PAPERCRETE AS A SUSTAINABLE MATERIAL: OPTIMIZATION OF MECHANICAL AND PHYSICAL PROPERTIES USING STATISTICAL APPROACHES

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ABSTRACT

In a context where sustainability has become a priority, this study explores the potential of papercrete as an environmentally friendly alternative in the construction sector. It is a composite material composed of recycled paper pulp, sand and cement. The aim of the study is to optimise the mechanical and physical properties (density, water absorption capacity, flexural tensile strength, dry compressive strength, wet compressive strength) of papercrete by identifying the most influential factors and the optimum formulation. The factors investigated (with their respective levels) are cement content (0%, 5%, 10%, 15%, 20%), sand content (0%, 10%, 20%, 30%) and compression ratio (1.00, 1.25, 1.50). Using a full factorial design, sixty experimental combinations were carried out. The results were then analysed using the Taguchi method and principal component analysis. It was shown that the mechanical properties of the papercrete and the proportions of the ingredients influenced the performance of the material. The identified optimum formulation of 20% cement, 30% sand and 50% recycled pulp with a compression ratio of 1.50 achieves balanced properties. The resulting papercrete is a high performance solution for sustainable construction. Despite this valuable data, further research, such as thermal characterisation, is required to complete the assessment of the material's performance. By recovering waste paper and reducing cement consumption, papercrete is a promising alternative to meet environmental challenges.

Keywords : *Full factorial design, Taguchi method, Principal Component Analysis, Optimal formulation of papercrete, Waste recovery*

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1. INTRODUCTION

The growing importance of ecological and sustainable building materials is undeniable in the context of environmental crises. Traditional materials, such as clay bricks and concrete, which are effective for structural applications, have significant drawbacks in terms of their environmental impact. Their production is often energy intensive and contributes to a high carbon footprint as well as the accumulation of waste in landfill sites [1]. In response to these challenges, papercrete made from recycled waste paper has emerged as a promising alternative. In addition to reducing the amount of waste sent to landfills, these materials offer interesting properties, such as light weight, thermal insulation, and improved water absorption [2].

The main objective of this study was to assess the influence of variations in the formulation of papercretes on their physical properties such as compressive strength, tensile strength, absorbency, and density. This research also aims to determine whether this material can compete with traditional bricks in terms of performance while offering significant environmental benefits. To achieve these objectives and obtain robust and reliable results, we will use a full factorial design analysis, the Taguchi method, and Principal Component Analysis (PCA).

To study papercrete formulations, the proportions of pulp, sand, and cement in the mixes, as well as the paper and water contents of the pulp, were varied. This allows their effect on the mechanical and physical properties of materials to be assessed [3] [4].

In addition to optimizing the properties of papercrete, this study is part of the research to optimize the productivity of Panorano passive solar stills. A recent study [5] identified wood as the best-performing construction material for stills among the materials studied (wood, normal concrete, acrylic plastic, and polyester). However, to reduce the need for wood and to preserve trees and the environment in general, it is essential to develop a still using materials with properties similar to those of wood. Therefore, by analyzing the properties of papercretes, this study investigated the applicability of this material in the construction of Panorano solar stills.

This study aims to provide valuable data for the adoption of papercretes in the construction industry, highlighting their potential as sustainable, high-performance materials.

2. LITERATURE REVIEW

2.1. Mechanical properties of the papercrete

Although the compressive strength of papercrete is lower than that of conventional bricks [9], it retains some integrity after exposure to extreme temperatures, such as 1000°C [10]. With regard to tensile strength, the data available on papercrete remains limited, but studies on this material suggest that its tensile properties can vary depending on its composition and formulation [2] [6]. However, further studies are required to quantify these differences. In terms of water absorption, papercretes show high rates (up to 89% after 28 days) [6] compared to 10-20% for fired bricks. This difference in absorption may affect the durability of materials in humid environments, which require waterproofing treatments for papercrete [11].

2.2. Pros and cons of papercrete

Using recycled materials, paper bonds offer a number of advantages, including reducing waste, conserving resources, and being a more economical alternative. It also offers specific applications such as lightweight structures, partitions, and temporary structures, where lightness and insulation are priorities. In addition, this material is particularly advantageous in contexts where resources are limited or quick, cost-effective solutions are required [12].

However, papercrete has drawbacks. Its durability can be compromised by its high absorption capacity and low fire resistance, making it less suitable than traditional bricks in certain structural applications [12] [13]. Furthermore, economic analyses have shown that despite the low production costs of papercretes, the costs associated with processing them to improve their durability can offset these initial savings [14].

3. METHODOLOGY

3.1. Paper pulp production

Paper pulp, the main component of papercretes, is made from cellulose waste, such as newspapers, cardboard, or vellum. The production process consists of eight steps [15].

- ***Step 1: Waste pre-treatment***

The waste paper was pre-cut into medium-sized pieces (1 cm²) to reduce the amount of unshredded material and optimize the shredding efficiency. Inadequate pre-treatment, such as 4 cm² pieces, increases the risk of clogging between the shredder rotor and the stator.

- ***Step 2: Shredding and homogenization***

Shredding was carried out in a water mixture with a ratio of 21 L for 1 kg of paper. A T30 blade was used to minimize the energy consumption while ensuring optimum pulp homogeneity. This process produces a uniform pulp, which is essential for the subsequent stages.

- ***Step 3: Formulation and preparation of blends***

The basic composition of the paper is as follows: 60% pulp, 30% sand, and 10% cement (CEMII/AP-32.5 UT PM). This ratio was studied and varied to optimize the material properties. This flexibility in the formulation implies that a wide range of mechanical properties can be explored.

- ***Step 4: Materials selection***

It is important to determine the characteristics of the materials used to ensure the reproducibility and quality of papercrete.

- Sand: A particle size analysis was carried out to ensure an optimum ratio between fine and coarse sand to achieve a fineness modulus of 2.5. This ensured a good cohesion in the mix.

Cement: The cement used is a standard product in the local market, offering good mechanical performance and increased availability. This choice ensures that the cement satisfies the quality standards required for construction applications.

- ***Step 5: Mixing the ingredients***

The ingredients were homogeneously mixed without the addition of additional water. The initial water content of the pulp (43.5% of the total mass) was considered to be sufficient to facilitate mixing and formation. This mixing process is critical for ensuring a uniform distribution of materials.

