastic bags. This research proposes a comprehensive analysis of the mechanical properties of adobe enhanced with CF and recycled LDPE, with the aim of developing a more resistant and sustainable building material. The implementation of these materials has the potential to provide safer and more durable housing in rural and seismically active areas such as the Andean regions of Peru [7]. In this way, it is expected to contribute to the development of constructive solutions that improve the well-being of populations and promote sustainability in construction. On the other hand, an exhaustive review of existing research is carried out to better understand the benefits and uses of these materials in adobe and other sectors that have been used over the years.

2. Literature Review

In Peru, natural fibers play a fundamental role in optimizing the mechanical and physical characteristics of adobe used in construction. Among these fibers, Festuca dolichophylla, known locally as chillihua, stands out for its adaptability and ecological and economic benefits. Chillihua is highly valued in livestock activity due to its high palatability and its availability in highland ecosystems [8]. Chillihua is characterized by a structured development, where it initially increases in magnitude, in the amount of branches and leaves. It is dispersed non-uniformly in the middle and lower regions, while in the upper region it spreads in a more concentrated manner. Its optimum habitat is in the mountainous region of Peru, at an elevation of 4186 meters above sea level. The plant reaches a leaf height of 29.66 with a variation of 0.56 cm and has a vegetation capacity of 993.88 cm^{3}with a deviation of 44.34 cm^3, demonstrating water use efficiency due to its flexible space optimization technique [9], [10], [11], [12].

Beyond its traditional use as fodder, chillihua has been explored in the production of plain concrete slabs. Two variants of traditional concrete were designed with strengths of F'c=175 kg/cm^{2}and 210 kg/cm^2, incorporating chillihua fiber proportions of 0.1%, 0.5%, and 1% by volume, with lengths of 2.5 cm and 5 cm. The results showed a decrease in cracking due to early shrinkage and an improvement in the flexural and tensile capacity of concrete reinforced with this fiber [13]. Additionally, the potential of chillihua for the rehabilitation of soils affected by mercury contamination in the district of Ananea-Puno, Peru, has been investigated. In this region, soils present a neutral pH and contain total mercury concentrations (THg) in the range of 44 to 53 mg/kg, almost twice the maximum threshold allowed in Peru. Despite not being a hyperaccumulator, chillihua showed a Bioaccumulation Factor (BAF) of 0.38 in its leaves. Furthermore, by combining the planting of chillihua with the application of ammonium thiosulfate, it was possible to reduce the THg content in the soil by 82% [14]. Despite its obvious benefits and applications, research on the use of chillihua in the construction field is still limited. This gap underlines the need for more in-depth and specific studies to optimize its integration in adobe construction. Enhancing the use of chillihua in this context will not only improve the mechanical properties of adobe, but also contribute to sustainable and resilient construction solutions in the Andean regions of Peru.

In contrast to the second material to be investigated, LDPE is widely used in the production of thin plastic bags, whose slow decomposition represents a serious environmental problem. However, due to its durability, flexibility and corrosion resistance, LDPE finds practical applications in construction. Studies have shown that a concrete mix with 5% LDPE and 3% sawdust ash significantly improves the compressive, split tensile and flexural strength of concrete [15], [16]. Furthermore, under wet conditions, the inclusion of 8% LDPE in the mix increases the stability by up to 22.03%, whereas, under dry conditions, 11% LDPE increases the stability by up to 19.30%. These findings indicate that LDPE can improve the stability of asphalt concrete under various climatic conditions, allowing the reuse of 8.7 tons of plastic waste in one kilometer of asphalt road with a width of 7 meters [17]. In addition, the compressive strength of concrete bricks (CHB) increased with a 10% replacement of the mix with LDPE pellets instead of sand. It has been inferred that the strength of the plastic material could have a direct contribution to the compressive strength of CHB with a low percentage of aggregate replacement [18]. Finally, regarding thermal properties, normal M30 (NC) concrete modified with recycled polyethylene terephthalate aggregates and recycled LDPE presents a slight increase in compressive and tensile strength in temperature ranges of 100 ℃-400 ℃ and 400 ℃-800 ℃. These results highlight how recycled materials can improve the properties of concrete, promoting more environmentally friendly and resource-efficient construction [19].

In Malaysia, researchers sought to improve asphalt quality by including LDPE in concentrations of 0% to 20% by weight of asphalt. They determined the optimum concentration to be 6%, according to criteria established by the Marshall test and the Wheel Tracking Machine test. This specific amount of LDPE improved the dynamic stability and reduced the rate at which the asphalt has to deform [20], [21]. On the other hand, in Russia, researchers analyzed the mechanical behavior of bitumen by including LDPE obtained from plastic bags in percentages of 0%, 2%, 4% and 6% in relation to the bitumen weight. The results indicated that 6% significantly increased rolling resistance, while 4% demonstrated maximum dynamic viscosity. In addition, the improvement in fatigue resistance with the addition of LDPE was highlighted [22], [23].

In Indonesia, researchers analyzed the use of LDPE with the addition of stone ash for the manufacture of pavement blocks. The results were favorable, showing a maximum compression of 13.43 MPa and good sodium sulfate resistance performance. Also, soil deformation resistance behaviors were analyzed, revealing that the addition of 0.7% plastic reinforcement improves the maximum value of the California Bearing Capacity Index, while the addition of 0.5% increases the maximum dry density [24], [25].

In Iraq, researchers studied the use of LDPE in concrete mortars with concentrations from 0% to 25%. The results showed that as the LDPE concentration increased, the strength of the concrete decreased. In particular, the density and compressive strength decreased to 2240 kg/m ^{3} and 18.7 MPa, respectively, at 15% addition [26]. On the other hand, in Asia Pacific, another study analyzed the deterioration of roads due to erosion caused by stormwater. In this study, LDPE was used in concentrations of 5% to 10%, and it was observed that this addition helped to increase pavement stability by up to 63.75% compared to a conventional pavement [27]. This analysis underscores the importance of continuing to research and develop alternative and sustainable construction materials. By taking advantage of both natural and recycled resources, the technical properties of conventional materials can be improved and the environmental impact of plastic waste can be mitigated.

