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Influence of prickly pear gum on the physical and mechanical properties of adobe reinforced with palm fiber

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Abstract

Throughout history, adobe has been essential to many cultures, but its vulnerability to climate and load-bearing limitations have led to research into new natural materials to improve it. Therefore, the objective of this research was to evaluate the influence of prickly pear gum on the physical and mechanical properties of adobe reinforced with palm fiber. Peruvian standard E.080 was used for adobe preparation under an experimental design, preparing samples with 5, 10, 15 and 20% of prickly pear gum (PPG) to replace the volume of water, reinforcing it with 0.25, 0.5, 1 and 1.5% of palm fiber (PF) by weight of the soil, carrying out tests to determine the physical and mechanical properties of the adobe under study. The results revealed that the optimal dosage was 15% PPG + 0.5% PF, suction and warping decreased by 27% and 3.4% respectively, and absorption increased by 68% compared to the control design. Compression strength in masonry unit, flexural strength in masonry unit, compressive strength in prisms, and diagonal shear strength walls showed significant increases of 24.47, 98, 24.39, and 73.4%, respectively, compared to the control design. It was concluded that the use of PPG and PF provides significant benefits to the physical and mechanical properties of adobe.

Keywords: Adobe, Climatic conditions and changes, Prickly pear gum, Palm fiber, Mechanical properties

1. Introduction

The land has an undoubted role due to its numerous benefits, to meet modern needs and preserve terrestrial heritage [1], with growing awareness of environmental and energy issues, adobe offers important ecological and economic advantages, in Algeria, the ksour (buildings mud) remain the only witness of this type of construction [2]. Since there are several adobe construction techniques, however, these constructions vary according to their physical, energy, ecological, and socioeconomic characteristics [3, 4]. Sustainability and seismic resistance in adobe constructions are achieved by improving the lateral behavior of adobe walls through the use of natural reinforcement materials such as palm fiber (PF) [5].

The interest in using natural fibers as soil reinforcement is rapidly developing due to their cost-effectiveness, high availability, and environmental friendliness. Many published studies have investigated the advantages of soil reinforced with fibers, but few of them have used natural fibers, such as palm fiber [6]. It is the oldest construction technique used by humanity, its application is economical and easy compared to other building materials, and above all, it is an environmentally friendly material [7].

In countries with high seismic activity such as Chile, the use of adobe as a structural construction material is not within the legal framework, despite this there are still numerous buildings with one or two floors, built with this material [8]. The adverse seismic behavior of these buildings have a considerable structural load and insufficient resistance, as their response is fragile to intense seismic events [9]. Research into reinforcing adobe with palm fibers, a natural waste product, reduces raw material consumption and waste disposal costs. These fibers strengthen the adobe due to their strength and durability, in addition to having low thermal conductivity [10]. These plant fibers constitute a natural waste abundant and renewable, being favored to develop and improve the thermal performance of adobe [11].

In Morocco, the use of natural fibers to reinforce earth construction materials is an ancient concept that has been expanded to include fibers of various origins, such as palm fiber [12]. Natural fibers added to the adobe mix create internal reinforcement that strengthens the adobe brick and prevents cracking [13]. The addition of palm fibers influences not only its strength but also the distribution of temperature in the walls and the heat flow passing through them, as well as the speed at which heat propagates, which depends on the palm fiber content [14].

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According to Khoudja et al. [15], in their research, they manufactured adobes stabilized with lime and palm fiber waste (PFW) at 2, 4, 6, 8, and 10% with the aim of evaluating the mechanical behavior of the adobe. Their results revealed a decrease of 9.2 and 8.7% in compression and flexural strength, respectively, in adobes containing 10% PFW. Guettatfi et al. [16], in their research, they produced adobes incorporating PFW at 0.25%, 0.50%, and 0.75% reinforced with cement and lime. Their results showed that with 5% cement and 0.5% PFW, the strength after 28 days of curing increased by 44% compared to the standard, while with 7% lime + 3% cement + 0.25% PFW, the compression strength increased by 57% compared to traditional adobe.

AlShuhail et al. [17], manufactured adobes using different percentages of natural fibers; their results revealed that the liquid limit of the soil was 20%, the plastic limit was 16%, and the plasticity index was 4%, indicating a silty clay soil. The inclusion of 1% date palm fibers (DPF) increased compression strength by 30% and water absorption by 15.5% compared to adobes containing wood chips. Similarly, Mohammadi et al [18], made adobe bricks with dimensions of 200 × 200 × 50 mm by adding palm fibers at 0.25%, 0.5%, 0.75%, and 1% of the soil weight. Their results revealed that adding 0.25% PF can increase compression strength by 50%, and adding 1% PF can double tensile strength.

Eslami et al. [13], evaluated adobe bricks with PF, and their results reveal superior performance in compression strength, with 0.25% PF surpassing the standard by 59%. Additionally, tensile strength increases with 1% fiber, exceeding the control adobe by 104%. The suction resistance test showed a positive effect with fiber addition. Furthermore, Abdeldjebar et al. [19], in their study, manufactured adobes with palm fiber of dimensions 4×4×16 cm. The results obtained show a plastic limit of 11.36% for the soil, a liquid limit of 19.45%, and a plasticity index of 8%. Moreover, combining lime and fibers treated with water is the optimal option that provides the best mechanical resistance, increasing by up to 18% for the tensile test and 38% for the compression test compared to the standard adobe.