- ***Step 6: Moulding and pressing***

The papercrete was molded in standard-size molds (230 mm × 200 mm × 100 mm) to produce self-locking bricks. Three compression levels were tested:

- 1.0: Natural filling with no additional compression;
- 1.25: compression with 25% excess mass;
- 1.5: compression with 50% excess mass.

These variations can be used to assess the effects of density on the mechanical and physical properties of a material. They provide information on how compression affects strength and durability.

- ***Step 7: Stabilisation***

Some water was lost during the compression process to ensure a stable and reproducible mass for each sample. This step was essential to ensure the consistency of the samples throughout the experiment.

- ***Step 8: Sample Drying***

The samples were air-dried in a covered environment for a minimum of 28 d. This natural drying process ensures that the cement sets completely and avoids cracking caused by rapid drying. Appropriate drying is essential to achieve the desired mechanical properties.

3.2. Experimental design: Full factorial design

Two-level full factorial designs (2^n) are widely used to study and optimize material formulations. They provided a comprehensive analysis of the factors influencing the mechanical, physical, and environmental performance. In this study, factorial design allows for

- Analysis of main effects of different proportions of cement, sand, and paper on properties of paper concrete.
- Use modelling to identify optimal formulations for specific applications.
- Explore the full factorial space to obtain robust results.

However, its main drawback is that an exponential number of tests is required as the number of factors increases.

A full factorial design was designed to include all possible combinations of the parameters under investigation. The factors and their levels are defined as follows:

- Cement content: 0%, 5%, 10%, 15%, 20%.
- Sand content: 0%, 10%, 20%, 30%.
- Compression ratio: 1.0, 1.25, 1.5.

Sixty experimental combinations were performed to fully investigate the effects of these factors and their interactions. This design makes it possible to analyze the individual and combined effects of the variables on the properties of papercretes.

3.3. Analysis of results

The mechanical and physical properties (compressive strength, density, and water absorption) of the samples were measured for each combination. The data were then entered into Minitab software for in-depth analysis using two complementary approaches:

- Taguchi method: This is a statistical approach used to optimize processes by identifying the most influential factors while minimizing variation. It is based on orthogonal experimental designs, allowing the impact of multiple parameters on a given response to be evaluated effectively. By calculating the signal-to-noise ratios, this method measures the robustness of a system and helps maximize the desired performance despite external variations [16]. Widely used in engineering, optimization is simplified by quickly identifying the optimal configurations while reducing the cost and effort of experimentation. In our case, it minimized the variability and maximized the overall performance of the material by identifying the optimal configurations for the formulations [17].

- Principal Component Analysis (PCA): PCA is a statistical method. This reduces the dimensionality of the data while retaining the essential information. It transforms correlated variables into new independent variables called principal components [18]. These components explain the variance in the data in a decreasing order of importance. PCA facilitates the visualization and interpretation of complex data by identifying the most significant axes. In this study, it was used to explore the correlations between the formulation parameters and the physical properties of papercrete. This multivariate method makes it possible to group similar formulations, visualize overall trends, and understand the complex relationships between factors and material properties [19].

3.4. Characterisation of samples

The samples were subjected to a number of laboratory tests to assess their properties:

- Density: Determined for each formulation to quantify density, which is essential for assessing structural performance.
- Mechanical strength: The compressive strength and flexural tensile strength were used to assess the ability of the material to withstand loads.
- Water absorption capacity: measured to assess porosity and durability in the face of moisture cycles, which is crucial for applications in humid environments.

These properties are the answers studied in this research; they define the performance of the papercrete and will be the subject of optimization.

4. RESULTS

4.1. Principal Component Analysis Results

Principal Component Analysis (PCA) is a method for simplifying and identifying the essential parameters that influence the mechanical properties of papercretes. This reduces the dimensionality of the data while retaining the essential information. This allows the relationships between the variables measured on the paper concrete material (cement, sand, compression ratio, density, dry compression, water absorption capacity, flexural tension, and wet compression) to be examined. Table 1 lists the eigenvalues of the principal components.

Table -1: Eigenvalues of principal components

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Eigenvalue	5.034	1.453	1.071	0.247	0.120	0.049	0.019	0.007
Proportion	0.629	0.182	0.134	0.031	0.015	0.006	0.002	0.001
Cumulative	0.629	0.811	0.945	0.976	0.991	0.997	0.999	1.000

Eigenvalues indicate the amount of variance explained by each principal component (PC). According to Table 1, the first principal component (PC1) explains 62.9% of the total variance. The second principal component (PC2) added 18.2%, resulting in a total of 81.1%. The third principal component (PC3) explained 13.4% of the variance, resulting in a total of 94.5%. The last five components explain a very small proportion of the variance (< 5%). This means that only the first three principal components (PC1, PC2, and PC3) are significant, as they together explain approximately

94.5% of the total variance. The other components provided little additional information. Table 2 shows the coefficients of the eigenvectors (or loadings), which indicate the extent to which each variable contributes to the principal component.

Table -2: Contribution of variables to the principal components (Eigenvectors)

Variable	**PC1**	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**	**PC8**
Cement	0.294	-0.018	0.710	-0.089	0.384	0.090	0.336	-0.363
Sand	0.233	-0.574	-0.476	0.025	0.016	-0.179	0.201	-0.562
Compression ratio	0.229	0.589	-0.443	-0.111	0.128	0.531	0.199	-0.231
Density	0.410	-0.279	-0.134	0.198	0.223	0.153	0.403	0.680
Dry compressive strength	0.421	0.099	-0.015	0.535	0.327	-0.070	-0.638	-0.086
Water absorption capacity	-0.387	0.307	-0.089	0.580	0.228	-0.387	0.451	-0.082
flexural tensile strength	0.385	0.338	-0.112	-0.450	0.082	-0.706	0.034	0.129
Wet compressive strength	0.404	0.162	0.183	0.339	-0.788	-0.044	0.183	-0.081

The variables with high coefficients for PC1 were the dry compressive strength (0.421), wet compressive strength (0.404), density (0.410), and flexural tensile strength (0.385). This indicates that PC1 was strongly influenced by the mechanical and physical properties of the material (compressive strength, density, and tensile strength).

The variables with high coefficients for PC2 were the compression ratio (0.589), flexural strength (0.338), and water absorption capacity (0.3070). PC2 was then influenced by properties related to deformation and water absorption. This could reflect a balance between the ability of the material to absorb water and its mechanical strength under load.

