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Published by the Faculty of Engineering, Khon Kaen University, Thailand

Durability and mechanical characterization of tapiales with lime and sugar cane fiber

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Received 21 December 2024
Revised 19 May 2025
Accepted 20 June 2025

Abstract

Worldwide, technological advances in construction have transformed construction materials, highlighting earth for its advantages. The traditional rammed earth method combines sustainability, efficiency and the creation of durable and attractive structures. Therefore, the objective of this research was to study the durability and mechanical characterization of rammed earth by adding lime and sugar cane fiber. Using an applied methodology and experimental design, preparing samples with the addition of lime in doses of 5%, 10%, 15%, 20%, obtaining an optimum to combine it with sugar cane fiber in doses of 0.5%, 1%, 1.5% and 2%. The fiber was 40 mm long and was randomly placed in the dry rammed soil mixture. The results indicated that the optimal percentage was 15% lime + 1.5% sugar cane fiber, since adding lime increases its mechanical properties and adding sugar cane fiber helps in durability analysis, improving by 10% compared to the initial samples.

Keywords: Rammed earth, Durability, Lime, Sugarcane fiber, Mechanical characteristics

1. Introduction

Technological advances in construction have rediscovered earth as a valuable material, noted for its multiple benefits [1]. Likewise, its use has spread to other parts of the world [2]. Parlato et al. [3], in approximately one third of the world's population has homes built with earth. Nevertheless, they present challenges in the face of seismic action [4], which is why materials such as concrete have dominated modern construction due to their superior thermo-mechanical properties [5].

By reinforcing the rammed earth with fibers, the aim is to improve its structural performance without losing the attractive qualities for sustainable construction [6]. The production of sugarcane and its derivatives has historically been linked to various developments [7]. Pan et al. [8] mention that sugarcane is responsible for meeting more than 70% of the world's sugar demand. In view of this, the demand for natural fiber-based composites is expected to increase due to the growing awareness about reducing waste and pollution [9].

Sugarcane is the second most produced agricultural product in the world [10]. Chantit et al. [11] mention that the use of fibers to reinforce earth structures also offers numerous benefits, improving mechanical characteristics and durability of the material [12]. Therefore, sugar cane fiber (SCF) represents an innovative, sustainable and economic solution for construction with earth, because it is an abundant and renewable resource [13]. On the other hand, a study shows that, by increasing the SCF percentage in the mixture, a decrease in the thermal conductivity of the material is noted [14].

In addition, in Peru there is the largest mud city in America, with the citadel of Chan Chan being especially renowned [15]. Nevertheless, at a national level, many earthen houses collapse during earthquakes, such as the 7.5 in Lamas, where 81% of the 900 affected houses, built with adobe, gave way, evidencing the lack of reinforcements in their design [16], despite this, it was revealed that in places with few resources the use of adobe is the most common [17]. Li Zavaleta [18] comments that in Lambayeque there is a percentage of 53.50% of houses in precarious conditions made of quincha and adobe. This study will investigate the synergistic potential between lime and sugarcane fiber to optimize tapiales in hot areas such as Lambayeque, where materials such as straw [19], [20], clay [21], cement [22], commercial fibers [23-25], metal mesh [26] and ashes [27] have traditionally been used. Unlike these conventional components, the use of SCF - an abundant regional agricultural by-product - would not only improve the mechanical properties of the walling, but also promote the circular economy [28], aligning with SDG 9 (resilient infrastructure) and SDG 12 (sustainable resource management) [29-32]. This innovation could offer an affordable and eco-friendly alternative for seismic-resistant and thermally efficient buildings in tropical climates.

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doi: 10.14456/easr.2025.45

It is also noted that in the axial compression test Ávila et al. [33] indicates that the optimal percentage is 12% lime, increasing resistance by 40% with a value of 1.63 MPa with respect to the standard rammed earth; while for Robles Rojo [34] the results indicate improvements in axial compression resistance by 35% respectively with respect to the standard adobe with the 10% SCF dose, in the same way Kumar and Barbato [13] carried out tests on axial compression resistance, obtaining that the adobe reinforced with 25% lime increases 40% to the standard adobe made. In effect, the greater the increase in lime as a stabilizer in the adobe, the greater its axial compression resistance of the adobe [4]. In conclusion, the higher the percentages, the greater the compressive strength.

In relation to the compressive strength in piles, Cáceres Vásquez [35], in his study, obtained an optimal percentage of 10% lime as an addition to the adobe, with a stress of 0.58 MPa with a decrease of 5% with respect to the standard sample. Accordingly, Hoyos Sangay [36], in his research, obtained an optimal percentage of 2.5% vegetable fiber, which increased by 20% with respect to the standard sample. In effect, the incorporation of fibers significantly improves the properties of adobe [37]. The incorporation of fibers in adobe piles significantly improves their compressive strength by increasing the cohesion between the material particles and controlling the propagation of cracks under load.

