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Variability in Compression Strength of Rammed Earth Walls

Variabilidade na resistência à compressão de paredes em taipa de pilão

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Maria Virgínia Simão Peixoto
ORCID: https://orcid.org/0000-0000-0000-0000
Escola de Arquitetura - UFMG, Brasil
E-mail: ninnaspeixoto@gmail.com
Marco Antônio Penido Rezende
ORCID: https://orcid.org/0000-0001-7896-8669
Escola de Arquitetura - UFMG, Brasil
E-mail: marco.penido.rezende@hotmail.com
Edgar Vladmiro Mantilla Carrasco
ORCID: https://orcid.org/0000-0001-7870-0283
Escola de Arquitetura - UFMG, Brasil
E-mail: marco.penido.rezende@hotmail.com
Rejane Costa Alves
ORCID: https://orcid.org/0000-0003-4059-3974
Departamento de Ciências Florestais e da Madeira – UFES, Brasil
E-mail: rejanealves.ufes@gmail.com
Maria Tereza Gomes Barbosa
ORCID: https://orcid.org/0000-0002-3839-5728
Faculdade de Engenharia – UFJF, Brasil
E-mail: teresa.barbosa@ufjf.br
Eliene Pires Carvalho
ORCID: https://orcid.org/0000-0000-0000-0000
Departamento de Engenharia Civil – CEFET-MG, Brasil
E-mail: eliene@cefetmg.br
White José dos Santos
ORCID: https://orcid.org/0000-0002-7451-3365
Escola de Engenharia – UFMG, Brasil
E-mail: whitejsantos@gmail.com

ABSTRACT

Rammed earth buildings are a crucial component of global cultural heritage. The conservation of these structures requires a detailed understanding of their structural behavior. This study investigates the compressive strength in different regions of a rammed earth prototype, constructed according to historical techniques and materials. During construction, rigorous control of moisture and compaction methodology was maintained. Samples were collected on the same day, ensuring that the integrity of compaction, internal structure, and adjacent components were not compromised. The results revealed significant variability in compressive strength, with no apparent correlation to the location of the samples. Variations in environmental moisture and incomplete homogeneity of layer compaction do not explain these discrepancies. This initial study indicates the need for further research to elucidate the factors contributing to this variability, representing a crucial step towards understanding and preserving rammed earth structures.

Keywords: Rammed Earth; Compressive Strength; Cultural Heritage; Structural Behavior; Moisture Variation.

RESUMO

As edificações em taipa de pilão constituem um componente essencial do patrimônio cultural global. A conservação dessas estruturas exige uma compreensão detalhada de seu comportamento estrutural. Este estudo investiga a resistência à compressão em diferentes regiões de um protótipo de taipa de pilão, construído conforme técnicas e materiais históricos. Durante a construção, foi realizado um controle rigoroso da umidade e da metodologia de compactação. As amostras foram coletadas no mesmo dia, garantindo que a integridade da compactação, a estrutura interna e as peças adjacentes não fossem comprometidas. Os resultados revelaram uma variabilidade significativa na resistência à compressão, sem correlação aparente com a localização das amostras. As variações na umidade ambiental e a não homogeneidade completa da compactação em camadas não explicam essas discrepâncias. Este estudo inicial indica a necessidade de pesquisas adicionais para elucidar os fatores que contribuem para essa variabilidade, representando um passo crucial para a compreensão e preservação das estruturas de taipa de pilão.

Palavras-chave: Taipa de pilão; Resistência à compressão; Patrimônio cultural; Comportamento Estrutural; Variação de umidade.

INTRODUCTION

In the field of science and technology, many significant discoveries have arisen from observations that were not aligned with the initial research objectives (FEYERABEND, 1977). This research is an example of such a phenomenon, as it initially aimed to correlate the velocities of ultrasound waves with the strength of rammed earth constructions, similar to the well-established protocol for reinforced concrete constructions (WHITEHURST, 1966; POPOVICS, 2001; EVANGELISTA, 2002; ABNT NBR 8802, 2019).