Zaidi et al. [20], in their study, they mixed soil, sand, and lime in appropriate percentages, then added palm waste (PW) in proportions of 0.3%, 0.6%, and 0.9% by weight of the dry mixture to be tested on cubic and cylindrical samples in a laboratory. Their results show that with the presence of PW in the mixture (soil + lime), an unfavorable effect was observed in terms of compression strength and water absorption. On the other hand, Aparicio et al. [21], in their study, carried out laboratory tests on clay blocks, made from 50% earth, 30% paper, 10% lime and 10% prickly pear mucilage. Their results show that in terms of compression resistance, it exceeded the standard sample by 8%. In addition, a 17% decrease in water absorption and a weight reduction of up to 25% and a 10% lower cost were observed. Taallah and Guettala [22], made adobes with different proportions of lime in 8, 10 and 12% and palm fibers between 0.05 and 0.2%, their results after 28 days of curing show an increase of 3.9% in compression resistance. With 0.05% alkali treated fiber content compared to fiber-free adobe, with increasing fiber content, there is a slight overall decrease in strengths and absorption increases.

The review reveals that there are studies on natural fibers in adobe; their characteristics depend on their chemical and physical composition. The knowledge gap is that adobes have only been made with natural fibers and very little with prickly pear mucilage, where the diagonal shear strength in masonry is not considered. Thus, there are still several gaps regarding the use of prickly pear mucilage combined with palm fiber added in the production of adobe units for housing construction. Currently, in Peru, this type of earth construction continues to exist in rural areas due to a lack of economic resources to purchase quality materials. These residual materials that make up the adobe are abundant in the area, and the need to use them is significant. The main objective of this study is to evaluate the physical and mechanical properties of adobe by adding prickly pear mucilage and reinforcing it with palm fiber. Parameters were established, such as percentages of prickly pear mucilage and palm fiber based on the weight of the soil to be used, to determine the optimal content of prickly pear mucilage and palm fiber.

2. Materials and methods

2.1 Materials

2.1.1 Soil

The extraction of the soil sample was carried out by manual excavation at a depth of 1.50 m from the city of Chiclayo, Peru; subsequently, the extracted sample was transported in plastic bags to maintain its humidity and avoid contamination [4]. However, due to the simplicity of its composition, adobe has some limitations such as its low resistance to continuous exposure to water, seismic force and other factors [23].

The soil was classified according to ASTM D2487 standard [24], and ASTM D4318 standard [25] was referred to determine the liquid limit, plastic limit, and plasticity index. Figure 1 shows the finest percentage on the grain size distribution curve passing through the No. 200 (75 µm) sieve is 30%, identified as clayey soil material (CS) according to the Unified Soil Classification System (USCS). Table 1 shows some characteristics of the study soil.

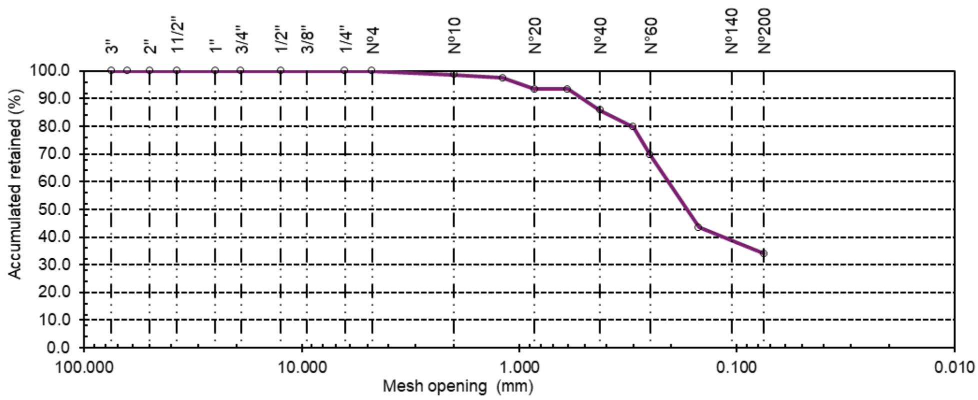

Figure 1 Natural soil grain size distribution

Table 1 Natural soil characteristics

Tests	Results	ASTM Standard
Liquid limit (%)	30.54	ASTM D4318 [25]
Plastic limit (%)	17.08	ASTM D4318 [25]
Plasticity index (%)	13.46	ASTM D4318 [25]
Natural humidity (%)	3.95	ASTM D2216 [26]

2.1.2 Prickly pear gum

It is a vegetal, gummy, thick, and viscous substance with a natural capacity to store large quantities of H_2O. This composition is found in the fruit pulp, cladodes, and peel in various proportions, with the cladodes accounting for 0.5% and the peel for 1.2%, as determined by many studies [27]. It was extracted in the Pátapo district, belonging to the Chiclayo province in the Lambayeque region, Peru. Table 2 below shows some physical properties of the material in use.

Table 2 Physical characteristics of prickly pear gum

Characteristics	Results	ASTM Standard
Specific weight	1.09	ASTM C188 [28]
Color	Green	-

2.1.3 Palm fiber

Palm fiber is a strong natural fiber, popularly called palm, obtained from the extraction of buri and raffia fibers, which is used in the manufacture of ropes, fabrics and other uses. Figure 2 shows the palm fiber for blending, tensile test and specific gravity to the study fiber. Table 3 shows the physical and mechanical characteristics.