With reference to diagonal compression in walls, Sandoval Alvarado [38] discovered that the adobe reinforced with lime in terms of weight by 10% increased significantly in 15 kg/cm² compared to the standard sample. Similarly, Cardenas Flores and Mantilla Perez [39] indicated that the optimal percentage for the rammed earth walls was 18% lime with a stress of 0.045 MPa and with a 10% improvement with respect to the standard wall. On the other hand, Chambilla Choquecota and Limachi Condori [40], showed that reinforcing the adobe with 1.0% barley fiber improves the diagonal compression in walls by 0.89 kg/cm^2 compared to the standard sample. In fact, lime and fibers significantly improve the properties of the adobe [40]. Therefore, the use of fiber increases resistance and controls the propagation of cracks as it provides greater ductility, which allows energy to be absorbed and dissipated better, especially in seismic zones.

Regarding flexural strength, Kumar and Barbato [13], found that the rammed earth reinforced with 0.5% SCF by weight of soil significantly increased the flexural strength by 14.95 kg/cm^2 compared to the standard sample. Hence, Rocca Villalobos [41], pointed out that when the rammed earth reinforced with 0.35% SCF, an increase of 6.05 kg/cm^2 was observed with respect to the initial sample. In contrast, Samame Guerrero [42], showed that the rammed earth reinforced with 10% of fibers showed improvements in the rammed earth by 10.93 kg/cm² compared to the standard sample. In effect, the increase in flexural strength with fibers significantly improves which helps to improve its behavior against lateral or bending loads [13]. Thus, the appearance of cracks is reduced and the material can withstand greater deformations, improving its performance under loads.

As regards capillary absorption, Rocca Villalobos [41], in his research the results showed significant improvements in absorption with 0.18% with a dose of 0.35% of SCF with respect to the standard adobe, Llontop Mejia and Santisteban Olaya [43], pointed out that by reinforcing the adobe with 2% of SCF the absorption is 5% with respect to the initial sample. In contrast, Samame Guerrero [42], showed that the rammed earth reinforced with 10% of fibers showed improvements in the rammed earth by 6.75% compared to the standard sample. In effect, the increase in capillary absorption with fibers significantly improves, which highlights its usefulness in construction applications [42]. Therefore, capillary absorption in mixtures with fibers improves at higher fiber concentrations since it can reduce this absorption by decreasing pore connectivity and improving water resistance.

For the durability analysis as an erosion test, Dalawai et al. [44], obtained that the adobe adding 20% lime by weight of the sample improved by 30% of its resistance to erosion compared to the standard adobe. However, for Sandoval Alvarado [38], in his research indicates that the greatest resistance to erosion is the sample with the addition of 15% lime that presents less cavity. Therefore, Gil-Martín et al. [2], indicated in his research that 30% lime helped to improve by 20% in the erosion of the adobe. Finally, it was obtained that lime as a stabilizer in the adobe improves its durability analysis by a greater percentage, since the greater the amount of lime, the lower the absorption or filtration that the adobe will have.

On the other hand, for the absorption test, Contreras Moreto et al. [45] indicated in their research that the adobe without additions was the most optimal since it managed to resist 24 hours immersed in water. In contrast, Carrillo De La Cruz [46] found that the optimal percentage of sugar cane fiber was 2.5%, improving 26.54% in the absorption test compared to the standard adobe. Consequently, Tisnado Godoy [37] showed that the adobe reinforced with 1% of sugar cane fiber improved by 18% in the absorption test with respect to the standard adobe. In conclusion, the addition of sugar cane provides significant improvements between 10% and 27% in the absorption test.

Currently, it indicates that there is research worldwide on natural fibers in tapiales, whose characteristics vary according to their chemical and physical composition. The knowledge gap is that only tapiales with natural fibers have been made and very little in combination with lime and SCF with different replacement proportions, where drip erosion and simulated flooding are not considered, X-ray fluorescence was also considered to determine the chemical composition of the SCF. Therefore, this study is based on analyzing the durability and mechanical characterization of tapiales by adding lime in 5%, 10%, 15 and 20% and sugar cane fiber in 0.5%, 1%, 1.5% and 2%. In this sense, the use of lime and sugar cane fiber is an interesting alternative since it improves its properties, and makes its application attractive, given that it is essential to use recycled materials from nature for the preparation of mixtures, in order to reduce the accumulation of organic waste.

2. Materials and methods

2.1 Materials

2.1.1 Soil

The soil sample was manually extracted at a depth of 1.50 m in Chiclayo, on the road to Lambayeque, Peru. Figure 1 shows the soil used in this research. The extracted sample was transported in plastic bags to maintain its humidity and avoid contamination. The soil was classified according to ASTM D2487 [47], the liquid and plastic limits, as well as the plasticity index, took ASTM D4318 as a reference [48]. Figure 2 indicates that the amount of material passing through the No. 200 sieve is 48.7%, which classifies it as a clayey sand (SC) according to the Unified Soil Classification System (USCS). Table 1 shows some physical properties of the soil studied.