This study evaluated the mechanical properties of adobe by incorporating Chillihua fiber (CF) and recycled low-density polyethylene (LDPE), with the objective of developing sustainable building materials for the Andean regions. The literature review highlighted that both materials offer significant improvements in adobe strength, in addition to being accessible and appropriate for use in remote areas where production is artisanal. These characteristics make them especially suitable for rural contexts, where economical and ecological construction solutions are required. Experimental tests were carried out to determine the performance of adobe with different percentages of fiber and recycled LDPE: 0%, 1%, 2%, 3%, 4%, 5% and 6%. The tests included compressive strength in 10 × 10 × 10 cm cubic units, indirect tensile strength in 10 × 20 cm cylinders, flexural strength in 40 × 20 × 12 cm prisms and water absorption using prismatic samples with the same dimensions. The results showed that the incorporation of CF and recycled LDPE significantly improved the strength and durability of the adobe, making it more suitable for regions vulnerable to climatic phenomena, such as floods. This research offers an efficient alternative to optimize the quality of adobe, promoting its use as a sustainable building material in rural areas, while encouraging the reuse of plastic waste.

3. Materials and Methods

The research analyzed the properties of adobe with the incorporation of Chillihua fiber and recycled LDPE. The Chillihua fiber was obtained from the field and the LDPE was obtained from recycled materials, both properly treated for incorporation into the adobe mix. Subsequently, the mechanical properties of the adobe were evaluated, both in individual units, cubes and cylinders, beams, as well as the absorption of the material with different dosages of Chillihua and LDPE.

3.1. Adobe

Adobe is a widely used material in the Andean and high Andean regions due to its easy availability. It is composed mainly of earth, with the addition of straw or coarse sand [28]. Unlike other building materials, adobe is not fired, but air-dried with the help of the sun. Its composition, including clay, silt and sand, gives it excellent thermal insulation properties and durability, as long as it is kept dry. In addition, it is a sustainable and environmentally friendly material, as it uses natural resources [29], [30]. Its low cost and ease of manufacture make it particularly suitable for use in remote areas.

Adobe was mainly used in the construction of housing walls, as shown in Figure 1, which presents a two-story house built with this material. To improve its mechanical and physical properties, an increase in its strength was observed by adding lime and cattle manure, which improved its consistency [31], [32], [33]. These additives strengthened the adobe structure, resulting in more resistant and durable walls. Additionally, the incorporation of materials such as fibers increased the density of the adobe and decreased its porosity, which led to a substantial increase in its mechanical strength and its ability to resist water penetration [34]. In the present research, we analyzed the addition of Chillihua fiber and LDPE in adobe to improve its properties.

Figure 1. House built with adobe in Huancayo

3.2. Chillihua Fiber

This fiber, known as (Festuca Dolichophylla), is a grass native to the Andes, which has a straw-like, non-fibrous appearance and reaches a height that varies from 50 to 90 cm [35]. This material helps to reinforce the soil and helps to improve mechanical properties in concrete for crack control, but its low resistance to corrosion and chemical factors leads to its deterioration in a short time. Being a biodegradable material, it offers environmental advantages [13]. In this study, 0%, 1%, 2%, 3%, 3%, 4%, 5% and 6% of this fiber were used to optimize the physical and mechanical properties of adobe.

Figure 2 illustrates the technical process for obtaining Chillihua fiber, carried out in the province of Huancayo, whose coordinates are 11°59'24.6"S 75°28'00.7"W. In step A, the extraction of the Chillihua plant was documented. Then, in step B, the plant was dried for 48 hours to reduce its moisture content. Subsequently, in step C, the plant was cut into fragments of 2 cm in length and diameter between 0.05 and 0.08 mm. Finally, in step D, the precise measurement of the fibers was carried out, ensuring that they complied with the appropriate dimensions for their integration into the adobe mix in percentages of 0, 1, 2, 3, 4, 5 and 6 %.

(A) Cutting (B) Drying

(C) Cut (D) Measurement

Figure 2. Procedures for the acquisition of Chillihua fiber

Table 1 summarises the physical and mechanical properties of Chillihua, obtained through a comprehensive analysis. The physical properties provide essential information on the structure and composition of the material, while the mechanical properties provide detailed insight into its structural capacity and sustainability. This data is crucial for assessing the suitability of Chillihua as a component in the adobe mix, supporting its use in sustainable construction applications.

Table 1. Mechanical and physical properties of Chillihua [13].

Physical Properties	**Value**
Density in large bushes	39.58%
Water level	48%
Specific mass	0.752 gr/cm ^{3}
Apparent weight	109 kg/m ^{3}
Compacted apparent weight	409 kg/m ^{3}
Mechanical Properties	**Value**
Large biomass development	67.03%
Carbon present in the biomass of the stems	87.37%

3.3. Recycled LDPE

Fiber (LDPE) is an olefinic polymer produced by the polymerization of multiple ethylene molecules. This material is recognized for its exceptional properties, such as its resistance to fats, oils and moisture, characteristics that give it wide applicability [36], [37]. In previous studies, the incorporation of LDPE fiber in soils has shown significant improvements in their mechanical properties. In particular, an increase in mechanical strength, higher toughness and robustness in compressive strength and deformation resistance has been observed [38]. In this research, the physical and mechanical properties of adobe were evaluated by adding LDPE fiber in proportions of 0%, 1%, 2%, 3%, 3%, 4%, 5% and 6%.

Figure 3 shows the detailed procedure used for the preparation of the fiber (LDPE). In the first step, identified as item A, the LDPE material was recycled. Subsequently, in item B, the cleaning process was carried out using a specialized washing method. Next, in item C, the LDPE was subjected to an air-drying process to eliminate any residual moisture. Next, in item D, the LDPE was precisely cut into 2.5 and 0.5 cm segments (length and width, respectively), ensuring dimensional uniformity. Finally, in item E, the dimensions of the prepared fibers were meticulously measured, ensuring their suitability for integration into the adobe mix in varying percentages (0%, 1%, 2%, 3%, 4%, 5% and 6%). This process ensured that the LDPE fiber was adequately prepared to significantly improve the physical and mechanical properties of the adobe used in the research.

(A) Recycling (B) Washing

(C) Drying (D) Cutting

Figure 3. LDPE fibre production process

Table 2 presents the mechanical properties of LDPE, addressing key aspects such as tensile strength, Young's modulus, strain at break, elongation at yield point, flexural strength and tear strength. These parameters are crucial to evaluate the response of LDPE to mechanical stresses.