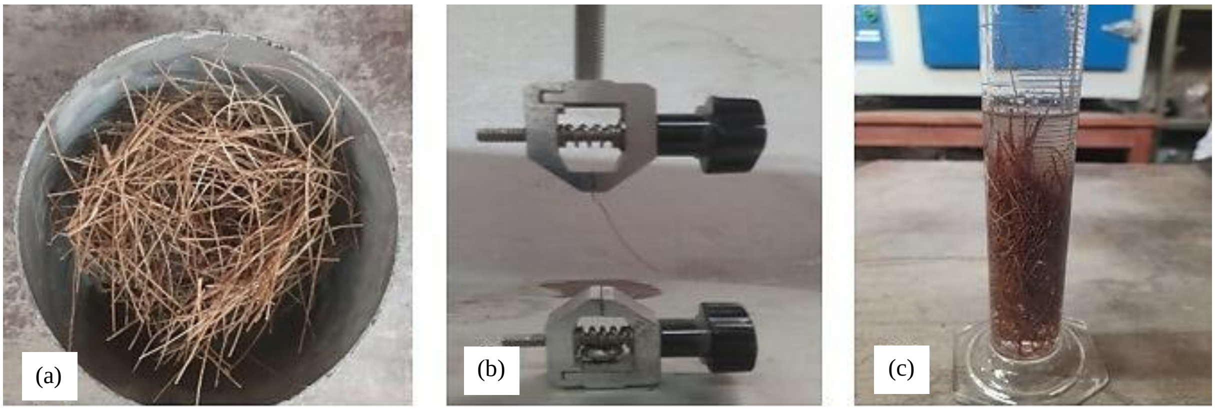

Figure 2 Palm fiber (a); tensile strength of palm fiber (b); specific gravity of palm fiber (c).

Table 3 Physical and mechanical characteristics of palm fiber

Characteristics	Results	ASTM Standard
Length (mm)	50	-
Dimensions (mm)	0.05	-
Specific weight	0.525	ASTM C188 [28]
Tensile strength (kg/cm^2)	722.8	-

2.2 Methods

A control design and four designs of adobe modified with prickly prickly pear gum (PPG) in the percentages of 5%, 10%, 15% and 20% by weight of dry soil were carried out. Then, the optimum dosage of PPG to be reinforced with palm fiber (PF) was considered at 0.25%, 0.50%. 1%, 1.5%. The proportions per unit of masonry and descriptions of each mixture are shown in Table 4, respectively. The Peruvian methodology was used to make the adobes under the E.080 standard [29]. The adobes were made manually, using conventional tools such as shovels for mixing.

The mixture of soil, water and prickly pear gum can be seen in Figure 3. Wooden molds measuring 40 cm long x 20 cm wide x 10 cm high were used. A release agent was used in each wooden mold to prevent the surface of the wood from sticking to the prepared mixture, in order to avoid cracks in the unit.

The amount of water was taken into account so as not to lose or exceed the plasticity of the mixture of each adobe. At the moment of pouring each mixture into the molds, the mixture had to be poured with 25 blows for every three layers to eliminate the air content that could be originated. Finally, after 5 minutes, it was unmolded and left in the open air under a plastic platform, leaving it for 24 hours for its final hardening, without any type of curing. Figure 4 shows the process flow from obtaining materials, testing and interpretation of the information obtained for the scientific study.

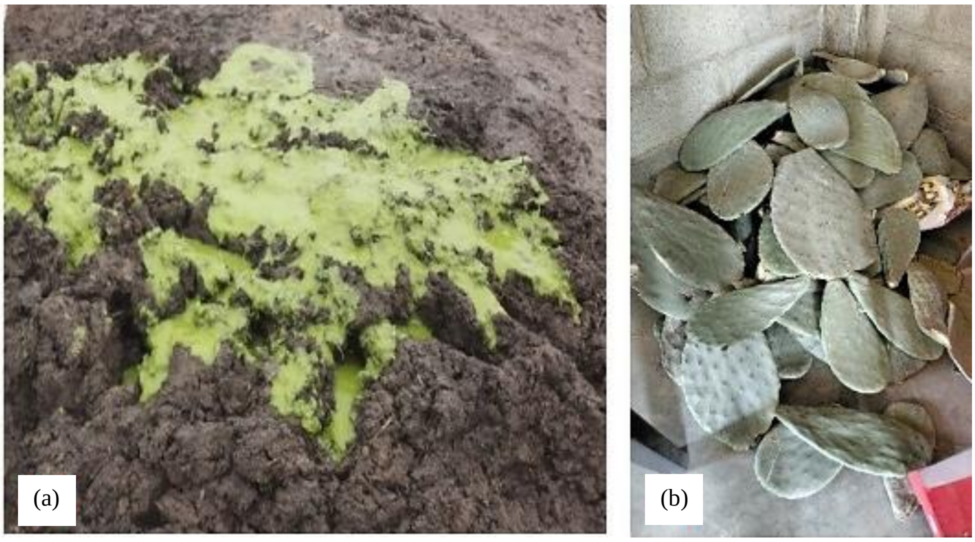

Figure 3 Addition of PPG in mud mixture (a); prickly pear stalk (b).