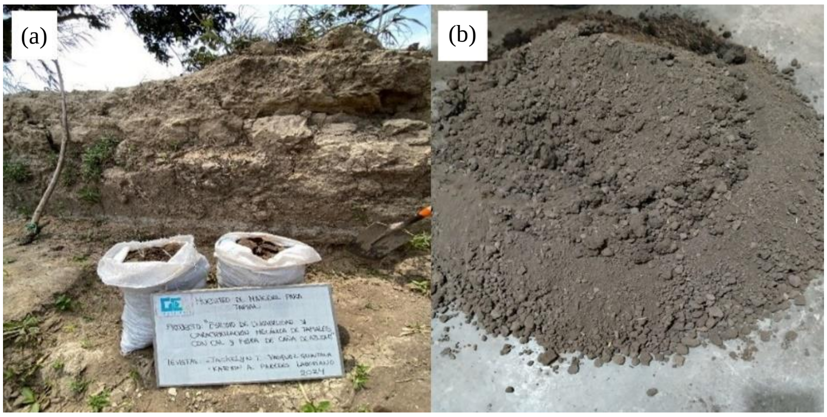

Figure 1 Soil (a) Material extracted from the field (b) Material in the laboratory

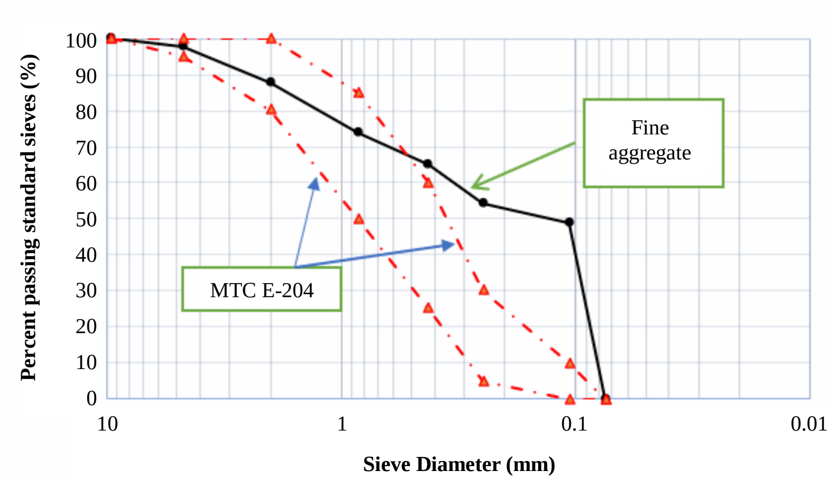

Figure 2 Natural distribution of soil grain size

Table 1 Atterberg limits and humidity tests

Properties	Results	ASTM Standard
Liquid limit (%)	35	ASTM D4318 [48]
Plastic limit (%)	23	ASTM D4318 [48]
Plasticity index (%)	12	ASTM D4318 [48]
Humidity (%)	13	ASTM C566 [49]

2.1.2 Lime

Lime is an essential building material due to its durability, properties antiseptic, insulation capacity and sustainability. Commercial hydrated lime, Topex brand, was used and obtained in 20 kg bags. Table 2 shows the chemical composition expressed as oxides obtained from the X-ray fluorescence test and Figure 3 shows the energy graph of the analysis.

2.1.3 Sugar cane fiber

Sugar cane fiber was obtained from the Pomalca SAA Agroindustrial Company located in the Lambayeque region, Peru, which had a maximum size of 40 mm in length [50]. The material used is shown in Figure 4. Table 3 shows the chemical composition expressed as oxides obtained from the X-ray fluorescence test and Figure 5 shows the energy graph of the analysis.

Table 2 Chemical composition of lime expressed as oxides

Chemical components	Results	Chemical components	Results
SiO_2	36.816	Fe_2O_3	0.353
CaO	28.709	TiO_2	0.185
MgO	20.246	Tb_4O_7	0.094
To_2O_3	11.418	MnO	0.067
K_2O	1.269	SrO	0.051
SO_3	0.778	ZrO_2	0.014