Rammed earth is a traditional construction technique that uses compacted layers of earth to form massive and durable walls (EIJK and SOUZA, 2006). Due to the variability of materials and construction methods, accurately assessing the strength of these structures is challenging. Non-destructive methods, such as the use of ultrasound waves, have been widely employed in evaluating reinforced concrete, but their application in rammed earth is still underexplored (BANDEIRA, 2009; PEIXOTO, 2011).

Although the initial tests with test specimens (TEs) were successful, it was not possible to establish significant correlations between the velocities of ultrasonic waves and the strength of the prototypes replicating the dimensions of historical rammed earth walls. However, the results showed a great variation in the stresses of the prototypes, which motivated the development of this study.

MANIATIDIS and WALKER (2008) conducted an experimental study on the behavior of rammed earth under simple, concentric, and eccentric compression loads for structural rammed earth columns. Small-scale compression tests were performed on cylindrical TEs (20 cm in height x 10 cm in diameter), which generally ruptured in the upper third of their height. In square prototypes (30 cm side and 180 cm height), a significant variation in performance was observed compared to the cylindrical TEs, attributed to the variation in material granulometry and the breaking of aggregates during compaction.

BUI and MOREL (2009) concluded that density can vary between different compaction layers, a phenomenon observed in rammed earth buildings. The moisture content also varied, affected by environmental conditions. In the laboratory, they identified two critical issues: determining the moisture content and the compaction energy needed to produce representative samples. Rammed earth is not homogeneous, with density variations along the layer, where the upper part is denser due to higher compaction intensity (BUI *et al*., 2014; JAQUIN *et al*., 2009).

BURROUGHS (2009) quantified the relationship between maximum dry density and simple compressive strength of rammed earth samples, observing that higher densities increase compressive strength. BECKETT *et al*. (2014) investigated changes in the macrostructure of rammed earth walls with compaction, noting that density decreases towards the base of the layer. BUI *et al*. (2009) emphasized the importance of using clayey-sandy soil with gravel, without organic material, prepared with optimum moisture content for effective compaction.

AL-JOKHADAR *et al*. (2024) investigated the relationship between moisture content and compressive strength in rammed earth mixtures in arid climates, showing that strength is directly influenced by moisture content. AVILA *et al*. (2022) reviewed the mechanical and physical properties of stabilized rammed earth, highlighting the importance of stabilization for increasing durability and strength. ARTO *et al.* (2021) analyzed the fracture behavior of rammed earth, observing that the macrostructure influences the propagation of fractures.

KOUTOUS and HILALI (2021) studied the reinforcement of rammed earth with plant fibers, improving tensile and flexural strength. RAAVI and TRIPURA (2020) evaluated blocks of unstabilized and cement-stabilized rammed earth reinforced with fibers, concluding that stabilization with cement and fibers significantly improves mechanical properties. NARLOCH and WOYCIECHOWSKI (2020) investigated the durability of cement-stabilized rammed earth in a humid continental climate, emphasizing the importance of adequate stabilization. KHAN *et al.* (2019) determined the characteristics of rammed earth using non-destructive testing methods, emphasizing the importance of these methods to assess the integrity of constructions. TOUFIGH and KIANFAR (2019) studied the effects of stabilizers on the thermal and mechanical properties of rammed earth under various moisture conditions and their environmental impacts, concluding that stabilizers not only improve mechanical properties but also reduce the material's thermal conductivity. HALLAL *et al.* (2018) found significant correlations between soil granulometry and the strength of compacted material. ADEGUN and ADEDEJI (2017) reviewed the economic and environmental benefits of earth materials for housing in Africa, highlighting their favorable thermal and acoustic properties.