Table 4 Proportions of materials for masonry unit

ID Mix	Soil (g)	Water (ml)	PPG (%)	PPG (ml)	PF (%)	PF (g)
Control design	8500	3000	-	-	-	-
5PPG	8500	2850	5	150	-	-
10PPG	8500	2700	10	300	-	-
15PPG	8500	2550	15	450	-	-
20PPG	8500	2400	20	600	-	-
15PPG+0.25PF	8500	2550	15	450	0.25	21.25
15PPG+0.50PF	8500	2550	15	450	0.50	42.5
15PPG+1PF	8500	2550	15	450	1	85
15PPG+1.5PF	8500	2550	15	450	1.50	127.5

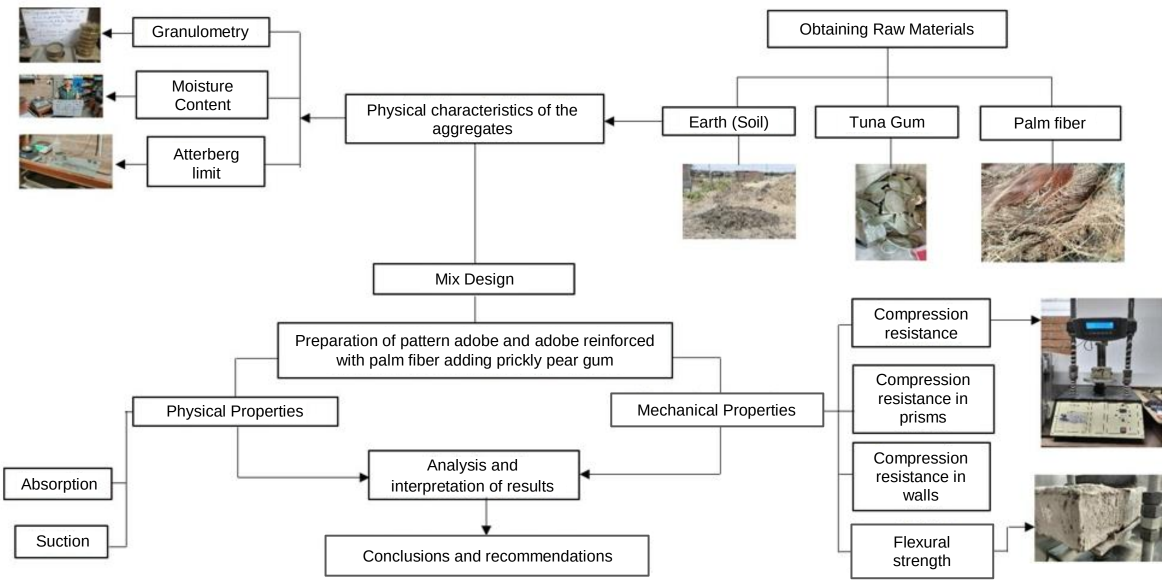

Figure 4 Procedure flow chart

3. Results

3.1 Physical properties of adobe with PPG and adobe with PPG+PF

3.1.1 Suction and absorption test

In Figure 5(a), it can be observed that by incorporating 10% PPG into adobe, the suction capacity reduces compared to control design, resulting in a value of 8.65 g/cm^2/min. In Figure 5(b), absorption is recorded at 17.61% as the lowest value. Conversely, adobe with 15% PPG showed the highest absorption index, reaching 28.06%. Prickly pear gum acts as a hydrophobic agent that reduces the water absorption capacity of the material.

In Figure 5(c), it is observed that adobe with 15% PPG reinforced with 0.5% PF decreases by 27% compared to traditional adobe with higher suction. In Figure 5(d), a predisposition of adobe to absorb more water is shown with dosages of 15% PPG + 1% PF, increasing by 68% compared to the control design. Beyond that percentage, absorption decreases but remains higher than control design. The amount of water absorbed by adobe bricks can affect their structural stability. If suction is excessive, adobes can lose their cohesion and strength, which can lead to cracking, warping, even collapse of the structure or deterioration over time. Controlling water suction can help prevent internal moisture accumulation in the house.

This is because PPG is known for having a greater water retention capacity, approaching the results of Eslami et al. [13], and Taallah and Guettala [22], who with palm fiber revealed a positive effect on water absorption capacity. Likewise, AlShuhail et al. [17], with 1% palm fiber, increased their water absorption capacity by 15.5%. Conversely, Alhakim et al. [6], reported an unfavorable effect on water absorption.