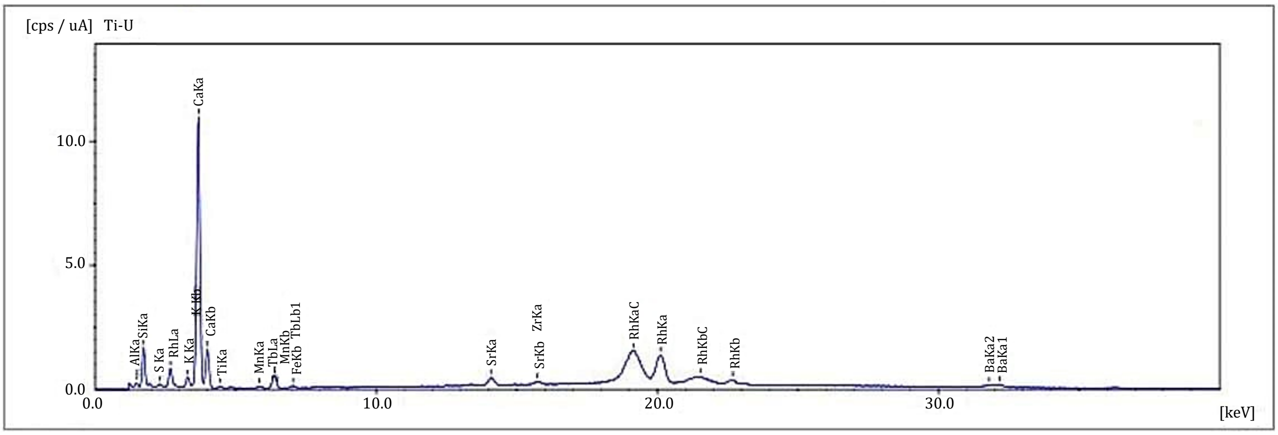

Figure 3 Lime energy analysis chart

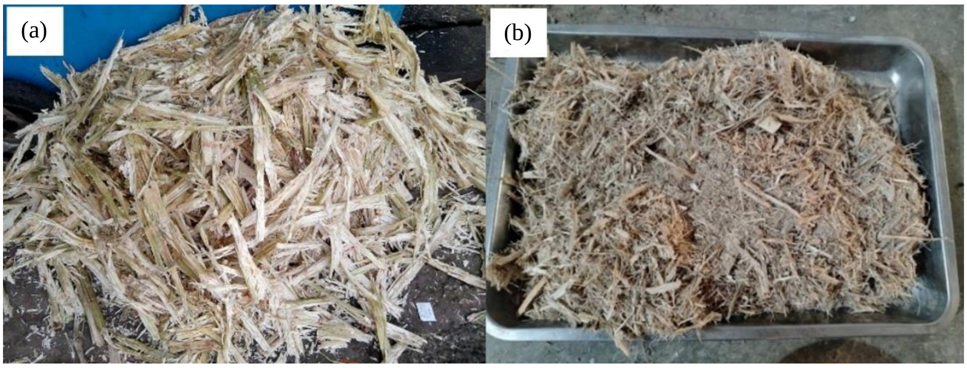

Figure 4 Fiber a) Sugar cane bagasse b) Sugar cane fiber

Table 3 Chemical composition of sugarcane fiber expressed as oxides

Chemical components	Results	Chemical components	Results
SiO_2	46.716	P_2O_5	2.997
K_2O	13.997	TiO_2	0.703
CaO	10.808	MnO	0.239
To_2O_3	8.544	ZnO	0.087
Fe_2O_3	7.098	CuO	0.063
SO_3	4.508	SrO	0.049
MgO	4.163	ZrO_2	0.028

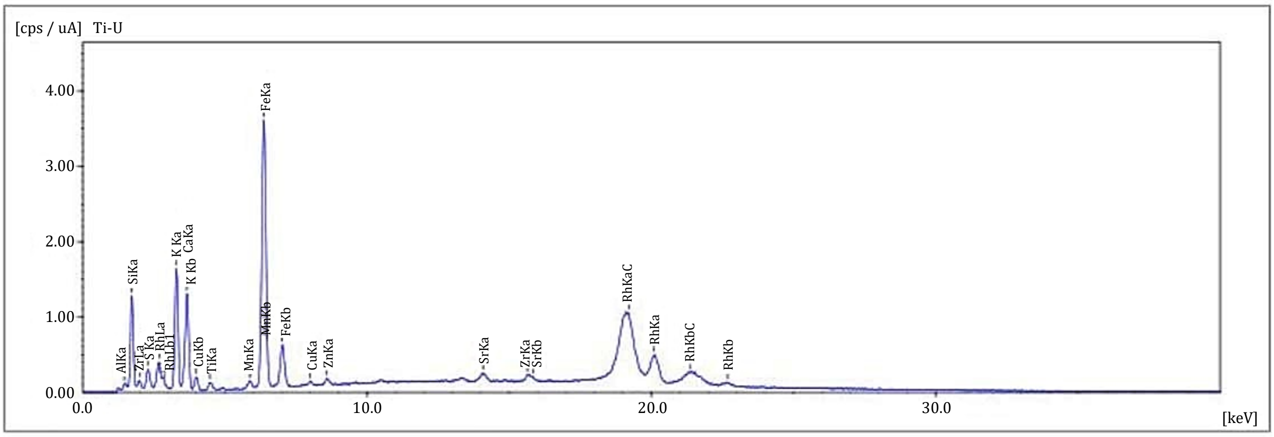

Figure 5 Sugar cane fiber energy analysis chart

2.2 Methods

In this project under study, the population consists of samples of adobe walls made with lime additions of 5%, 10%, 15% and 20%, obtaining an optimal percentage for adding sugar cane fiber at 0.5%, 1%, 1.5% and 2%. In this research the samples are made up of

574 adobe specimens, of which 53 will be sample pattern (SP) made without the addition of sugar cane fiber (SCF) and lime, and 209 samples made with the corresponding lime percentages to find the optimal percentage and 212 samples made with the optimum of lime and sugar cane fiber. Table 4 shows the treatments detailing the proportions of rammed earth materials plus the addition of lime and sugarcane fiber, and Figure 6 shows the flow chart of the process carried out for this research.