While the literature points to the variability of stresses in rammed earth walls due to variations in moisture and compaction across different layers, no existing study specifically addressed measuring stresses at different points in rammed earth walls, an important gap for a complete understanding of the structural behavior of this material.

Therefore, the present study aims to fill this gap by showing, for the first time, the significant variation of stresses at different points in rammed earth walls and discussing their implications for the preservation and improvement of construction techniques with this material.

MATERIALS AND METHODS

The experimental part of the study involved constructing a prototype using techniques and dimensions similar to those of historical walls. Samples were extracted from different regions of the prototype for simple axial compression tests to evaluate the rupture behavior under load.

Prototype Execution

To construct the prototype, historical construction techniques and typical wall dimensions were reproduced, with particular emphasis on the width, which significantly diverges from contemporary practices. The resulting prototype has dimensions of 1.5 m in length, 1.0 m in height, and 0.9 m in thickness. The soil selection was based on a granulometric proportion and a plasticity index recognized for producing high-quality rammed earth constructions, reflecting characteristics frequently observed in historical buildings, considering regional variations. The granulometric analysis, physical indices, and consistency limits of the soil used are described in Table 1.

Table 1 – Soil Characteristics

Granulometry (ABNT) corrected soil (%)	
Clay (d < 0.002 mm)	20.2 %
Silt (0,002 < d < 0.06 mm)	9.2 %
Sand (0,06 < d < 2.0 mm)	63.4 %
Gravel (d > 2.0 mm)	7.2 %
Physical Indices	
Optimal moisture content	14.0 %
Dry density	1.865 g/cm³
Specific gravity of solids	2.659 g/cm³
Consistency Limits	
Liquid limit – LL	26
Plastic limit – PL	16
Plasticity index – PI	10

Source: PEIXOTO, 2017

Formwork Construction and Moisture Control

The formwork (taipal) was made using traditional wooden pieces, replicating historical construction techniques (Figure 1). It comprises caps or sides (sideboards), front (smaller, removable boards), needles (upper locking elements), lower braces (lower locking elements), backs (vertical pieces fixed to the sides of the form passing through the needle and brace holes), and wedges (aid in locking between the backs, needles, and braces).

In constructing the wall, besides the quality of the form, two fundamental aspects were the control of moisture content and compaction. The optimal moisture content was determined at 14% through the Proctor Normal Compaction Test (NBR 7182, 1986). To control this moisture in the field, the rapid pan test was performed for each layer. In this procedure, the soil sample for the layer was distributed into three metal capsules, with weights duly noted using a precision balance of 0.001 g. The minimum stipulated soil weight was 80 g in each capsule. The capsules were placed in a tray with heated sand, supported on a stove, for drying the soil by heat, a process that took 30 to 40 minutes. After reaching room temperature, the capsules with the soil were weighed again. With the recorded weights, the soil moisture content was calculated. Based on the optimal moisture content and the moisture content presented by the soil of each layer, a mathematical equation was developed to correct the moisture content, Equation (1).

Figure 1 - Formwork used in the compaction of the prototype

Source: The authors, 2024

$$A = \frac{Mh * (h_{ót} - X + P)}{(100 + X)} \qquad (1)$$

Where: Mh is the original weight of the wet soil, A is the weight of water to be added, $h_{ót}$ is the optimal moisture content of the soil when compacted with Proctor normal energy, X is the original percentage of water in the soil, and Y is the percentage of water to be added defined for the compaction of the rammed earth wall. This equation ensured that the moisture values of the soil used were close to the determined optimal moisture content.

Regarding compaction, it was performed by the same person using a wooden rammer with a conical base, 9.0 cm in diameter and weighing 4 kg. Two variables were considered: the drop height of the rammer and the number of blows. The drop height of the rammer was set at 40 cm, with 4 blows per area equivalent to the base area of the rammer. The soil layers initially had a height of 15 cm inside the form (taipal) and, after compaction, reached approximately 10 cm in height.