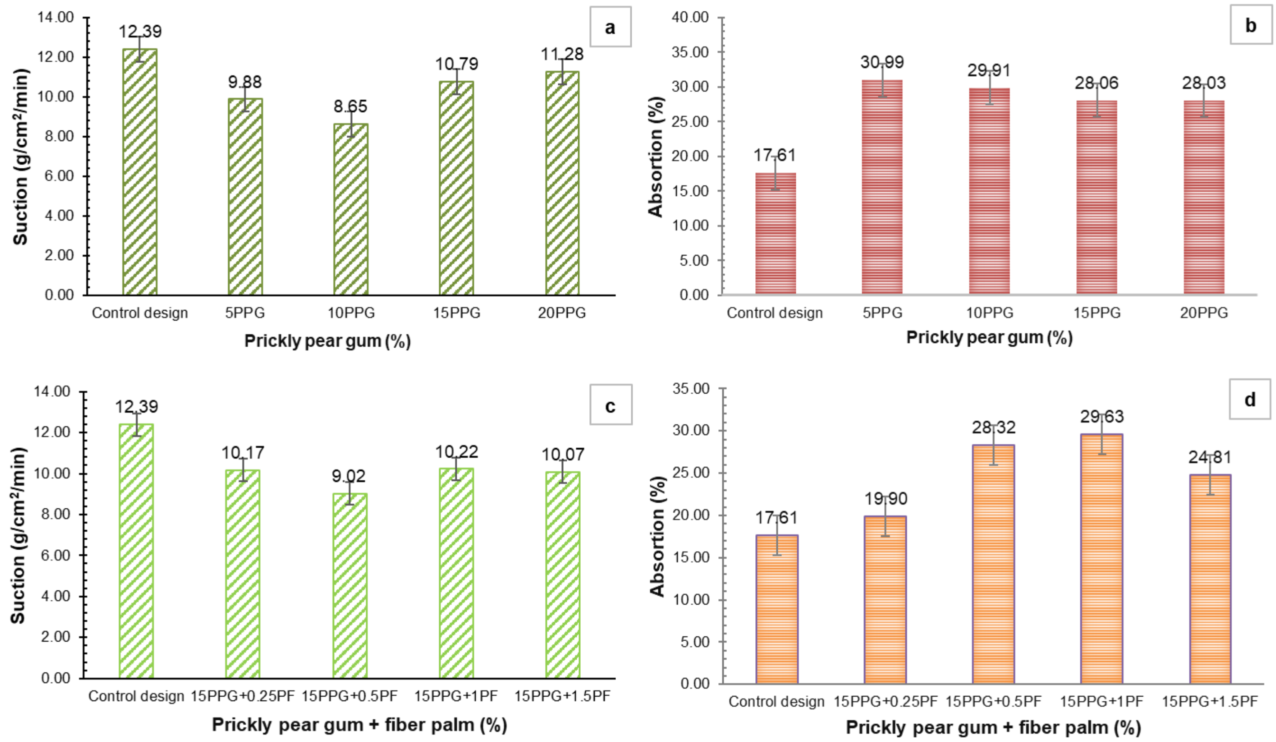

Figure 5 Physical properties of adobe, adobe suction with PPG (a); adobe absorption with PPG (b); adobe suction with PPG+PF (c); absorption of adobe with PPG+PF (d).

3.2 Mechanical properties of adobe with PPG and adobe with PPG+PF

3.2.1 Compressive strength in masonry unit

The Figure 6 shows that adobe with 15% PPG shows an improvement of 32.08% compared to the control design; then it decreases with adobe with 20% PPG compared to the control design, exceeding the minimum compression resistance at 28 days value given by the E 0.80 standard, which is 10.2 kg/cm^2. The addition of Prickly pear gum can significantly increase the compressive strength of adobes. This is due to the improvement of the bond between soil particles and the decrease of imperfections in the internal structure of the adobe, resulting in a higher load-bearing capacity.

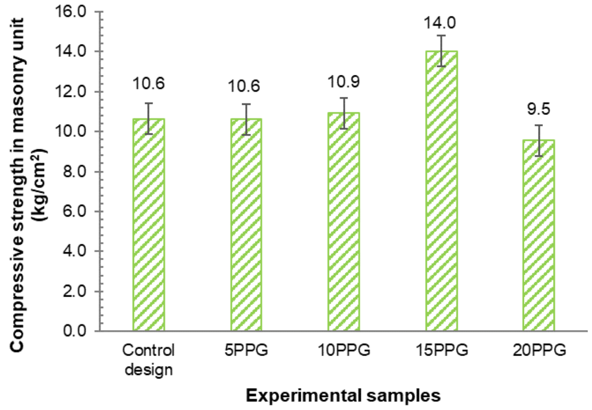

Figure 6 Box-and-whisker plot of compressive strength in adobe masonry units with PPG

Figure 7 shows that adobe with 15% PPG + 0.5% PF presents the best results, surpassing the control design by 98%; then its compression resistance at 28 days decreases as the percentage of PF addition increases. It is observed that the addition of palm fiber in the highest proportion of 1% does not generate a positive impact on the strength of the adobe unit, which means that there is a permitted limit of no more than 0.5% addition of palm fiber. This behavior may be due to the fact that when the fiber is randomly placed at the time of mixing, it generates an accumulation of fibers, which contributes to generate hollow spaces inside the adobe, resulting in low resistance at the time of testing.

This aligns with the research by Guettatfi et al. [16], and Vatani Oskouei et al. [30], where cube strength with 0.5% palm fiber increased by 44% and 82.12%, respectively, but differs from Taallah and Guettala [22], where 0.05% PF yielded better results, and differs from Eslami et al. [13], and AlShuhail et al. [17], where 1% fiber found better results.

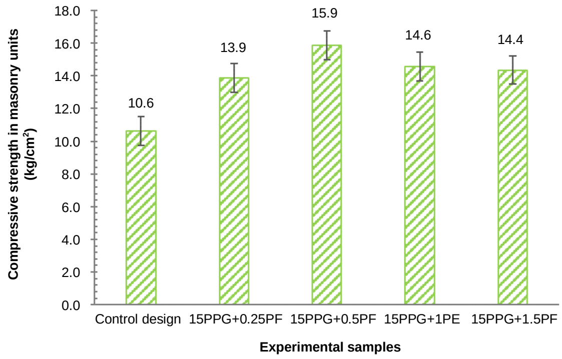

Figure 7 Box-and-whisker plot of compressive strength in adobe masonry units with PPG and PF

3.2.2 Compressive strength in prisms

In Figure 8, it can be observed that adobe with 15% PPG increases by 23.97% compared to the control design. Similarly, the traditional adobe obtained a compression strength at 28 days value in prisms of 6.19 kg/cm^2, with percentages of 5%, 10%, and 20% also surpassing the standard adobe; however, it is shown that with 20%, the strength begins to decrease.