Table 4 Sample of tapıal plus addition of lime and sugar cane fiber

Mix label	SP+%Lime+%SCF	Soil (gr)	Water (ml)	Lime (gr)	SCF (gr)
T1	Sample Pattern	5000	3000	-	-
L1	SP+ 5 % Lime	5000	3650	250	-
L2	SP+ 10% Lime	5000	4200	500	-
L3	SP+ 15% Lime	5000	4850	750	-
L4	SP+ 20% Lime	5000	5400	1000	-
T2	15%Lime+0.5% SCF	5000	4850	750	25
T3	15%Lime +1.0% SCF	5000	4850	750	50
T4	15%Lime+1.50% SCF	5000	4850	750	75
T5	15%Lime +2.0% SCF	5000	4850	750	100

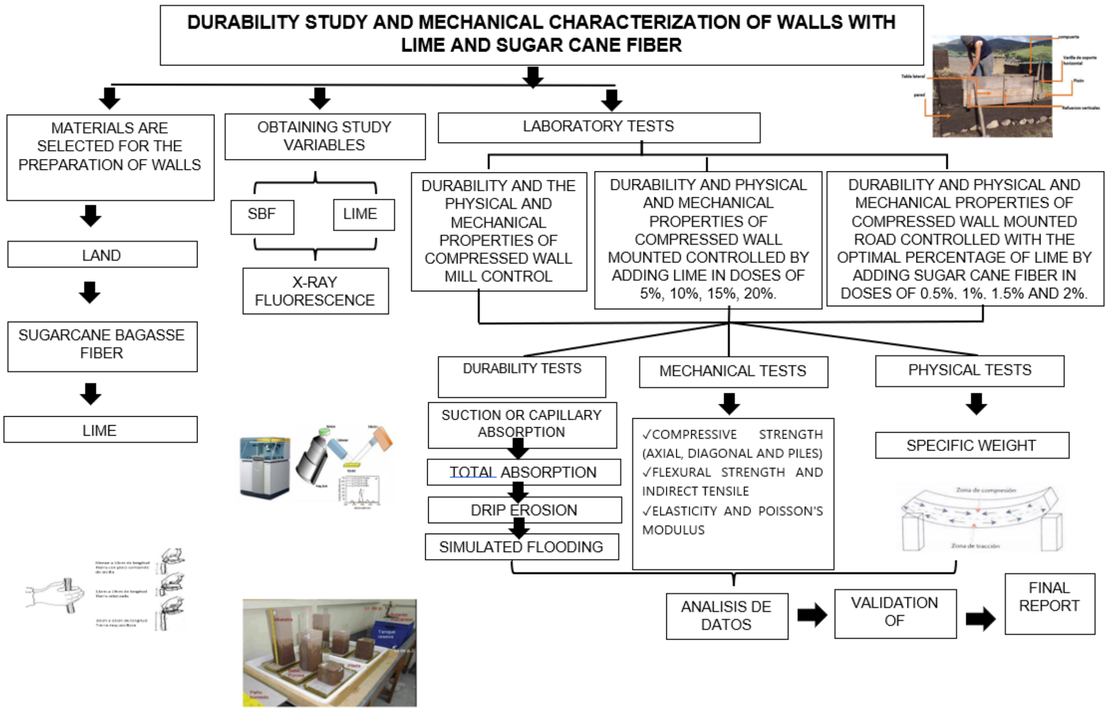

Figure 6 Flowchart of procedures

2.2.1 Resistance to axial compression, in piles, diagonal and flexural

Axial compressive strength, pile compressive strength, diagonal compressive strength, and flexural strength tests were determined according to E.080 [51]. Axial compressive strength determines the ability to resist compressive forces. Pile compressive strength is crucial to understanding how adobe piles respond to vertical loads. Diagonal compressive strength provides insight into a wall's capacity. Flexural strength also determines a block's ability to resist forces that act to bend or curve the material. The execution of these tests is shown in Figure 7.

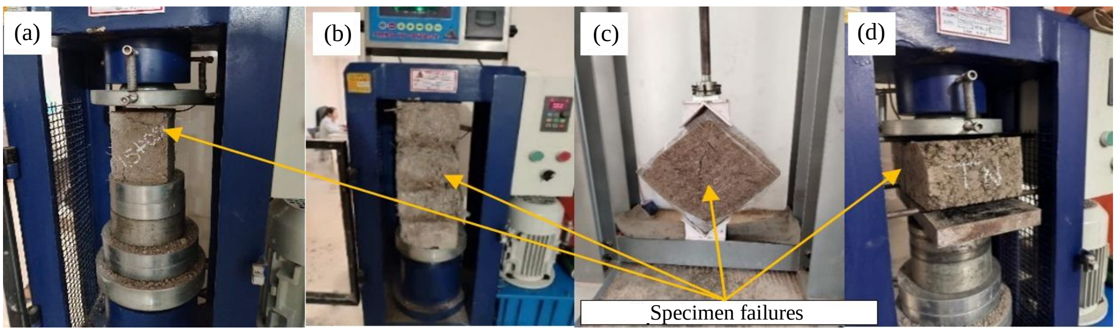

Figure 7 Mechanical tests (a) Axial compressive strength, (b) Compressive strength of piles, (c), Diagonal compressive strength and (d) Flexural strength

2.2.2 Durability features

2.2.2.1 Capillary absorption, total absorption, drip erosion, simulated flooding

The tests were carried out according to the technical standard for adobe construction E.080 [51]. Capillary absorption, total absorption, drip erosion and simulated flooding tests are essential to evaluate the durability of adobe under humid conditions or when exposed to water. All of these tests are shown in Figure 8.