Compression Strength Test

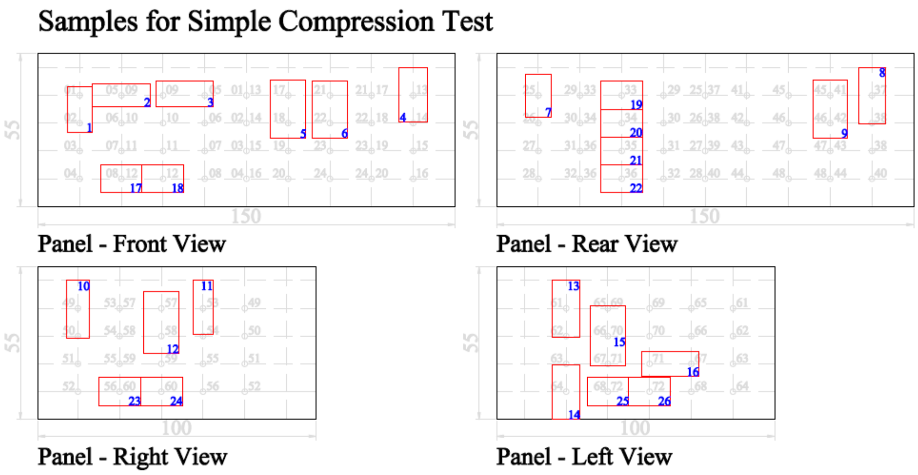
From the prototype, 26 samples in the form of parallelepiped blocks with approximate dimensions of 10 cm (depth) x 20 cm (length) x 30 cm (height) were extracted from the points established in the grid, as shown in Figure 2. The samples were taken from the following positions:

- Samples 1, 2, 3, 4, 5, 6, 17, and 18: front face of the wall.
- Samples 7, 8, 9, 19, 20, 21, and 22: rear face of the wall.

- ➢ Samples 10, 11, 12, 23, and 24: right lateral face.
- ➢ Samples 13, 14, 15, 16, 25, and 26: left lateral face.

The blocks were cut using cutting machines (circular saw with diamond blade) to preserve the original compaction. Figure 3 illustrates this process. These test specimens (ETs) were subjected to axial loading until rupture, using a manually regulated hydraulic press equipped with an intelligent pressure controller, model RFP – 03.

Figure 2 - Location of the prototype samples for compression testing



Source: The authors, 2024

Figures 3 - Sample extraction process from the prototype for compression testing

Source: The authors, 2024

RESULTS AND DISCUSSION

Table 2 presents the results of the compression tests for each sample. The left column lists the sample numbers, while the right column displays the corresponding rupture stress for each one. Descriptive statistics results are also presented.

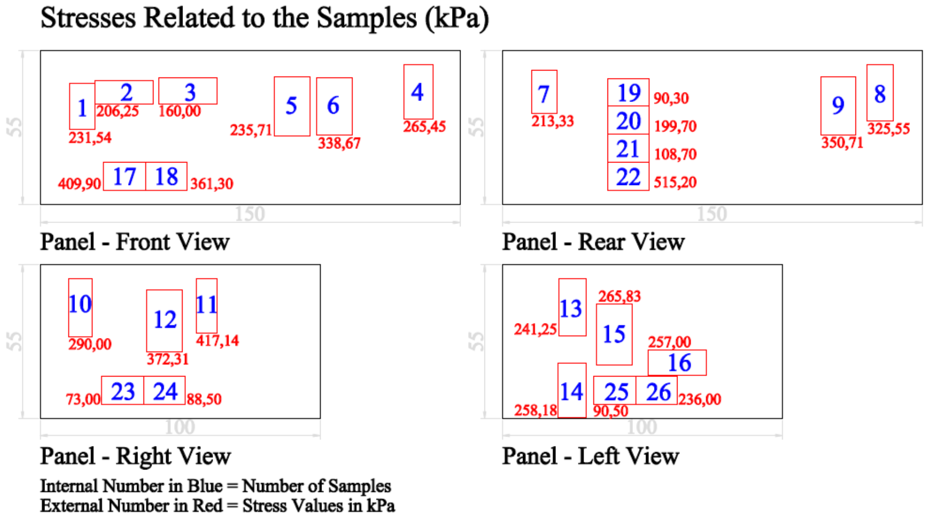
Table 2 – Results of the compression strength tests and descriptive statistics values