The variables with high coefficients for PC3 were cement (0.710) and sand (-0.476). This means that PC3 was dominated by the amount of cement and sand in the material. This component appears to capture the effect of the proportion of the constituents on the overall properties.

This PCA shows that the mechanical properties dominate the variability observed in the data (compression, density, and tensile strength), followed by aspects related to water absorption and constituent proportions. This approach allows for a better understanding and optimization of the performance of papercrete.

Figures 1 and 2 show the relationships between the variables and observations in space defined by the first two principal components (PC1 and PC2).

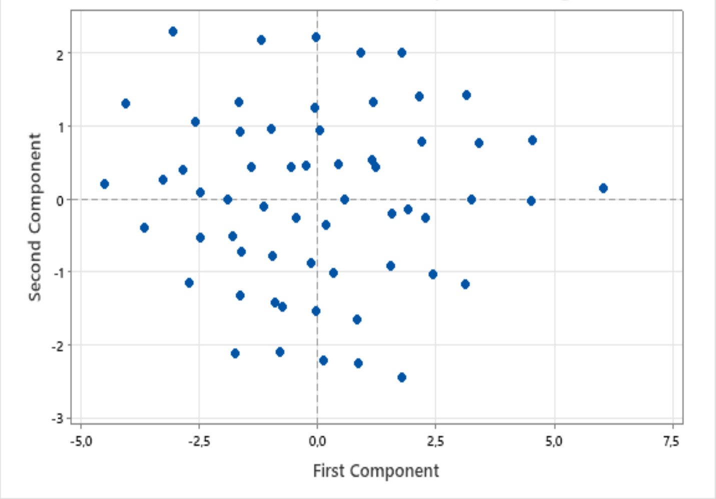

Fig -1: Score Plot

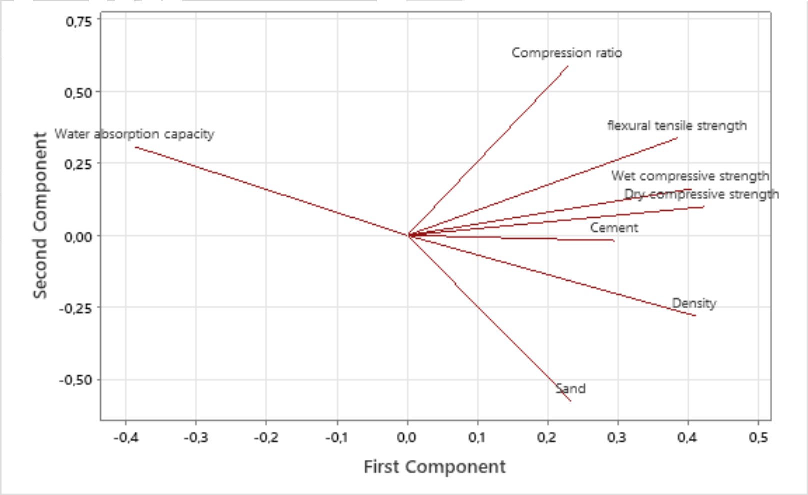

Fig -2: Loading plot

Figure 1 shows the scores of the observations for the first two principal components (PC1 and PC2). Each point corresponded to one observation. The dispersion of the points reflects the variability of the observations in space defined by PC1 and PC2. Observations close to the center are similar to the overall means, whereas those farther away show significant variation. There is no obvious structure (such as clear clusters) in Figure 1, suggesting that the data are not divided into distinct groups in this reduced space. This homogeneous scatter, without clear clusters, indicates continuous variability in the papercrete properties with no obvious subgroups.

The loading plot (Figure 2) shows how the variables contributed to the first two principal components: the horizontal axis (PC1) explained 62.9% of the variance and the vertical axis (PC2) explained 18.2% of the variance.

The dry compression, wet compression, density, and flexural tensile strength variables have close and long vectors in the direction of PC1. This indicates that they are highly correlated and dominate the component. These variables reflect the mechanical and physical properties of the material.

The compression ratio was the variable that contributed the most to PC2, followed by the water absorption capacity. These variables appear to represent aspects related to deformation under stress and interactions with water.

Contradictions were observed between the variables. The vectors for sand and cement were almost opposite, indicating an inverse relationship between these two components in the space defined by PC1 and PC2. The water absorption capacity is oriented in a different direction from the mechanical properties (compression, density, etc.), suggesting a weak correlation or inverse influence.

4.2. Taguchi method results

4.2.1. Density as a function of cement content, sand content and compression ratio

Graphs of the main effects of these factors and their interactions on the S/N ratios of the density are shown in Figures 3 and 4, respectively.

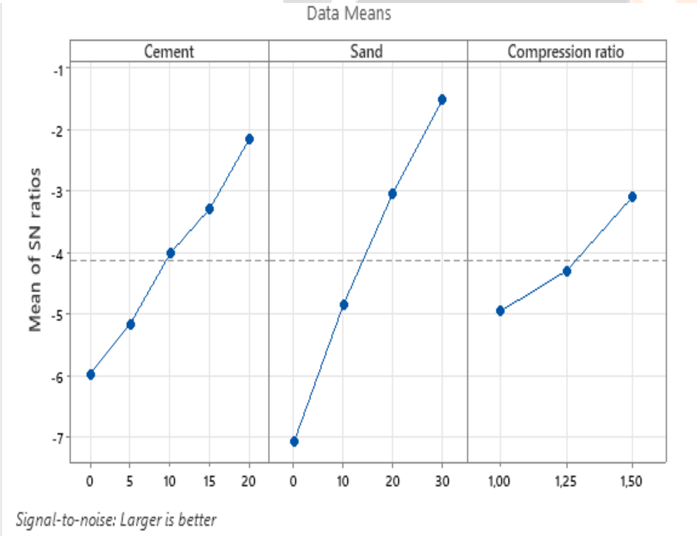

Fig -3: Main effects plot for S/N ratios (Density)