Table 2. Mechanical properties of LDPE

Mechanical Property	Value or Rank
Tensile strength	10 MPa
Young's module	0.25 GPa
Deformation at break	400%
Elongation at yield point	5-520%
Flexural strength	0.241-0.262
Tear resistance	20-373 JN/m

3.4. Obtaining the Soil Sample

Soil extraction was carried out in the Huancayo region, at the Uñas quarry located at geographical coordinates 12°01'55.0 “S 75°11'18.0 ”W, as shown in Figure 4. To validate the suitability of the soil for use in the manufacture of adobe, specific tests were carried out according to Peruvian standard E.080 (Design and Construction with Reinforced Soil), including the pellet test and the mud belt test. These tests were crucial to ensure that the soil properties meet the indispensable requirements for the production of optimum quality adobe. Subsequently, the validated soil was used in the formulation of adobes, incorporating Chillihua fiber and LDPE in proportions of 0%, 1%, 2%, 3%, 4%, 4%, 5% and 6%, with the objective of improving their physical and mechanical properties.

Figure 4. Soil sample extraction

3.4.1. Dry Strength Test

The dry resistance test is performed according to standard E.080 [39]. In Figure 5, in item A), a portion of clay extracted from the site is taken, for which 4 small balls were formed by adding a small amount of water. To form small balls in the palms, then in item B) the process of drying in the open air is observed, which was done in 45 hours, making sure at all times that they do not get wet or wet by weather conditions, then in Item C) we proceeded to press the 4 dry balls, with the thumb, in which we noticed that it does not break, so the soil served as clay material in the adobe.

Figure 5. Production and measurement of the pellet

3.4.2. Mud Tape Test

The mud tape test was performed using the E.080 standard [39], which is shown in Figure 6, which began with item A) where the previously extracted sample was used with a humidity that allowed us to make cylinders of 12 mm in diameter, then in item B) we observed that the mud tape reached 27 cm in length complying as very clayey soil.

(A) Sample (B) Measurement

Figure 6. Production and measurement of the clay tape

3.5. Laboratory Tests

To evaluate the adobe with the incorporation of CF and LDPE, tests were carried out in accordance with Peruvian standard E.080 [39]. Compressive strength, water absorption, and water absorption were analyzed, and moisture content, granulometry, specific gravity and unit weights were analysed. These tests ensured that the modified adobe met the structural and durability specifications required for use in adobe construction in Andean areas.

3.5.1. Granulometry

The granulometry was carried out on the extracted soil sample, which was preliminarily verified by dry strength tests and the mud tape test. These methods confirmed the suitability of the clay material for use in adobe manufacture. Granulometry, which is an essential technique to describe the particle size distribution in the material, was carried out by the sieving process according to the Peruvian technical standard NTP 339.128 [40]. The procedure started with the complete drying of an 8 kg sample of soil, which was then divided into 500 gram fractions. Each fraction was subjected to a sieving process, using a series of meshes ranging from 3 inches to 200 mesh. This procedure allowed a detailed characterisation of the particle size distribution of the material to be obtained. Figure 7 illustrates the laboratory sieving process, showing both the equipment used and the stages of the process. This rigorous methodological approach ensured that accurate and reliable data were obtained, which were essential for assessing the physical properties of the soil.

Figure 8 shows the particle size distribution of the material, where it was observed that 41.61% of the soil passed through the N° 200 sieve. This distribution classifies the material as fine soil, according to the criteria established by the plasticity chart. According to this reference, soil with a content of 12% passing through the N° 200 sieve is considered standard for the manufacture of adobe.