Compression strength		**Descriptive statistics result**	
Test Specimen	**Rupture Stres (kPa)**	**Statistical Properties**	**Rupture Stress (kPa)**
1	231	Maximum	515
2	206	Minimum	73
3	160	Mean	254
4	265	Standard Deviation	111
5	236	Variance	12308
6	339		
7	213		
8	326		
9	351		
10	290		
11	417		
12	372		
13	241		
14	258		
15	266		
16	257		
17	410		
18	361		
19	90		
20	200		
21	109		
22	515		
23	73		
24	88		
25	90		
26	236		

Source: The authors, 2024

The maximum and minimum rupture stress values exhibit significant differences, indicating high variability. Additionally, the variance is also high, indicating data dispersion. The samples, besides presenting distinct rupture stress values, do not demonstrate a regular trend in the structural behavior of the wall. The stress values are distributed heterogeneously in different areas of the wall, without a clear concentration of regions with higher or lower resistance, as illustrated in Figure 4 and discussed below.

Figure 4 - Stress Values of Samples Extracted from the Prototype for Compression Testing



Source: The authors, 2024

Initially, it was assumed that the variation in strengths could be attributed to layered compaction and the direction of testing. When the test was conducted in the Z and X directions (perpendicular to compaction), the results differed from those obtained in the Y direction (parallel to compaction). Thus, the test specimens (TEs) were reclassified according to the layers and test directions (Y direction and Z and X directions).

To determine the strength distribution throughout the prototype, the strength in each compacted layer of the wall was considered. Strength was analyzed in the Y direction (compaction direction, i.e., height) and in the X and Y planes (directions perpendicular to compaction, i.e., length and width). The test was conducted in the direction of the greatest dimension, 30 cm. The details of the TEs, including number, layer location, and direction of strength, are presented in Table 3.

Table 3 – Test Specimen details, Including Number, Layer, and Direction of Strength

Strength in Y Direction		Strength in Z and X Directions	
Layer	**TE**	**Layer**	**TE**
1-2	14	1-2	17, 18, 22, 23, 24, 25, 26
3-4	15	2-3	21, 16
3-4-5	5, 6, 9, 12	3-5	1, 20
4-5	4, 8, 10, 11, 13	4-5	2, 3, 7, 19