Figure 8 Durability tests (a) Capillary absorption, (b) Total absorption and (c) Drip erosion (d) Simulated flooding

3. Results

3.1 Axial compression strength analysis

Figure 9 shows the sample pattern, which initially showed a strength of 1.16 MPa after 28 days of drying. With the addition of lime, the sample with 15% lime showed the highest strength, increasing by 72% with the value of 2 MPa. Likewise, the combination of 15% lime + 1.5% SCF was used, since its strength was 2.63 MPa with an improvement of 83% with respect to the standard sample. The analysis of variance (ANOVA) showed significant differences between treatments (T1-T5) ($p = 0.012$, $\alpha = 0.05$). Since $p < \alpha$, the null hypothesis is rejected, indicating that at least one treatment significantly influences the response variable. Post-hoc tests are required to identify which

The increase in strength (72% with 15% lime and 83% with 15% lime + 1.5% SCF) is due to chemical stabilization (formation of calcium silicates) and fibrillar reinforcement (SCF), which compact the matrix. The reduction in other dosages could be attributed to excess fiber (porosity) or insufficient lime for complete reactions, showing an optimal balance between components.

3.2 Compressive strength analysis of piles

In Figure 10, the T1 (sample pattern) treatment showed a resistance of 0.60 MPa after 28 days of drying. With the incorporation of lime and SCF in treatment T4 it demonstrated the greatest resistance, since its effort was 0.69 MPa with an improvement of 10.9% with respect to treatment T1. The ANOVA revealed significant differences between the treatments ($p = 0.000 < 0.05$), in addition the Tukey test identified that treatment T4: sample pattern with 15% lime + 1.5% SCF, achieved the best performance, reaching a significantly higher average resistance whose recorded value was 2.73 MPa, higher than the other treatments evaluated.

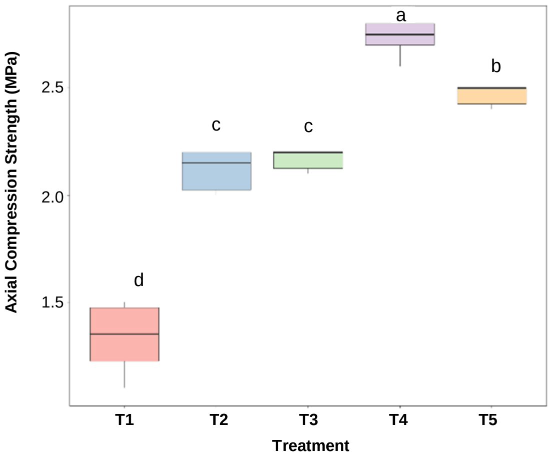

Figure 9 Axial Compression Strength

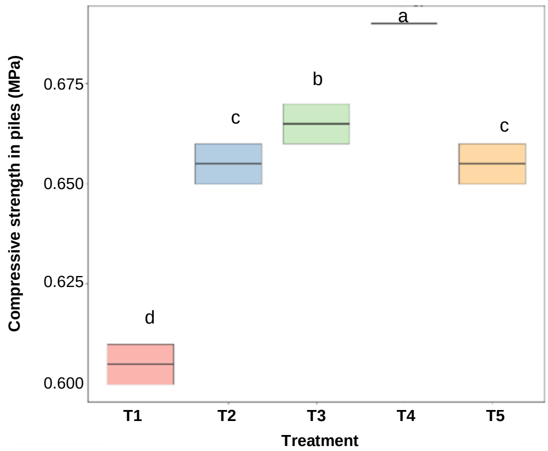

Figure 10 Compressive strength of rammed earth piles and with lime addition

The rammed earth piles failed mainly by diagonal cracking (shear stresses) and crushing (excessive compression). In Figure 10, treatment T4 (lime + SCF) increased its strength by 10.9% (0.69 MPa vs. 0.60 MPa in T1) due to: (1) the pozzolanic reaction of the lime, which densifies the matrix, and (2) the fibrillar reinforcement of the SCF, which redistributes stresses. The reduction in the last treatment is associated with suboptimal doses that generated porosity and lack of cohesion.

3.3 Diagonal compression resistance analysis in low walls

In Figure 11, treatment T1 initially showed a strength of 0.0261 MPa after 28 days of drying. With the incorporation of lime and SCF in treatment T4 it showed the highest strength, since its strength was 0.104 MPa with an improvement of 80% with respect to treatment T1. The ANOVA results did not show significant differences (p = 0.862> 0.05) between treatments, however, treatment T4: sample pattern with 15% lime + 1.5% SCF, presented the highest average strength with a value of 0.11 MPa. The ANOVA results did not show significant differences (p = 0.862> 0.05) between treatments, however, treatment T4: sample pattern with 15% lime + 1.5% SCF, presented the highest average strength with a value of 0.11 MPa.