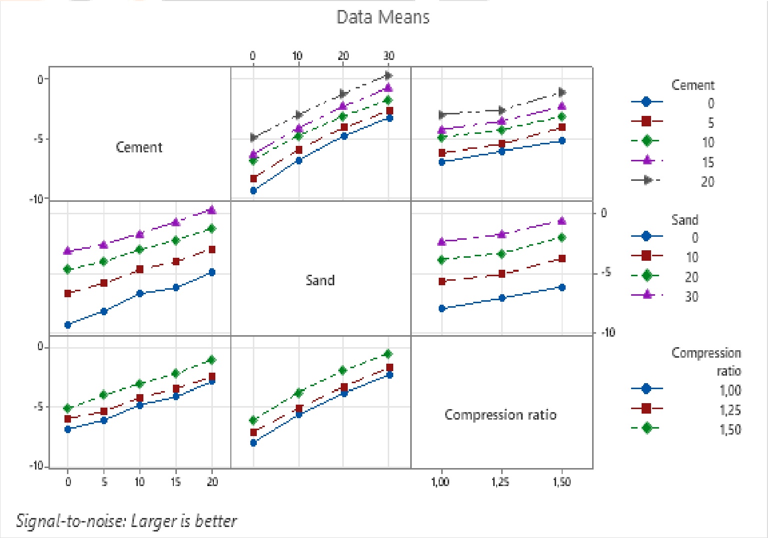

Fig -4: Interaction plot for S/N ratios (Density)

Figure 3 shows that sand has the greatest influence on the S/N ratio, followed by cement and then the compression ratio. For each of these factors, the density was maximized when the highest level was applied, that is, when the sand level was 30%, cement level was 20%, and compression ratio was 1.50.

Figure 4 shows that there was a moderate interaction between cement and sand. At high sand contents (20%), the effect of cement on the SN ratios was amplified, reflecting a synergy between these two factors to maximize density. There was little interaction between the cement and compression ratio (the lines were almost parallel). The interaction between sand and compression ratio is moderate. At high sand content (20%), increasing the compression ratio slightly improved the S/N ratios.

Figures 5 and 6 show plots of the main effects of the factors and their interactions on the density means, respectively.

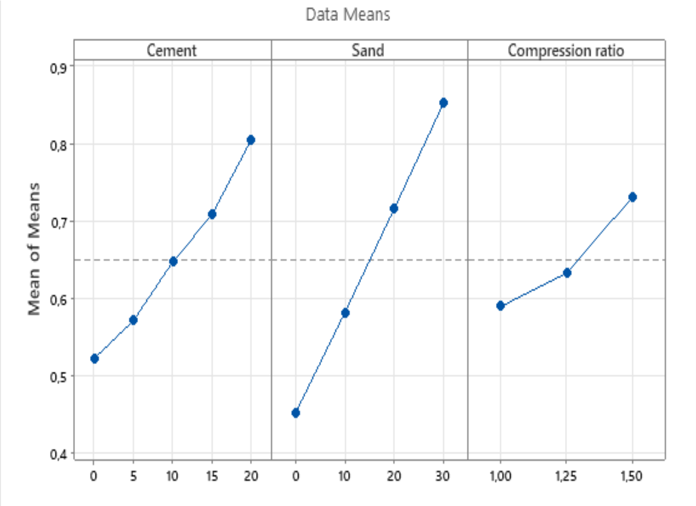

Fig -5: Main effects plot for Means (Density)

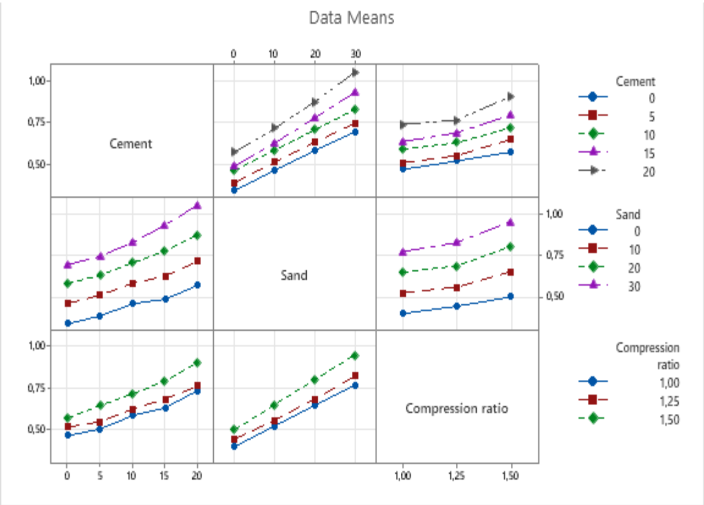

Fig -6: Interaction plot for Means (Density)

Figure 5 clearly shows that sand has the greatest influence on the mean density, with the most favorable level being 30%. Cement was the factor with the second largest effect, with the most favorable level being 20%. The compression ratio was the factor with the smallest effect, but its most favorable level was 1.50.

Regarding the interactions between the factors (Figure 6), the interaction between cement and sand was moderate (the lines were not parallel). At high levels of sand (20%), the effect of cement is amplified, suggesting that these two factors act synergistically to increase density. The relationship between the cement and compression ratio is weak (the lines are almost parallel). The increase in cement content improved the density, regardless of the compression ratio. The relationship between sand and compression ratio was moderate. At high sand content (20%), the effect of the compression ratio increased slightly.

The results of the S/N ratios and means analyses agree on the order of importance of the factors, their respective best levels, and the importance of their interactions.

- Sand is the main factor influencing density (best level: 30%);
- Cement is secondary, but still significant (best level: 20%);
- The compression ratio has a lesser effect, but is also significant (best level: 1.50).
- The cement–sand and sand-compression ratio interactions have a moderate influence on density but remain secondary to the main effects.

4.2.2. Water absorption capacity as a function of cement content, sand content and compression ratio

To maximize the overall performance (durability, dimensional stability, mechanical strength, and longevity) of papercrete, its water absorption capacity should be minimized.

Figure 7 shows the main effects of these factors, while Figure 8 illustrates the interactions between the factors on the S/N ratios of the water absorption capacity. All the graphs in Figure 7 have significant slopes, which means that each factor has a significant effect on the S/N ratio, although the degree of importance varies. Cement appears to be the factor with the most significant effect, and its level minimizing the S/N ratio is 20%. An increase in the cement content seems to reduce water absorption. This was due to the increased density and reduced porosity of the material. Sand is the second most influential factor, with a level of 30%, minimizing the S/N ratio. Poor cohesion between grains increases the water absorption capacity. The compression ratio had a less pronounced but not negligible effect, with the most favorable level being 1.50.