Source: The authors, 2024

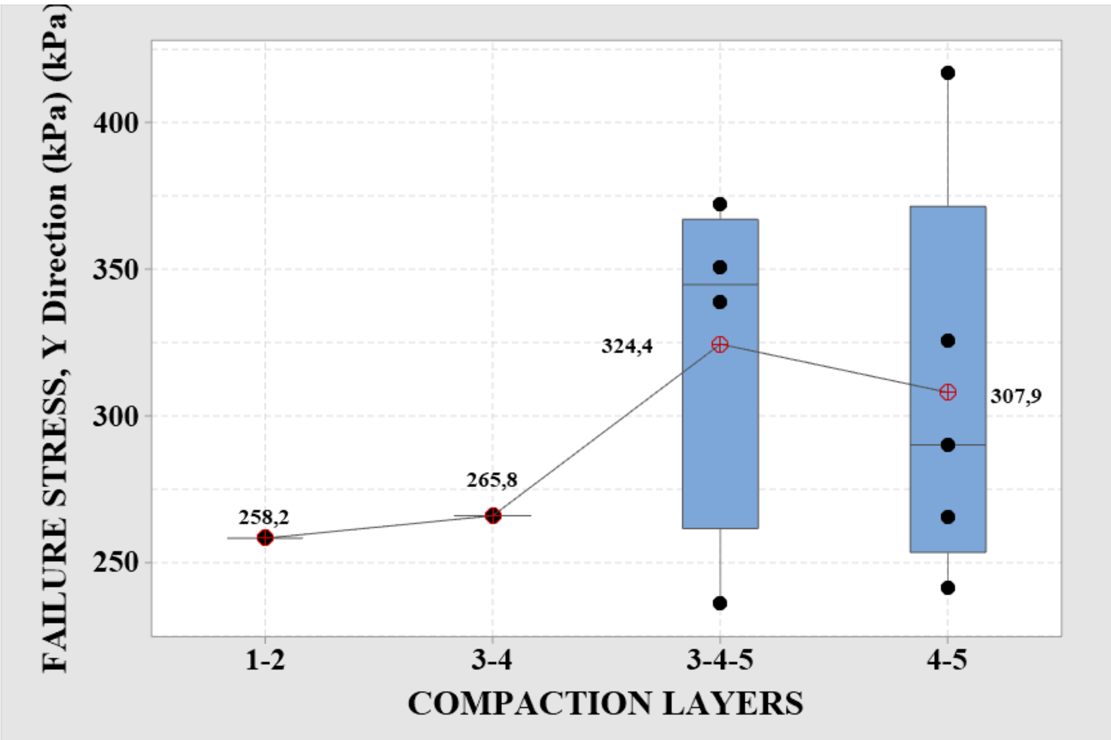
Figure 5 presents the results of the strength tests in the Y direction. A variation in the means for each layer is observed, with considerable dispersion of individual values.

This suggests that layers 1-2 and 2-3 may have had lower compaction density. However, a statistical analysis was conducted using one-way ANOVA (Tukey's test) to verify if there is a statistical difference between the mean rupture stress values in each analyzed layer.

The null hypothesis assumed was that all means are equal, with a significance level of 5%. The result indicates that there is no significant difference between the means, with 95% confidence. Therefore, it can be concluded that the rupture stresses in the Y direction are statistically equal throughout the height of the prototype, with 95% confidence.

However, it is important to note that there is considerable variability in each layer. For example, in layer 3-4-5, values range from 235.7 kPa to 372.3 kPa, and in layer 4-5, they range from 241.3 kPa to 417.1 kPa. Part of this variability can be attributed to fluctuations in the intensity of compaction energy applied by the rammer during the compaction process, as well as variations in relative humidity, which influence the optimal moisture content of the soil. However, the large variation points to the existence of another phenomenon, or even a characteristic of rammed earth walls, to be investigated.

Figure 5 - Rupture Stress in the Y Direction as a Function of Compaction Layers.