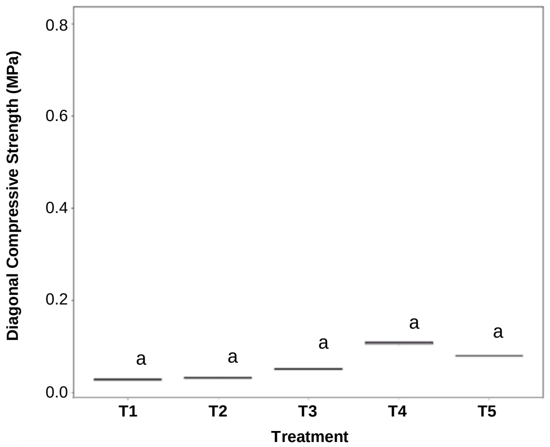

Figure 11 Diagonal compressive strength in low walls

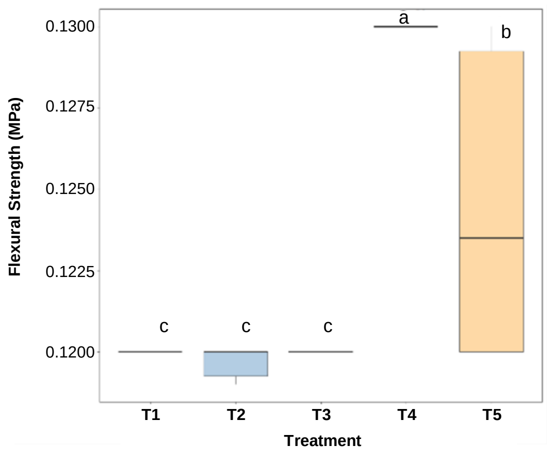

Figure 12 Flexural strength of standard rammed earth with lime addition

Sample T4 (lime + SCF) reached 0.104 MPa (80% more than T1 with 0.0261 MPa) due to: (1) lime, which strengthens the matrix through pozzolanic reactions, and (2) SCF, which redistributes stresses. The predominant failures were diagonal cracking (T1, shear) and localized crushing (T4, more gradual). The lower strength in other treatments was due to imbalances in the proportions, generating weak points.

3.4 Flexural strength analysis

In Figure 12, treatment T1 initially showed a resistance of 0.116 MPa after 28 days of drying. With the addition of lime and SCF, treatment T4 showed the highest resistance, since its strength was 0.129 MPa with an improvement of 10.54% with respect to the standard sample. The ANOVA revealed significant differences (p=0.000<0.05), with treatment T4: sample pattern with 15% lime + 1.5% SCF reaching the highest value of 0.13 MPa.

Treatment T4 (lime + SCF) showed a 10.54% increase in flexural strength (0.129 MPa vs. 0.116 MPa in T1) due to: (1) the formation of cementitious compounds by the lime, which increase cohesion, and (2) the reinforcing effect of the SCF, which improves toughness. The predominant failure mechanism was tensile cracking in the lower zone, although a more ductile behavior with less crack propagation was observed in T4. The reduction in other mixes was associated with inadequate dosage of additives.

3.5 Durability tests: Capillary absorption test, drip erosion, total absorption and simulated flooding

The results in Figure 13 show interesting trends in the durability indicators. Capillary absorption decreases noticeably from 15.72% in T1: sample pattern to 9.48% in T2: sample pattern with 15% lime + 0.5% SCF, showing that the addition of lime and SCF improves the resistance to water penetration by capillarity. Drip erosion also exhibits a favorable reduction, going from 10.10 mm in T1 to 6.78 mm in T5: sample pattern with 15% lime + 2% SCF, indicating greater resistance to water erosion. Regarding the simulated flood, a progressive increase in the resistance time is observed, from 9 hours in T1 to 101 hours in T5, demonstrating that higher contents of lime and SCF significantly improve resistance to prolonged exposure to water.

Total absorption also shows an upward trend, increasing from 2 hours in T1 to a maximum of 14 hours in T4: sample pattern with 15% lime + 1.5% SCF, suggesting an optimization in the matrix densification. These results indicate that the combined incorporation of lime and SCF significantly improves the durability of rammed earth against different water deterioration mechanisms, being particularly effective in increasing resistance to erosion and the exposure time before collapse due to flooding.

4. Discussions

4.1 Mechanical properties

The results align with those reported by Ávila et al. [33], who identified 12% lime as the optimal percentage for enhancing axial resistance, achieving a 40% increase (1.63 MPa) compared to sample pattern. In contrast, Carrillo De La Cruz [46], found that 1% sugarcane fiber (SCF) as an additive yielded the highest performance, with a stress value of 2.80 MPa (a 50% increase over the sample pattern). Similarly, Cáceres Vásquez [35], reported an optimal lime content of 10%, which improved compressive strength by 5% (0.58 MPa) relative to the sample pattern. Conversely, Hoyos Sangay [36], demonstrated that 2.5% vegetable fiber increased strength by 20%.

For diagonal compression, the results correlate with the findings of Cardenas Flores and Mantilla Perez [39], who determined 18% lime as the optimal dosage, resulting in a stress of 0.045 MPa (a 10% improvement over standard walls). In contrast, Chambilla

Choquecota and Limachi Condori [40] observed that 1% barley fiber enhanced diagonal resistance by 40% in low walls. Regarding flexural strength, Cardenas Flores and Mantilla Perez [39], identified 4% lime as the optimal percentage (0.28 MPa), while Kumar and Barbato [13] reported that 1% SCF by weight significantly increased flexural strength to 0.59 MPa compared to the sample pattern.