Figure 7. Granulometry test

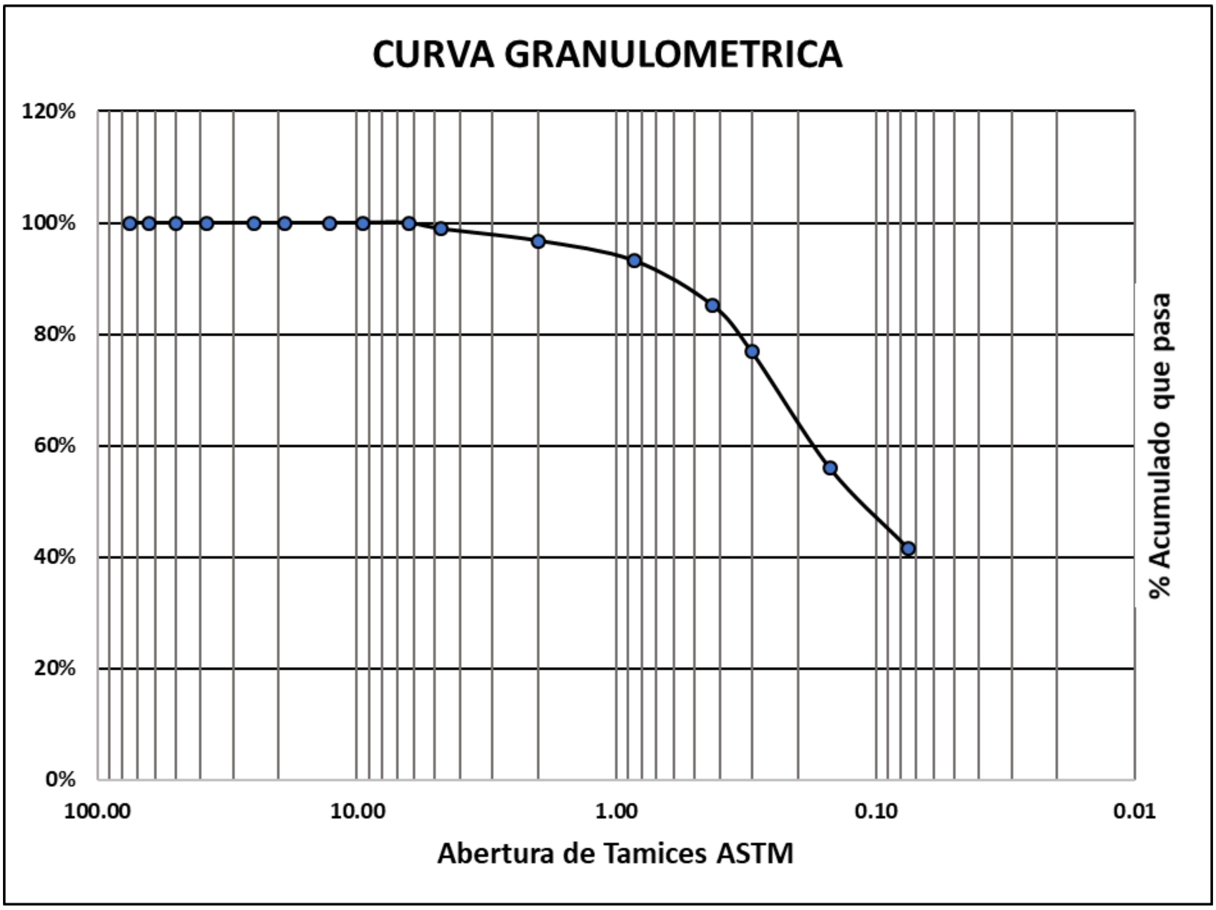

Figure 8. Granulometric Curve3.5.2. Moisture Content

3.5.2. Moisture Content

The moisture content of the soil was determined according to the guidelines established in the Materials Testing Manual (MTC) E 108 [41]. This test quantified the moisture content expressed as a percentage of the weight of water in the soil sample. Initially, the soil sample was weighed, and then it was dried in a controlled oven at 110 ± 5 ℃, as illustrated in Figure 9. To determine the moisture content, Equation 1 was used, determining a water weight of 16.29 grams and a dry soil weight of 263.14 grams, resulting in a moisture content of 6.19%. This value is in accordance with the criteria defined by standard E 080 [40], which specifies that the mortar mix should not exceed 20% moisture, thus confirming the suitability of the soil for adobe manufacture.

$$W = \frac{Water\ \ weight}{Weight\ \ of\ \ dry\ \ soil} . 100 \qquad (1)$$

3.5.3. Land Classification

For the detailed soil classification, we started with a preliminary granulometric test to identify the particle size distribution. Subsequently, a more rigorous analysis was carried out using the liquid and plastic limits, which are crucial parameters for calculating the Plasticity Index (PI). This index is obtained by subtracting the Plastic Limit (PL) value from the Liquid Limit (LL), as specified in MTC E 111 [41].

The evaluation of the liquid limit is shown in Figure 10, where the Casagrande cup method was used, starting by preparing a 200-gram soil sample, previously sieved through a sieve No. 40 to ensure a uniform distribution of the particles. This sample was meticulously mixed with distilled water until a suitable consistency was reached to form a homogeneous and plastic paste. The soil paste was then placed inside the Casagrande cup, which has a standard slot. Through a controlled mechanism, the cup was repeatedly lifted and dropped, carefully recording the number of strokes necessary for the opening to close to a standard dimension of 1.3 cm (0.5 in.), for which we obtained an LL of 42.19%.

As for the Plastic Limit shown in Figure 11, the procedure involved moulding a portion of the soil sample into the shape of an ellipse and then rolling it on a flat surface. The objective was to assess the ability of the soil to deform under controlled pressure. Once the sample was moulded, the diameter of the resulting ellipse, which represents the moisture content at which the soil paste begins to exhibit plastic rather than brittle behaviour, was carefully measured, yielding an LP of 23.40%. Finally, by replacing equation 2, we obtained the PI of 18.79%.

$$IP = LL - LP \qquad (2)$$

Based on the granulometric analysis and the PI, the soil has been classified as clay (SC), since the plasticity index reached a value of 18.79%. This high measure indicates a remarkable capacity for volumetric change in response to moisture fluctuations, which is characteristic and desirable for soils used in adobe construction, providing an adequate basis for the stability and durability of structures.

Figure 9. Moisture content test

Figure 10. Liquid limit test

Figure 11. Plastic limit test

3.5.4. Specific Gravity of Soil Solids

The evaluation of the specific gravity of solids was carried out in accordance with MTC E 113 [41], using a water pycnometer, as shown in Figure 12. The material that passed through the No. 4 sieve was selected and a pycnometer with a capacity of 250 mL was used. The soil sample was dried beforehand at a constant temperature of 110 ± 5℃. For the test, 45 grams of SC soil were used. The pycnometer was filled with the soil sample and de-aerated water was added to remove any air bubbles, ensuring complete saturation of the sample. After this process, a specific gravity (SG) of 2.639 g/cm^3 was determined, which is considered adequate for construction applications. This value indicates a good bearing capacity, stability and durability of the material.

To ensure the optimum performance of the SC soil under actual use conditions, additional tests were performed. Compaction tests determined unit weights, while permeability tests evaluated the soil's ability to handle water and moisture. In addition, strength tests were performed to verify the soil's ability to withstand the expected loads. These complementary tests confirmed the suitability of the soil for use in adobe construction.

3.5.5. Indirect Tensile Test

To perform this test, according to MTC E 708 [41], specimens of 10 and 20 cm (diameter and length, respectively) were prepared, adding Chillihua and LDPE fibers in the following percentages: 0%, 1%, 2%, 3%, 4%, 5% and 6%. The procedure began with the marking of diameters at both ends of the sample using appropriate equipment to ensure that they were in the same axial plane. The diameter was measured to an accuracy of ±0.25 mm, recording an average of three values: one near each end and one in the middle of the cylinder. Length was also measured to an accuracy of ±0.25 mm, averaging at least two measurements. To position the specimen, a support bar was used on the bottom plate, ensuring that the cylinder was centered on it. A second batten was placed longitudinally over the cylinder to ensure alignment. The load was applied continuously and without impacts, with a rate between 689 kPa/min (100 lb/in^2/min) and 1380 kPa/min (200 lb/in^2/min), as depicted in Figure 13.

3.5.6. Compressive Strength Test on Cubes

The compressive strength was performed using adobe specimens (10x10x10 cm), with the addition of CF and LDPE in proportions of 0%, 1%, 2%, 3%, 4%, 5% and 6%. These fibers had been previously verified and confirmed as suitable for incorporation in adobe. The test procedure strictly followed the E.080 standard [41], which establishes a minimum strength of 10.2 kg/cm^2 In order to guarantee the rigor and credibility of the results, six samples were prepared for each percentage of fiber addition. The samples were subjected to a 28-day drying process prior to compression testing. Figure 14 illustrates the compression test performed on these adobe units. The results were obtained using the average of the four outstanding specimens for each addition ratio, ensuring that the value obtained was equal to or greater than the minimum strength specified in the standard. This approach made it possible to accurately evaluate the impact of Chillihua and LDPE fibers on the compressive strength of the adobe.

Figure 12. Specific gravity test using the water pycnometer

Figure 13. Indirect tensile test on specimens 0, 1, 2, 3, 3, 4, 4, 5 and 6% addition of Chillihua and LDPE

Figure 14. Compression testing of cubes

3.5.7. Bending Test

This test was carried out according to the MTC E 711 standard [41], and prismatic specimens were prepared with dimensions of 40x20x12 cm, using additions of Chillihua and LDPE in proportions of 0%, 1%, 2%, 3%, 4%, 5% and 6%. Once the specimens were prepared, they were placed in the testing machine. The samples were subjected to a 28-day drying process prior to the flexural tests. The specimens were then rotated relative to their molded position and carefully centered on the loading blocks, ensuring that the loading system was correctly aligned with the specimen. The load was applied continuously and smoothly, following a constant rate of stress increase, ranging from 0.9 MPa/min to 1.2 MPa/min, until specimen breakage was reached, as seen in Figure 15. This method of load application allowed accurate evaluation of the flexural strength of the specimens, ensuring that the measurements accurately reflected the mechanical properties of the materials tested under controlled conditions.