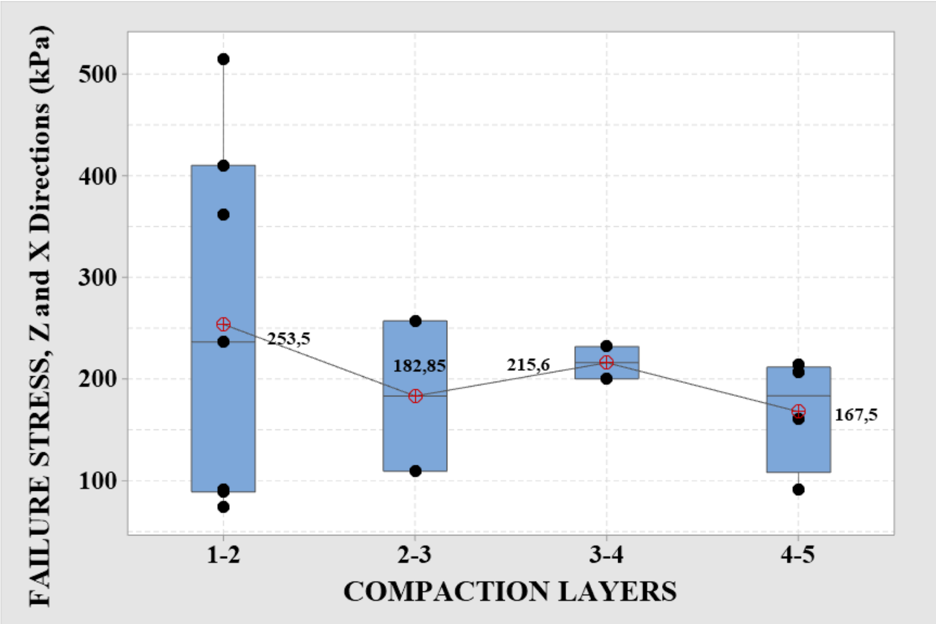


Source: The authors, 2024

Figure 6 presents the results of the strength tests in the Z and X directions. The average rupture stress values are quite similar in all layers. Through ANOVA analysis and Tukey's test, it can be concluded that there is no statistically significant difference between the mean rupture stresses in the Z and X directions in each layer. Therefore, it can be stated that these stresses are statistically equivalent throughout the height of the prototype, with 95% confidence.

Moreover, considerable variability is noted in each layer. Layer 1-2 exhibits the greatest variability, which can be explained by the distance between the person applying the rammer and the layer, in addition to the previously discussed issues.

Figure 6 - Rupture Stress in the Z and X Directions as a Function of Compaction Layers



Source: The authors, 2024

Previous studies (MANIATIDIS and WALKER, 2003; BUI and MOREL, 2009; BURROUGHS, 2008; BECKETT *et al.*, 2014) highlighted the importance of granulometry, moisture content, and compaction energy on the strength of rammed earth. Our observations corroborate these findings, emphasizing the need for strict control of these variables during construction to ensure homogeneity and structural quality of the walls.

Additionally, the literature suggests the influence of the material's macrostructure and microstructure on fracture propagation and durability of constructions (ARTO *et al.*, 2021; AL-JOKHADAR *et al.*, 2024; AVILA *et al.*, 2022). The variability observed in our study may be partially attributed to these characteristics, indicating that improvements in compaction technique and control of environmental conditions could reduce this dispersion.

Material stabilization with additives such as cement and the inclusion of vegetable fibers have also shown promise in improving the mechanical properties of rammed earth (RAAVI and TRIPURA, 2020; KOUTOUS and HILALI, 2021). These methods can be considered for future research and construction practices aimed at increasing the strength and durability of rammed earth constructions.

CONCLUSION

The presented study aimed to investigate the variability of rupture stresses in rammed earth prototypes, focusing on different compaction layers and test directions. While the literature already pointed to issues such as moisture and density variation along the layers, no previous research had sought to directly measure the stresses at different points of the wall.

The results obtained show significant dispersion in rupture stresses, both in the compaction direction (Y) and in the perpendicular directions (X and Z). This variation indicates that the material density is not uniform throughout the height of the wall, possibly due to fluctuations in the intensity of compaction energy and variations in relative humidity during the construction process.

Statistical analysis, using ANOVA and Tukey's test, revealed that despite the observed variations, there are no statistically significant differences in the mean rupture stresses between the layers, both in the Y direction and in the X and Z directions, with 95% confidence. However, the considerable variability within each layer suggests the presence of other factors influencing the material's strength that require further investigation.

In summary, this study highlights the complexity and intrinsic variability of rammed earth constructions, emphasizing the importance of rigorous control of compaction and moisture conditions. The findings point to the need for further research to fully understand the factors influencing the strength and durability of this historical material and to develop techniques that ensure the uniformity and quality of rammed earth constructions.

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