For interactions, Figure 8 shows that the best performance is obtained with high cement and compression ratios, while the sand ratio needs to be optimized to avoid excessive absorption. We also observed that combinations with lower cement or compression ratios exhibited significantly higher absorption, reflecting a less dense pore structure.

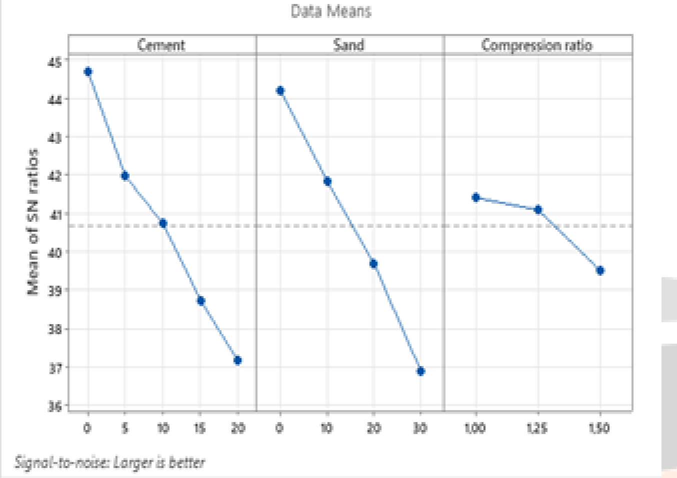

Fig -7: Main effect plot for S/N ratios (Water absorption capacity)

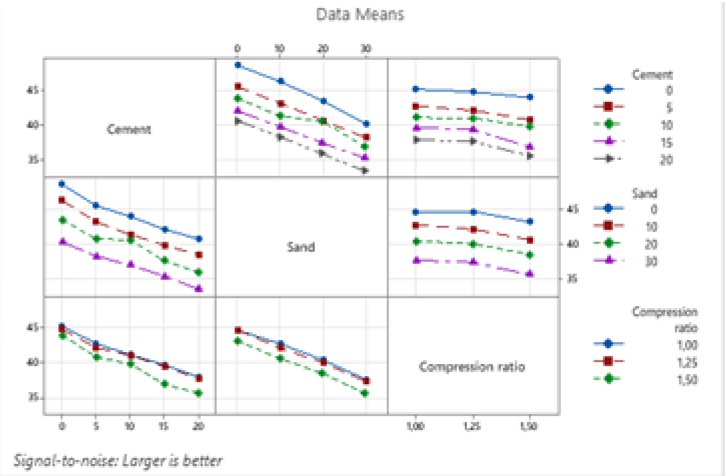

Fig -8: Interaction plot for S/N ratios (Water absorption capacity)

Graphs of the main effects of the factors on the means are shown in Figure 9, and those of the interactions of the factors are shown in Figure 10.

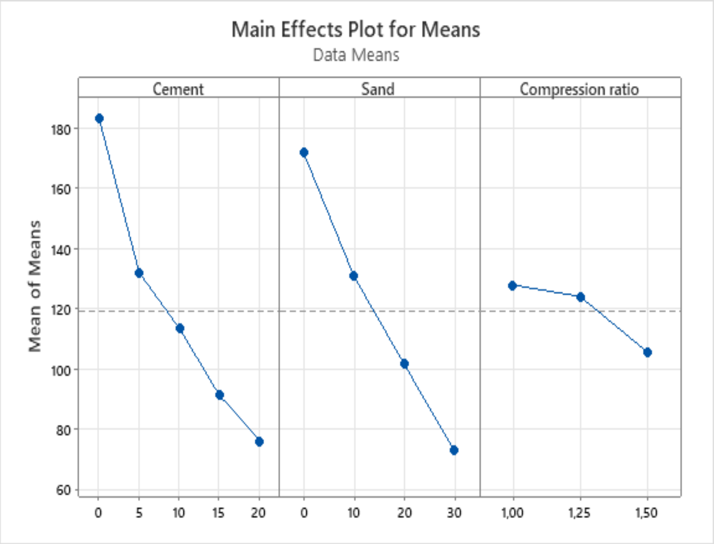

Fig -9: Main effects plot for Means (Water absorption capacity)

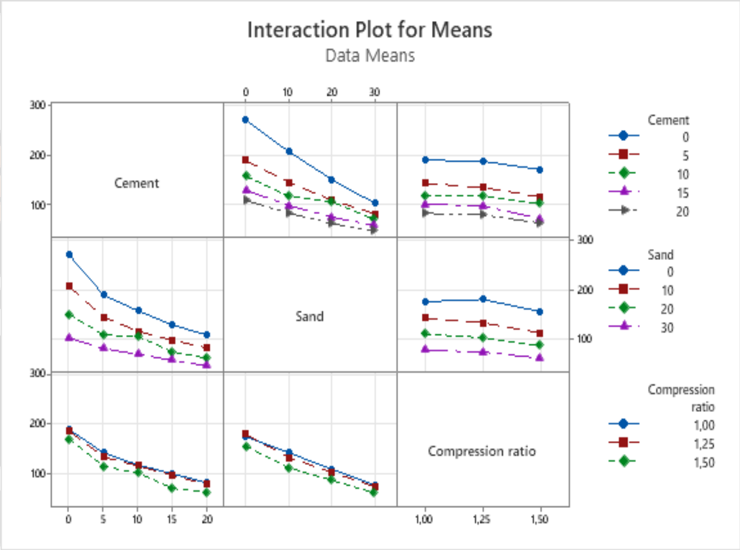

Fig -10: Interaction plot for Means (Water absorption capacity)

As shown in Figure 7, the graphs in Figure 9 show significant slopes, indicating that the influence of these factors on the mean water absorption capacity is significant. The graphs show a decreasing trend, indicating that higher levels of the factors minimize the water absorption capacity and therefore maximize the performance of the papercrete. The factor with the most significant effect was the cement, with an optimum level of 20%. This was followed by sand at an optimum level of 30%. Finally, the compression ratio for which the optimum level is 1.50.

The interactions (Figure 10) between the cement and compression ratios were particularly marked. A combination of both factors seems to minimize the water absorption. The interactions between the sand ratio and the other two factors (cement and compression) are more complex, indicating that the role of sand is highly dependent on the levels of other parameters.

Taguchi's analysis of the water absorption capacity of the papercrete showed that:

- Cement is the dominant factor (best level: 20%);
- Sand has a very significant effect (best level: 30%);
- The compression ratio has a small but significant effect (best level 1.50).