3.5.8. Absorption Resistance Test

The absorption evaluation was carried out following MTC E 205 [41] and the recommendations of NTP 399.613 [42]. As shown in Figure 16, the process involved adobe samples with dimensions of 40x20x12 cm. These samples were subjected to a saturation process in potable water, maintained at a controlled temperature between 15.5 ℃ and 30 ℃, for a period of 24 hours. Subsequently, the samples were removed and weighed within a maximum of 5 minutes to ensure the accuracy of the results. For each percentage addition of CF and LDPE (0%, 1%, 2%, 3%, 4%, 5% and 6%), four samples were prepared and analyzed, thus allowing an accurate evaluation of the impact of these additions on the absorption capacity of the adobe.

$$Absorption\ \% = \frac{M2-M1}{M1}.100 \tag{3}$$

Where:
M1= Initial dry mass (gr)
M2= Water saturated mass of simple (gr)

Figure 15. Flexure tests of samples 0, 1, 2, 3, 4, 4, 5 and 6% addition of Chillihua and LDPE

Figure 16. Absorption test of samples 0,1,2,3,4,5,6 % addition of Chillihua and LDPE

4. Results

This section presents the study of the behaviour under indirect tensile, compressive and flexural strength of the adobe units and the absorption of saturated samples, which were prepared with additions of chillihua and LDPE in proportions of 0%, 1%, 2%, 3%, 4%, 5% and 6%. The average tensile strength, compressive flexural strength and absorption values of the best samples of each ratio, identified as exhibiting the highest performance in both aspects, have been calculated. These data are crucial to determine the suitability of the modified adobe for construction applications in the Andean region. In addition, a detailed economic analysis has been carried out to evaluate the cost per linear metre of an adobe wall, considering the use of these fibres in comparison to conventional adobe. This analysis will provide a solid basis for assessing the economic viability of incorporating chillihua and LDPE in housing construction in the region.

4.1. Test Results Indirect Traction

Figure 17 shows the findings of the indirect tensile test carried out with 10 cm x 20 cm samples. The standard sample showed a strength of 2.18 kg/cm^2. With the addition of 1% of fibers (Chillihua and LDPE) it increased to 2.69 kg/cm^2, which represents an improvement of 23.39%. With an addition of 2%, the strength increased to 3.43 kg/cm^2, an increase of 57.34%. The addition of 3% raised the strength to 5.61 kg/cm^2, marking an improvement of 157.34%. With a 4% fiber addition, the strength increased to 6.92 kg/cm^2, an increase of 217.43%. With a 5% fiber addition, the strength started to decrease to 4.82 kg/cm^2, representing a decrease of 121.10%. Finally, by increasing the dosage to 6%, the strength decreased to 3.77 kg/cm^2, which is equivalent to a 72.94% decrease. These results highlight that, although the initial incorporation of fibers significantly improves the indirect tensile strength of the material, higher dosages can lead to a reduction in strength, indicating that there is an optimal limit to the amount of fibers that maximizes the strength of the material.

4.2. Compression Test Response

Figure 18 shows the results of the compression test performed on adobe blocks (10x10x10 cm). The standard sample showed a strength of 22.17 kg/cm^2, exceeding the required minimum of 10.2 kg/cm^2. The addition of 1% of both fibers (chillihua and LDPE) increased this strength by 7.62%. The inclusion of 2% fibers resulted in a 20.30% increase in compressive strength, while 3% fibers produced a 32.88% increase. However, from the addition of 4% fibers, a decrease in strength was seen. With 4% fibers, the strength decreased by 4.51%, while with 5% fibers, the reduction was 1.26%. Finally, the addition of 6% fibers led to a 5.99% decrease in strength. These results indicate that, although the initial addition of fibers significantly improves the mechanical properties of the adobe, above a certain concentration, the benefit is offset by possible negative effects. It is crucial to take these observations into account in order to optimize the dosage of fibers in construction applications that require high resistance to external loads.

4.3. Bending Test Results

The results of the bending test are presented in Figure 19. The standard specimen exhibited a strength of 12.10 kg/cm^2. With the addition of 1% fibre, the strength increased to 12.88 kg/cm^2, an increase of 6.45%. With the addition of 2% fibre, the strength increased to 13.87 kg/cm^2, marking an increase of 14.63%. With the addition of 3%, the strength reached 16.20 kg/cm^2, equivalent to an increase of 33.88%. The addition of 4% produced the highest strength, reaching 17.80 kg/cm^2, representing a remarkable increase of 47.11%.

However, from 5% onwards, the strength started to decrease, decreasing to 13.45 kg/cm^2, which is equivalent to a decrease of 11.16%. Finally, with the addition of 6%, the strength decreased to 11.87 kg/cm^2, a decrease of 1.90%. These results highlight that, although the addition of fibre initially improves the flexural strength of the material, higher dosages can reduce the strength, suggesting that there is a sweet spot in fibre dosage to maximise the mechanical properties of the material. The observation of this trend underlines the importance of properly adjusting the amount of fibre to obtain the optimum balance between strength improvement and potential adverse effects.