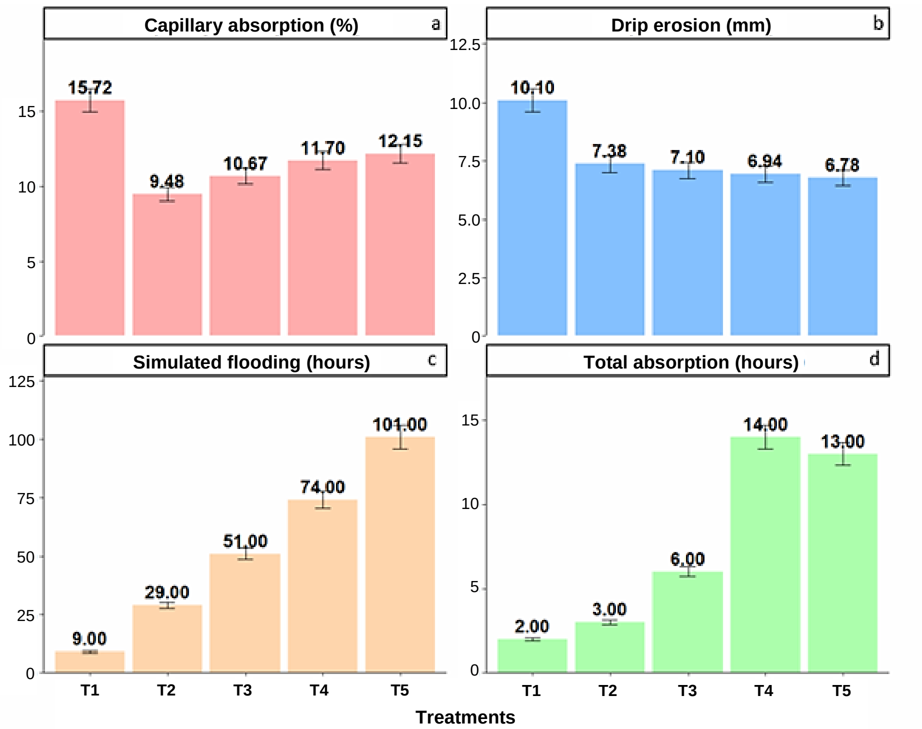

Figure 13 Capillary absorption (a), drip erosion (b), simulated flooding (c), total absorption (d).

4.2 Durability properties

The results are consistent with Rocca Villalobos [41] who noted a 0.18% reduction in water absorption when using 0.35% sugarcane bagasse compared to standard adobe. Sandoval Alvarado [38], found that 15% lime provided the highest erosion resistance, minimizing cavity formation. However, Contreras Moreto et al. [45], concluded that unmodified adobe performed optimally, resisting 24 hours of water immersion. Additionally, Sandoval Alvarado [38], reported that 5% cement stabilization extended the wall's durability, sustaining 18 days in prolonged flooding tests.

5. Conclusions

This study aims to analyze the durability and mechanical properties of rammed earth (tapial) made from lime and sugar cane fiber. Based on the results obtained, the following most relevant findings are highlighted:

The soil under study in this research was classified as SC soil, because the material passing through the sieve in mesh No. 200 is 48.7%, with a liquid limit of 35%, a plastic limit of 23% and a moisture content of 13%.

It was evaluated that the optimal percentage for soil stabilization is 15% lime with respect to the weight of the soil, due to its resistance with respect to the other percentages, and its better performance in the mechanical properties of the modified tapial compared to the traditional tapial. Regarding the resistance to axial compression, piles, walls and bending increased by 72% with the value of 2 MPa, 7% with the value of 0.63 MPa, 12% with the value of 0.0312 MPa and 11.2% with the value of 0.129 MPa respectively, likewise with the resistance to indirect traction was 0.108 MPa with an improvement of 8% with respect to the sample pattern, following the Standard E.080.

It was determined that the optimal dosage is 15% lime + 1.5% SCF since it significantly improves the durability of the wall. In particular, a greater resistance was observed in the total absorption test and simulated flooding, with a duration of 14 hours improving 4% and with a collapse duration of 101 hours with capillarity of 5.4 cm respectively, with respect to the combination of 15% lime + 0.5 SCF, the capillary absorption test showed a lower absorption, 9.6% with respect to the sample pattern, finally the combination of 15% lime + 2% SCF in the drip erosion test, was the most optimal demonstrating a smaller cavity, with a result of 6mm.

The results showed that the addition of lime and sugar cane fiber to the rammed earth improves the durability and mechanical properties of the material, while the use of recycled materials of natural origin reduces organic waste and promotes sustainability in construction.

The use of SCF (Sugar cane fiber) and lime aligns with SDGs 9, 11 and 12, promoting sustainable construction. This solution reduces organic waste, CO_2 emissions and the use of non-renewable materials, integrating circular economy in compacted soil techniques.

6. Acknowledgement

This article was developed thanks to the support of the Universidad Señor de Sipán through the Research course. We thank Eng. Sócrates Muñoz Pérez for having been our constant guide to successfully complete this article.

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