4.2.3. Flexural tensile strength as a function of cement content, sand content and compression ratio

Knowledge of flexural strength is essential to ensure the safety, reliability, and durability of papercrete. This allows the assessment of the mechanical performance of the material in structural applications.

The results of Taguchi's analysis of this response are shown in Figures 11 and 12 for the S/N ratios, and Figures 13 and 14 for the means.

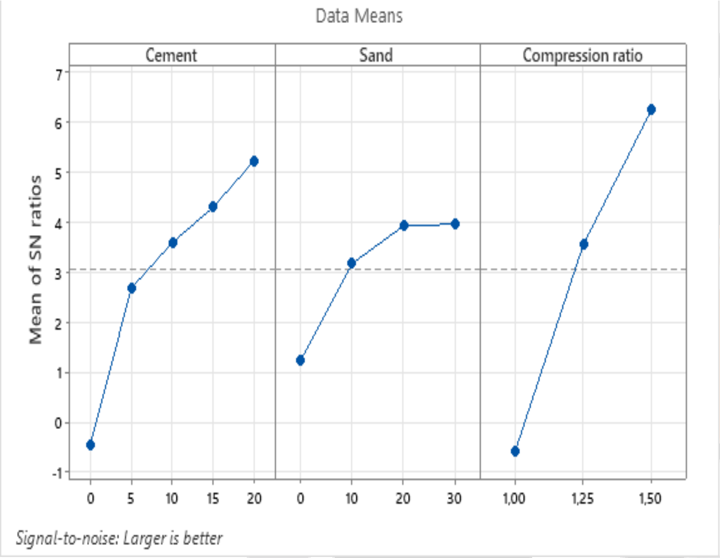

Fig -11: Main effects plot for S/N ratioS (Flexural tensile strength)

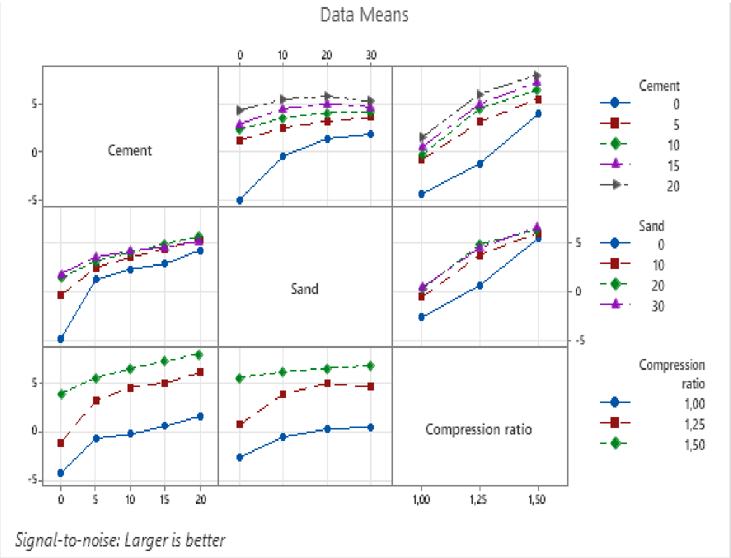

Fig -12: Interaction plot for S/N ratios (Flexural tensile strength)

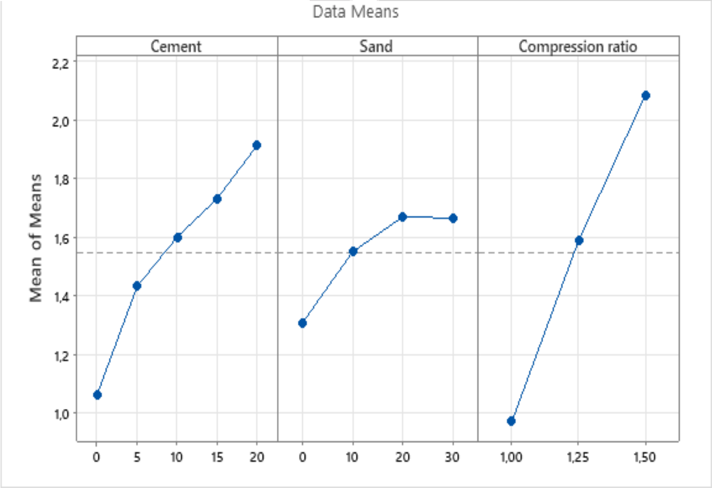

Fig -13: Main effects plot for Means (Flexural tensile strength)

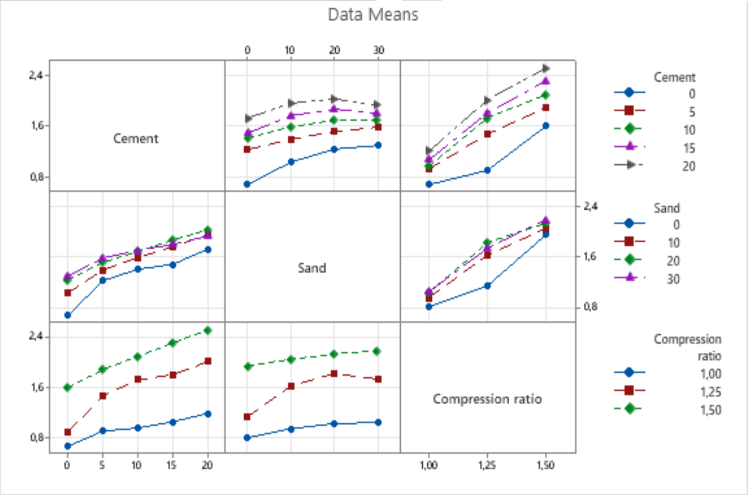

Fig -14: Interaction plot for Means (Flexural tensile strength)

From these figures, it can be observed that the graphs in Figure 11 and 13 are almost similar. These two figures indicate that the dominant factor was the compression ratio. The graphs associated with this factor showed a strong increasing trend. This implies that a high compression ratio (best level: 1.50) increases the flexural tensile strength. The graphs associated with cement are less linear, but their consistent slopes suggest that the effects of this factor on flexural tensile strength are significant. The maximum response rate was 20%. As for the effect of sand, the graphs are complex: they show an increasing trend up to the 20% level and then leveled off. The effect of sand was less marked, but not negligible. At the highest levels (20% and 30%), sand increased the flexural tensile strength.