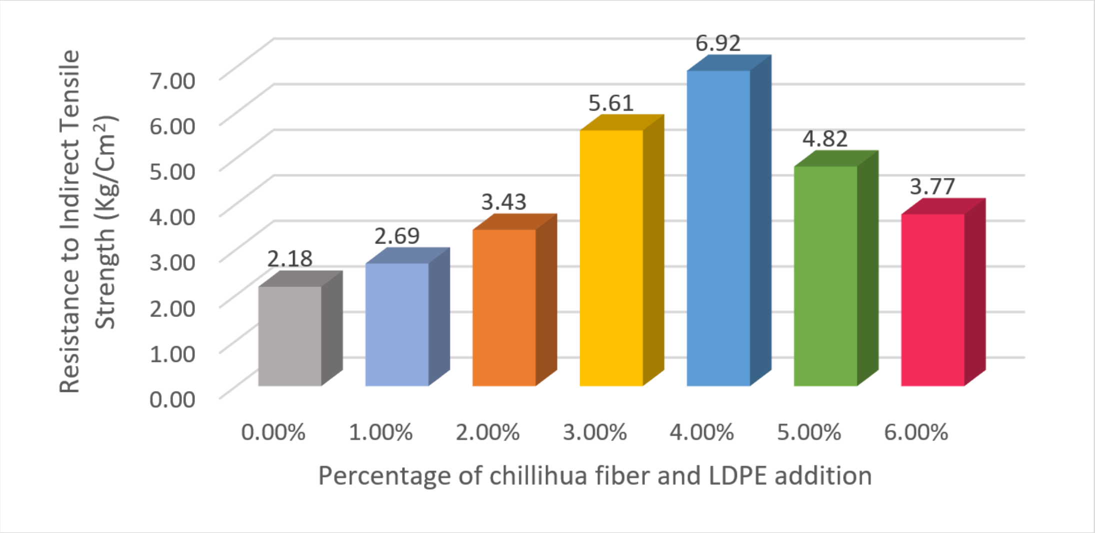

Figure 17. Indirect Tensile Test

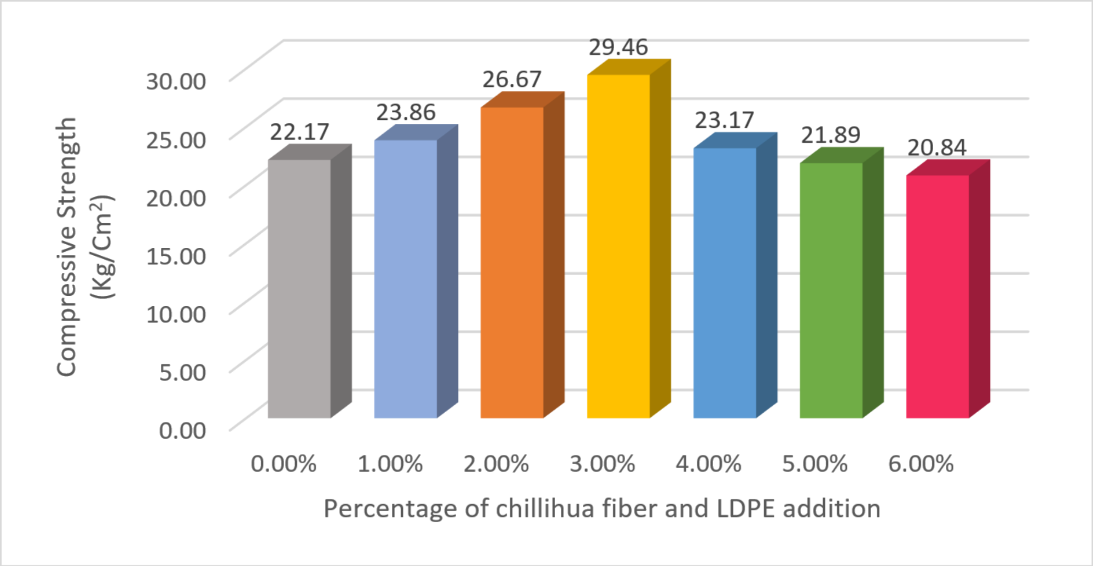

Figure 18. Compression testing of adobe units

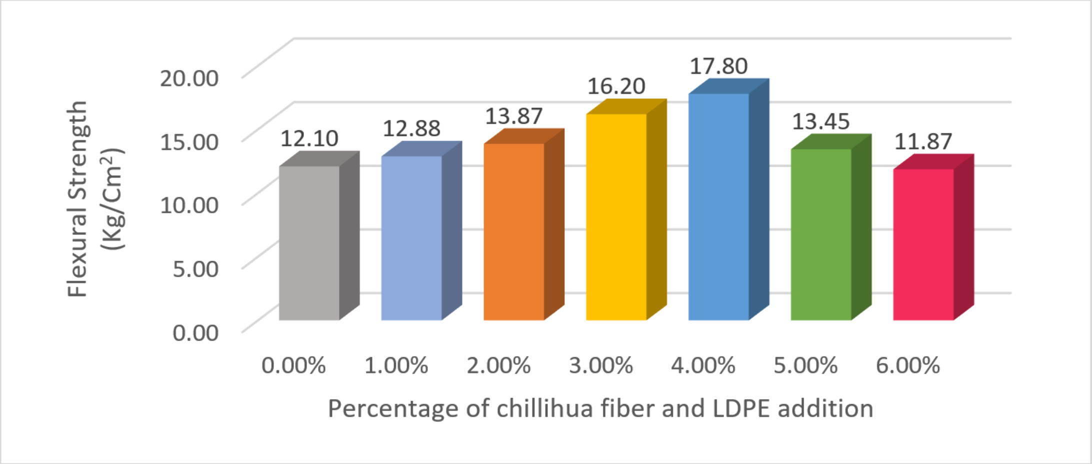

Figure 19. The Bending Test

4.4. Absorption Test Results

Figure 20 presents the results of the absorption test on adobe units of dimensions 40x20x12 cm. The standard sample exhibited an absorption of 22.67%, which, although exceeding the required 20%, is lower than the 25% stipulated by the E.080 standard [39], and showed disintegration and collapse when saturated with water, evidencing the need to avoid direct contact with this liquid. The incorporation of fibres significantly improved the properties of the adobe: with 1% fibres, the absorption decreased by 1.68%; with 2%, it decreased by 3.40%; with 3%, the reduction was 9.93%; with 4%, a decrease of 16.45% was observed; with 5%, the absorption decreased by 19.59%; and with 6%, it reached a decrease of 22.72%. These results demonstrate that the addition of chillihua and LDPE fibres substantially improves the adobe's ability to resist water absorption.

The significant reduction in moisture absorption due to the addition of fibres suggests that this material can act as an effective insulator against water. This property is fundamental for consideration in building applications that require protection against water contact, especially in flood-prone areas. Therefore, the incorporation of fibres in adobe represents a viable solution to improve the durability and resistance of the material in wet conditions, thus ensuring its effectiveness and longevity in the construction context.

4.5. Cost Analysis of Producing Conventional Adobe and Adobe with the Addition of Chillihua Fiber and LDPE

Based on the analysis of the physical and mechanical properties of the adobe evaluated in the laboratory, significant improvements were determined with the addition of 3% and 4% fibers. However, a better performance in water absorption was observed with the addition of 6% Chillihua and LDPE fiber. Therefore, both the best addition percentage in relation to the mechanical properties of the adobe and the complete range from 0% to 6% will be analyzed, the latter being the one that showed the greatest effectiveness against flooding.