In Figure 9, it is evident that adobe containing 15% PPG and reinforced with 0.5% PF exhibits a compression strength at 28 days value in prisms of 7.70 kg/cm^2, surpassing the control design by 24.39%. The other reinforcement percentages, such as 0.25%, 1%, and 1.5%, also exceeded the compression strength in prisms of the control design by 9.3%, 18.7%, and 18%, respectively. The prickly pear gum improves the cohesion of the adobe matrix, while the palm fibers reinforce the structure. This results in a stronger adobe that can withstand higher loads without deforming or breaking.

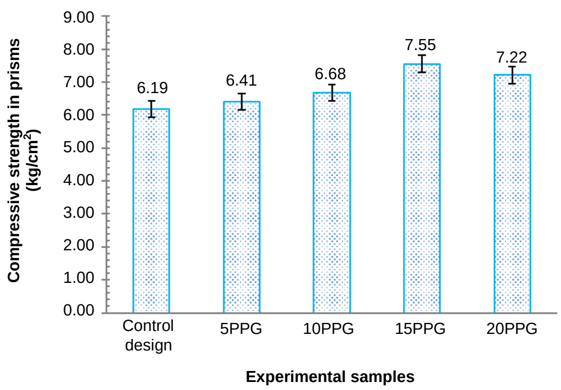

Figure 8 Box-and-whisker plot of compressive strength of adobe prisms with PPG

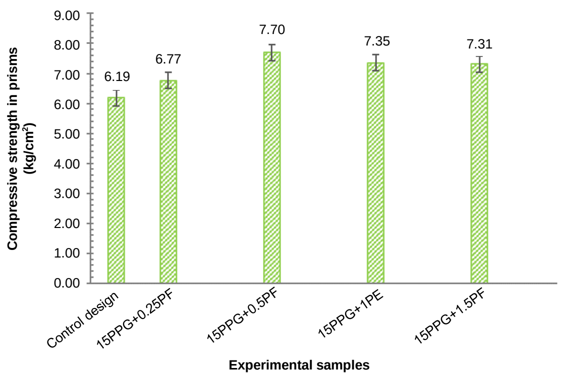

Figure 9 Box-and-whisker plot of compressive strength of adobe prisms with PPG and PF

3.2.3 Diagonal shear strength in walls

In Figure 10, it can be observed that increasing the proportion of PPG in the adobe mix results in higher diagonal compression strength at 28 days. This strength becomes maximum when a concentration of 15% PPG is used in the adobe, achieving a 64% increase compared to the control design. In Figure 11, it is observed that adobe with 15% PPG + 0.5% PF obtained a value of 1.11 kg/cm^2, surpassing the control design by 73.4%, while percentages of 0.25%, 1%, and 1.5% also surpass the control design by 28.1%, 64.9%, and 48.4%, respectively, which are lower values compared to the adobe reinforced with 0.5% PF.

It was observed that the adobe walls containing prickly pear gum and palm fibers showed fewer occurrences of diagonal crack formation as opposed to the wall samples containing only prickly pear gum, due to the fact that the palm fiber acts as reinforcements that redistribute stresses within the material, which reduces the probability of cracking.

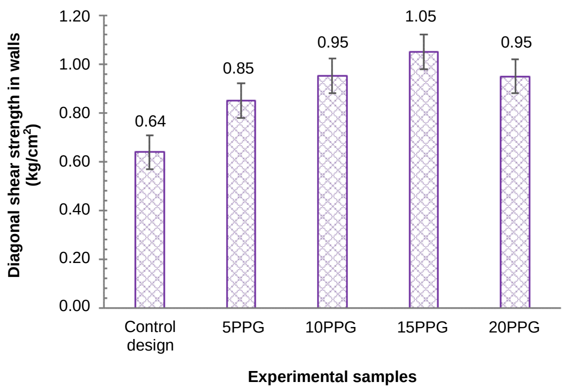

Figure 10 Box-and-whisker plot of diagonal shear strength of adobe walls with PPG

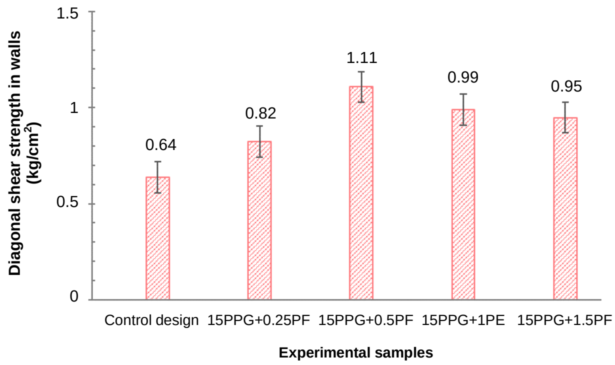

Figure 11 Box-and-whisker plot of diagonal shear strength of adobe walls with PPG and PF

3.2.4 Flexural strength in masonry unit

In Figure 12, the incorporation of PPG positively affects the flexural strength at 28 days, where with 15%, a strength of 10.01 kg/cm^2 is achieved, representing an increase of 24.97% compared to the control design. In Figure 13, additionally, it is observed that with 15% PPG + 0.5% PF, a strength at 28 days of 9.97 kg/cm^2 was achieved, showing an increase of 24.47% compared to the control design. This effect generated by PPG and PF in the adobe improves the resistance to the tensile stresses to which the adobe is subjected, being the ideal combination to generate greater resistance to the control design.