The graphs in Figure 12 and 14 on the interactions of the factors also show a certain similarity. For the interactions between sand and cement, they showed that an increase in sand had a positive effect on the response; however, this effect was more pronounced when the cement was at high levels. This suggests a moderate interaction between the two factors. The figures also show that the responses (S/N ratios in Figure 12 and the means in Figure 14) increased as the compression ratio increased. However, cement levels influenced this trend: higher cement levels (10%, 15%, and 20%) maximized the effect of the compression ratio. Therefore, there is a significant interaction between the cement and the compression ratio. We also observed that at low levels of sand (0% and 10%), the compression ratio had a more marked impact, signifying the existence of a moderate but non-negligible interaction between these two factors. The strongest interaction appeared to be between the cement and compression ratio, followed by cement and sand.

4.2.4. Dry compressive strength as a function of cement content, sand content and compression ratio

The results of Taguchi's analysis of the dry compressive strength of papercrete are shown in Figures 15 and 16 for the S/N ratios and Figures 17 and 18 for the means.

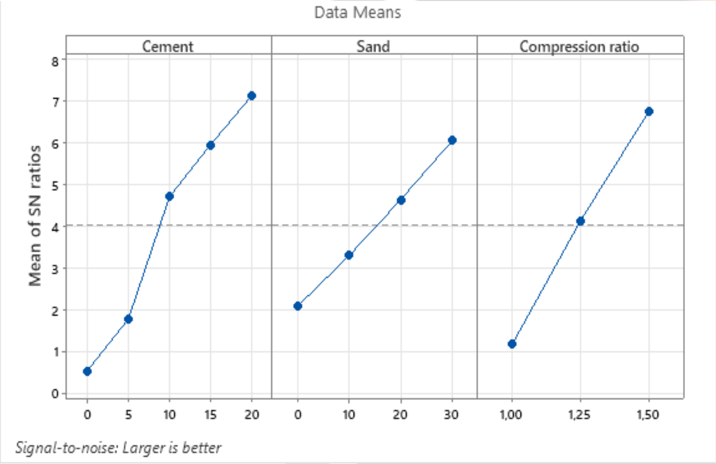

Fig -15: Main effects plot for S/N ratios (Dry compressive strength)

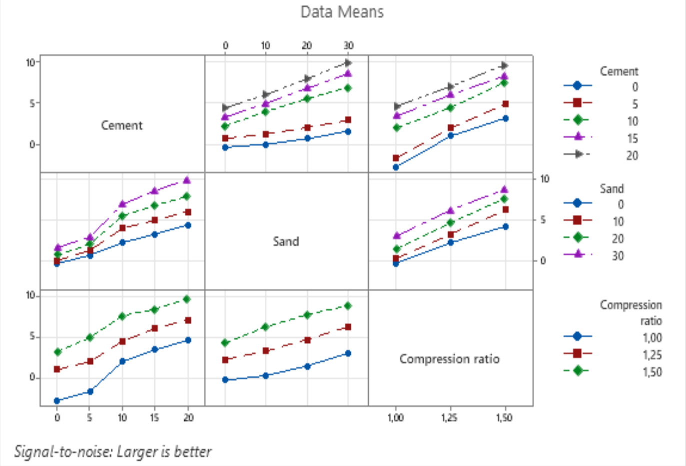

Fig -16: Interaction plot for S/N ratios (Dry compressive strength)

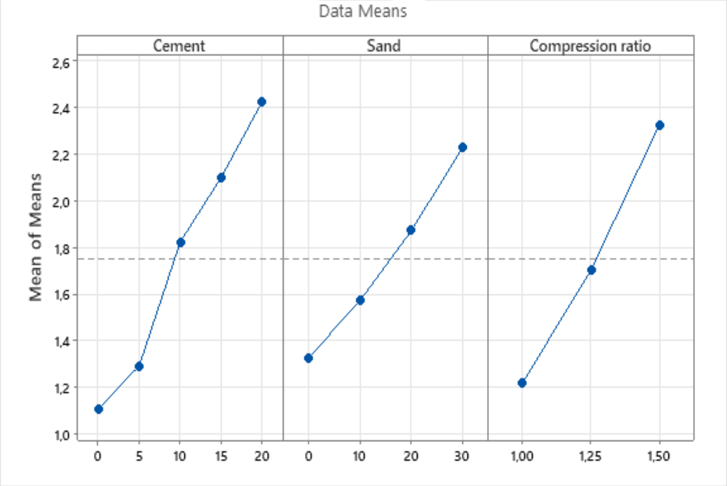

Fig -17: Main effects plot for Means (Dry compressive strength)

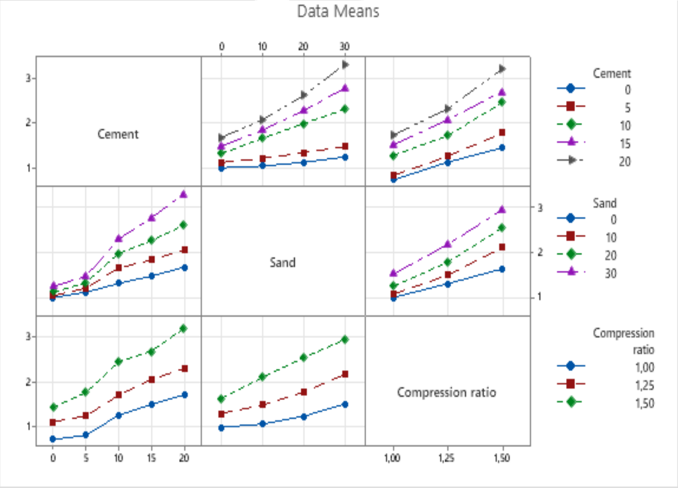

Fig -18: Interaction plot for Means (Dry compressive strength)

These figures reveal consistent results, with similar trends for the S/N ratios (Figures 15 and 16) and data means (Figures 17 and 18). The S/N ratios highlight the variability and interactions between factors more clearly, while the means offer a more direct view of overall performance.