A detailed analysis of the unit costs per square meter of wall was carried out, using adobe units with dimensions of 0.40 x 0.20 x 0.12 m. Figure 21 shows these costs, considering the salaries of the labor force: one worker and one laborer, with salaries of 84.70 soles and 59.80 soles for 8 hours per day, respectively [43]. As for materials, adobe bricks were used in accordance with the E.080 standard, requiring 17 adobe units per square meter, with a unit cost of S/ 0.25 soles per unit. In addition, 5% of the total cost was included for hand tools, resulting in a total cost of S/ 525.36 nuevos soles per square meter of wall for adobe without the addition of CF and LDPE.

However, the costs of stabilized adobe remained the same as conventional adobe, with the exception of the increase in labor costs due to the addition of Chillihua and LDPE fibers, which required pre-treatment for drying and cutting. In addition, the price of adobe changed due to the addition of CF and LDPE fibers. To calculate the cost of LDPE, a simple rule of three was used, starting from the fact that 0.745 $m^3$of LDPE cost S/ 29.90 Nuevos soles [44]. With a volume of adobe of 0.0096 m^3, the cost of LDPE corresponding to each addition percentage, from 1% to 6%, was determined. This additional cost was added to the base price of the adobe. It should be noted that the Chillihua fiber was excluded from the additional cost calculation, since it was obtained at no additional cost as it was collected from the field.

The total cost of the stabilized adobe with the best addition of 6% was S/ 590.69 Nuevos soles, which represented a difference of S/ 65.33 Nuevos soles with respect to conventional adobe, equivalent to an increase of 12.43%. Despite this difference in cost, the adobe stabilized with Chillihua and LDPE fibers showed significant improvements in its mechanical and physical properties [45], [46]. This suggests that, although the cost is higher, the performance and durability of the stabilized adobe against adverse conditions, such as flooding, justify the additional investment.

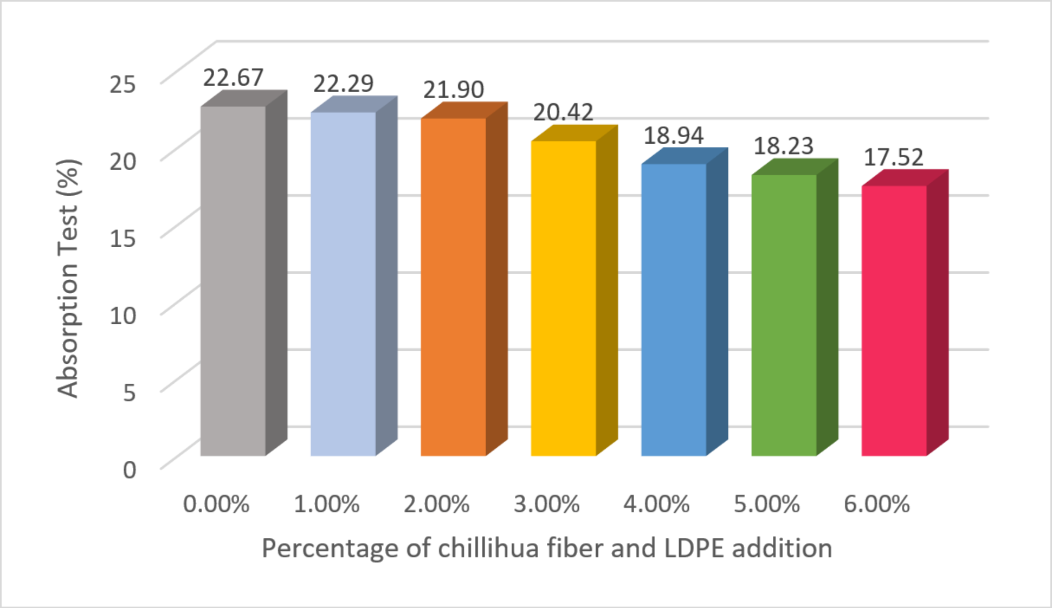

Figure 20. The Absorption test

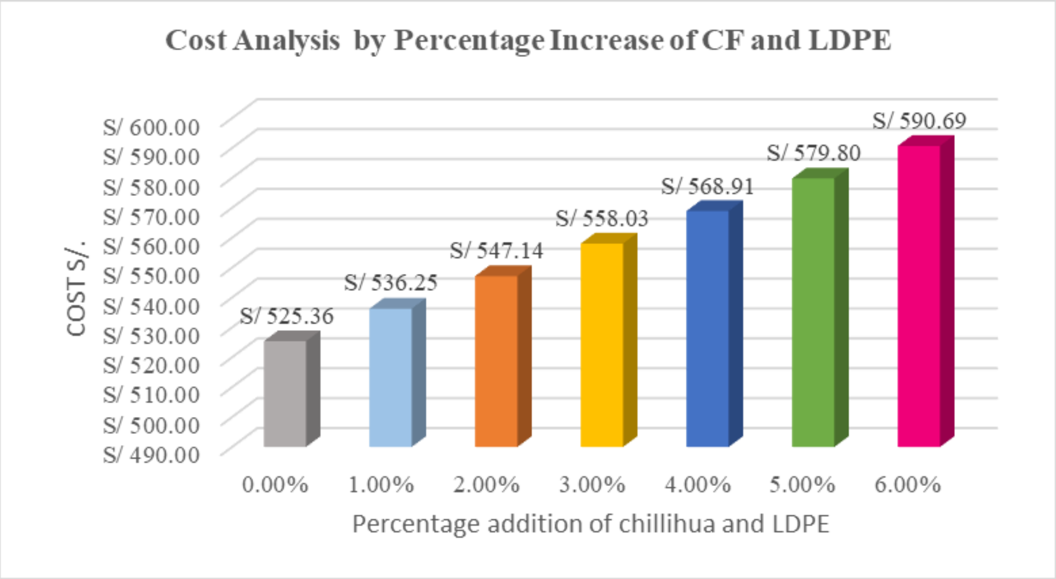

Figure 21. The fiber increment cost analysis

5. Discussions

The study revealed significant advances in the use of Chillihua and LDPE in various construction material applications. In particular, the research of Y. G. Chavez Cruz and Y. Y. Coasaca Huayapa [13] showed that the incorporation of Chillihua in concrete, with a proportion of 1.0%, increased the compressive strength to 230.34 Kg/cm ^{2} at 28 days, compared to the standard of 216.82 Kg/cm ^{2}. In addition, the tensile strength at 14 days, with a percentage of 0.5%, reached 108.90 Kg/cm ^{2} compared to the standard of 88.08 Kg/cm ^{2}, highlighting the potential of the Chillihua. In our research, we observed results consistent with these findings when adding Chillihua and LDPE instead of only Chillihua. Although the percentage used was not as low as in the reference study, we also achieved remarkable improvements in compressive strength, reaching 29.46 kg/cm ^{2} with a 3% addition, compared to 22.17 kg/cm ^{2} for the standard. Likewise, the tensile strength improved significantly with a 4% addition of both fibers (Chillihua and LDPE), reaching 6.92 Kg/cm ^{2} compared to 2.18 Kg/cm ^{2} of the standard. These results confirm that the addition of Chillihua and LDPE has a positive impact on the mechanical properties of the construction materials, aligning with the conclusions of Chávez Cruz and Coasaca Huayapa's research.