However, with a higher percentage of palm fiber reinforcement, the strength starts to decrease, consistent with the research by Bolaños Rodríguez [31], where flexural strength increased by 30% with 15% prickly pear rubber. Contradicting Khoudja et al. [15], who found that flexural strength decreased by 8.7% in adobes containing 10% PF.

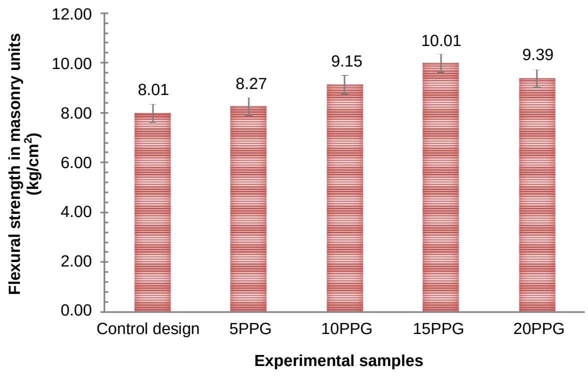

Figure 12 Box-and-whisker plot of flexural strength of adobe masonry units with PPG

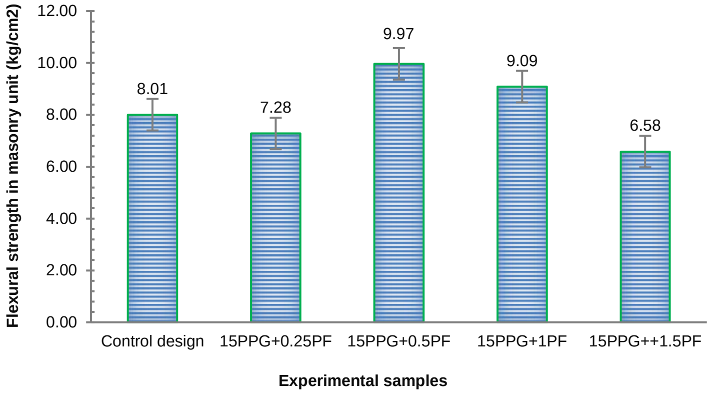

Figure 13 Box-and-whisker plot of flexural strength of adobe masonry units with PPG and PF

3.2.5 Optimum combination percentage of prickly pear gum and palm fibers

Figure 14 shows that the 15% PPG mix, reinforced with 0.5% PF, performed better than the control design sample. This behavior is due to the fact that PPG in its optimum dosage is able to act as a binder with the palm fiber in the adobe mix. The use of a very low proportion of fiber manages to generate the highest strength in most of the tests evaluated. A higher fiber dosage does not always generate a greater impact on the mechanical properties. It should be clarified that the arrangement of the palm fibers was random, which also generates hollow internal cavities generating internal microcracks, resulting in lower strength.

The physical and mechanical properties in comparison with the control design and the other percentages, which shows agreement with the results obtained by Guettatfi et al. [2], in which the optimal percentage was 0.5% of PF. However, Mohammadi et al. [18], in their article, presents 0.25% of palm fiber as the optimal percentage.

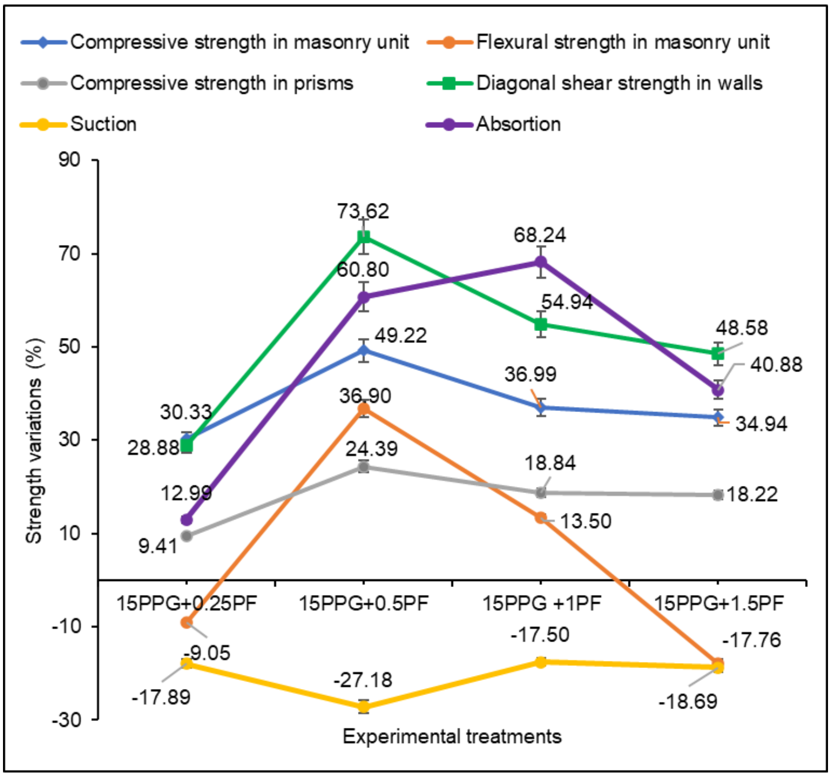

Figure 14 Percentage variations of modified adobe results in physical and mechanical properties.

4. Discussions

4.1 Suction and absorption

The suction in adobes with PPG shows a decrease, being the lowest with 10% PPG where the suction was 8.65 gr/cm^2/min. The suction in adobes with 15% PPG + 0.5% PF had a lower suction of 9.02 gr/cm^2/min compared to traditional adobe, decreasing by 27%. Regarding absorption, it increased by 76%, 69.8%, 59.3%, and 59.1% for dosages of 5%, 10%, 15%, and 20%, respectively, compared to the control sample, which had an absorption of 17.61%. Additionally, the dosage of 15% PPG + 1% PF showed the highest absorption, surpassing conventional adobe by 68%. This is because PPG is known for having a greater water retention capacity, approaching the results of Eslami et al. [13], and Taallah and Guettala [22], who with palm fiber revealed a positive effect on water absorption capacity. Likewise, AlShuhail et al. [17], with 1% palm fiber, increased their water absorption capacity by 15.5%. Conversely, Alhakim et al. [6], reported an unfavorable effect on water absorption.

4.2 Flexural

The incorporation of PPG positively affects the flexural strength at 28 days, where with 15%, a strength of 10.01 kg/cm^2 is achieved, representing an increase of 24.97% compared to the standard adobe. Additionally, with 15% PPG + 0.5% PF, a strength of 9.97 kg/cm^2 was achieved, showing an increase of 24.47% compared to the reference adobe. However, with a higher percentage of palm fiber reinforcement, the strength starts to decrease, consistent with the research by Bolaños Rodríguez [31], where flexural strength increased by 30% with 15% prickly pear rubber. Contradicting Khoudja et al. [15], who found that flexural strength decreased by 8.7% in adobes containing 10% date palm waste.

4.3 Compression, axial compression in piles and diagonal cutting in walls

The compressive strength in adobe cubes with PPG up to 15% substitution shows an improvement of 32.08%. Similarly, in pile compression tests, adobe with 15% PPG increases by 23.97% compared to the control adobe. Likewise, in diagonal shear strength with the same percentage, adobe strength increases by 64%. On the other hand, the compressive strength in cubes with 15% PPG + 0.5% PF shows the best results, surpassing standard mortar by 98%; then its strength decreases with increasing PF percentage, although other dosages also exhibit good performance, exceeding the standard adobe.

Similarly, in pile compressive strength, adobe with 15% prickly pear rubber and reinforced with 0.5% palm fiber obtained a value of 7.70 kg/cm^2, surpassing the standard adobe by 24.39%. With other reinforcement percentages of 0.25%, 1%, and 1.5%, they also exceed the standard adobe by 9.3%, 18.7%, and 18%, respectively. Additionally, in diagonal shear strength with the same dosage, adobe strength increases by 73.4%. This aligns with the research by Guettatfi et al. [16], and Vatani Oskouei et al. [30], where cube strength with 0.5% palm fiber increased by 44% and 82.12%, respectively, but differs from Taallah and Guettala [22], where 0.05% PF yielded better results, and differs from Eslami et al. [13], and AlShuhail et al. [17], where 1% fiber found better results.

5. Conclusions

The present study shows the relevant findings on the addition of PPG in adobe, and the combination of the optimum dosage of PPG with various proportions of palm fiber, presenting the following conclusions:

The soil studied was classified as SC soil because the material passing through the sieve in the No 200 mesh is 30%, with a plastic limit of 17.08%, a plasticity index of 13.46%, and a moisture content of 3.95%.

With the partial replacement of water with PPG, better performance in the physico-mechanical properties of the modified adobe was achieved compared to the control design. With the addition of 10% PPG, the suction decreased from 12.39 g/cm^2/min to 8.65 g/cm^2/min. On the other hand, with 15% PPG, the absorption increased by 28.06%.

With 15% PPG, the flexural, compressive, prism, and diagonal wall strength increased by 24.97, 32.08, 23.97%, and 64%, respectively, compared to the control design. These mechanisms and interactions contribute to the creation of more durable and resistant adobes when prickly pear gum is used in their manufacture.

The combination of 15% PPG + 0.5% PF showed better results than the control design, as its suction values decreased by 27%, on the other hand, absorption increased by 68%.

In addition, flexural strength, compressive strength, prism strength and diagonal strength in walls with the same dosage increased by 36.90%, 49.22%, 24.39% and 73.62%, respectively, compared to the control design.

Therefore, the optimum combination for adobe manufacture was 15% PPG + 0.5% PF, as this combination resulted in optimum improvements in the physical and mechanical properties of the modified adobe.

In summary, the combination of prickly pear gum and palm fibers in adobe provides a significant improvement in the mechanical properties of the material, including higher compressive strength, higher tensile and flexural strength, as well as increased durability and water resistance. This makes adobe a more viable and sustainable option for the construction of strong and durable structures, which in turn could benefit communities that rely on this traditional building material

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