Similarly, research by A. S. Lubis et al [20], focusing on the use of LDPE in asphalt, showed promising results in terms of dynamic stability, underlining the relevance of their study in the field. It was found that the inclusion of 6% LDPE significantly improved the stability of asphalt to resist deformation, with an increase in the dynamic stability value from 508.06 track/mm to 3497 track/mm. Furthermore, according to E. M. Kakisina et al [21], the optimum addition of LDPE is between 1% and 5%, which increases the stability of the asphalt material by up to 4%. These findings highlight the effectiveness of LDPE in improving stability in asphalt mixtures, which is relevant to our research. Although our study does not directly focus on asphalt or soil stability, the use of LDPE showed significant benefits. In our research, we observed that the best addition of LDPE and CF for indirect tensile strength was 4%, improving by 217.43%, followed by 3% in compressive strength improving by 32.88% and 4% in flexural strength improving by 47.11%. This underlines the ability of LDPE to improve mechanical properties in similar materials, highlighting the importance of previous studies in optimizing the use of LDPE in various applications.

However, despite these advances, the research also highlighted certain limitations and areas that require further exploration. For example, the use of Chillihua in construction is still at an early stage of study, underscoring the need for more specific research tailored to local adobe construction conditions in the Andean regions. Similarly, although studies on LDPE in asphalt and bitumen have shown remarkable benefits, more research is needed to optimize the proportions and mixing conditions that maximize its positive effects without compromising other material properties. It should be noted that there is little information on the specific application of these inputs in adobe, which limits knowledge of their full impact on this type of construction.

6. Conclusions

In conclusion, the use of Chillihua fibres and recycled LDPE significantly improves the properties of the adobe, according to the tests performed that evaluated both the mechanical characteristics and the absorption of the material. Compared to an adobe without fibres, which presented a compressive strength of 22.17 kg/cm^2 as a baseline, the addition of 1% Chillihua and LDPE improved this strength by 7.62%. This improvement is attributed to the ability of the fibres to distribute internal stresses, reducing the probability of fracture failure. The addition of 2% fibres resulted in a 20.30% increase in strength, while the addition of 3% fibres resulted in a 32.88% increase. The addition of 4% fibres resulted in a 4.51% decrease in strength, while increasing the dosage to 5% resulted in a 1.26% decrease in strength. This behaviour is due to less interaction between the fibres and the adobe matrix, which initially improves internal cohesion. However, the use of 6% fibres led to a further 5.99% decrease in strength. Thus, the optimum dosage to obtain the highest strength was 3%, as, from this point, the increase in fibre dosage started to reduce the strength. These results indicate that, although the addition of fibres can improve the internal cohesion of the adobe, dosages above the optimum can result in a decrease in the strength of the material.

Secondly, the incorporation of Chillihua and LDPE fibres in adobe has proven to be effective in reducing water absorption, thus improving the durability of the material. With 1% fibres, water absorption decreased to 22.29%, representing a reduction of 1.68%. This effect is attributed to the fact that Chillihua and LDPE fibres decrease the porosity of the adobe, limiting the amount of water absorbed. As the amount of fibres increased, water absorption continued to decrease. With 2% fibres, absorption dropped to 21.90%; with 3%, it dropped to 20.42%. By increasing the proportion to 4%, the water absorption decreased to 18.94%, which is equivalent to a decrease of 16.45%. With 5% fibres, the absorption decreased further to 18.23%, as more fibres act as a more effective barrier against water penetration. Finally, with 6% fibres, water absorption decreased to 17.52%, representing a decrease of 22.72%. These results indicate that a higher fibre content significantly increases the material's ability to prevent water infiltration, improving its durability.

Third, the findings of the indirect tensile test show that the inclusion of CF and LDPE significantly improves the strength of the adobe. The standard sample showed a strength of 2.18 kg/cm^2, which increased significantly with the addition of 4% fibers, reaching an increase of up to 217.43%. This percentage was identified as the optimum dosage in this test. However, when exceeding 4% fiber addition, the strength started to decrease. This remarkable increase in strength highlights how the fibers reinforce the structure of the material and contribute significantly to its load-bearing capacity. The results highlight the importance of fibers in enhancing the mechanical properties of adobe, which is essential for construction applications that require high indirect tensile strength capacity.

Fourth, the results of the flexural test show that the strength of the material reaches its maximum value with a 4% fiber dosage, reaching 17.80 kg/cm^2, which is equivalent to an increase of 47.11% with respect to the standard sample. However, when increasing the fiber proportion to 5% and 6%, a reduction in load-bearing capacity is observed, dropping to 13.45 kg/cm^2 and 11.87 kg/cm^2, respectively. This indicates that, from 5% fiber, the strength begins to reduce, suggesting that the ideal level of CF and LDPE addition to maximize flexural strength is 4%.

Fifth, the comparative cost analysis between adobe without fiber and adobe with the incorporation of chillihua and LDPE fiber shows that the unit cost per square meter of wall increases by approximately 12.43% with the incorporation of fibers. This increase is mainly due to the higher labor and input costs necessary for the treatment and incorporation of the fibers. Despite this increase, stabilized adobe presents significant improvements in compressive strength and water absorption capacity, which may justify the additional investment in contexts where these improved properties and the durability of the material against adverse conditions such as floods are valued.

Finally, in order to advance in the effective application of Chillihua fibers and recycled LDPE in adobe, it is recommended that long-term durability studies be carried out under extreme environmental conditions and prolonged cycles of humidity and dryness. This will allow a comprehensive evaluation of the behavior of the modified adobe in real situations. In addition, it is crucial to carry out tests in different soil types to determine the effectiveness of these additives in various environments, which will help to generalize the results and confirm the feasibility of their use in different geographic regions.

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