Figures 15 and 17 show the main effects of all three factors have a significant effect on the dry compressive strength. However, the cement appeared to be the most significant factor. Increasing the level of cement (from 0 to 20%) greatly improved the S/N ratios and means. The effect was particularly marked between the 0 and 5% levels. The optimal cement content was 20%. Compression ratio was the second factor with the most significant effect. A gradual increase in the compression ratio (from 1.00 to 1.50) leads to a steady increase in S/N ratios and means, but the effect is slightly less marked than that for cement. The best level for this factor was 1.50. The effect of sand was the third. Increasing the sand content (from 0 to 30%) considerably improved the S/N ratios and means. This effect was linear and marked, and the best level for this factor was 30%.

Figures 16 and 18 illustrate the interactions between these factors. The non-parallel curves indicate an interaction between cement and sand, where an increase in cement amplifies the positive effect of sand on the S/N ratios and means. Similarly, a significant interaction was observed between cement and compression ratio; as cement increased, the beneficial effect of compression ratio on S/N ratios and means was accentuated. Finally, the interaction between sand and the compression ratio was moderate, and the effect of the compression ratio was more pronounced at low sand levels. The strongest interaction was between the cement and compression ratio, followed by the interaction between the cement and sand.

4.2.5. Wet compressive strength as a function of cement content, sand content and compression ratio

Because one of the intended applications for the papercrete in this study is its use as a construction material for the Panorano solar distiller, the analysis of its mechanical behavior in the presence of water is crucial. Figures 19 and 20 show the results of the Taguchi analysis for the S/N ratios, and Figures 20 and 21 show the results for wet compressive strengths.

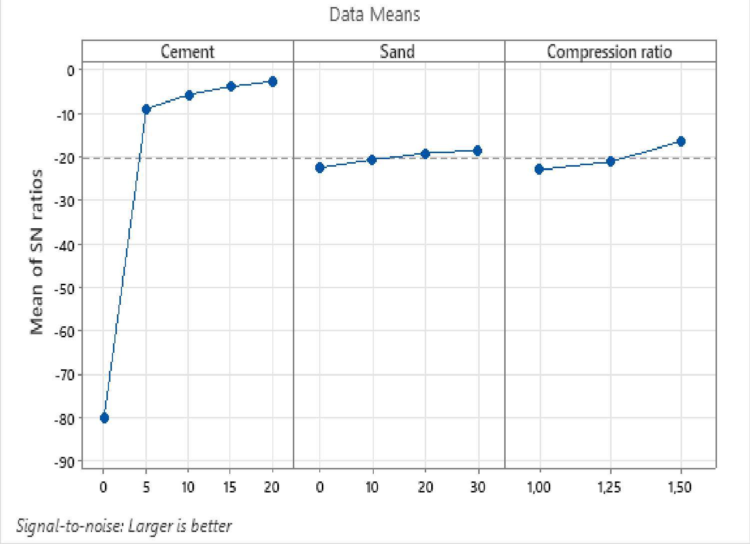

Fig -19: Main effects plot for S/N ratios (Wet compressive strength)

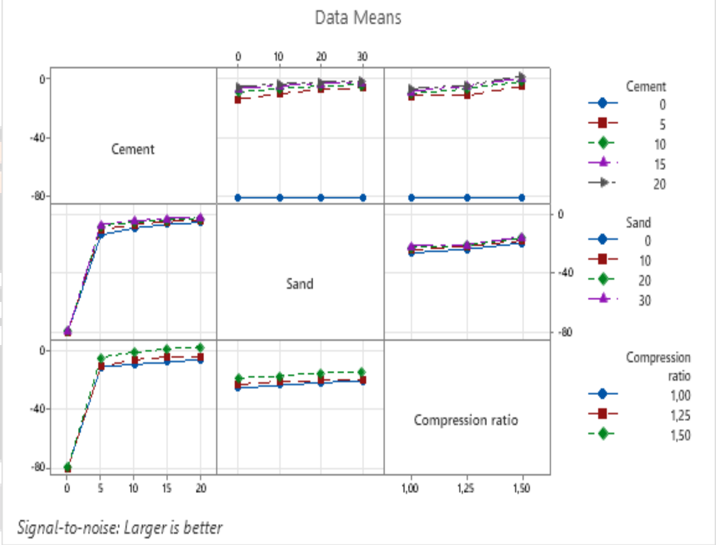

Fig -20: Interaction plot for S/N ratios (Wet compressive strength)

Figure 19 shows that cement had the greatest influence on the S/N ratios of the compressive strength in the wet state. A significant increase in the S/N ratio was observed between 0 and 5% cement. At higher levels, the increase in the S/N ratio was much less marked. The compression ratio (best level: 1.50) and sand (best level: 30%) had a positive influence on the S/N ratio, with lesser, but not negligible, effects.

Figure 20 shows that the three factors studied - cement, sand, and compression ratio–had a significant influence on the S/N ratio, with notable interactions. Cement interacts strongly with sand, particularly at low levels, while the effect of sand varies with the compression ratio, particularly at low sand levels. The interaction between the cement and compression ratio is weaker, but high compression ratios generally increase the S/N ratios. Overall, increasing cement, reducing sand to low levels, and using a high compression ratio appear to improve performance.

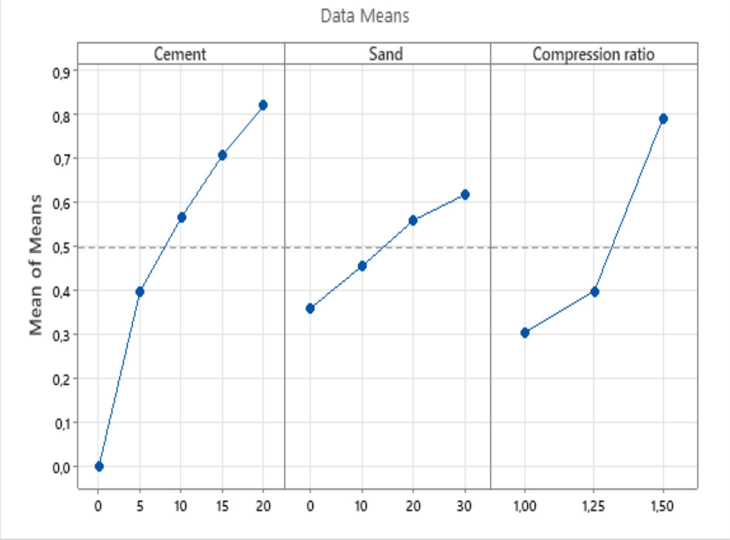

Fig -21: Main effects plot for Means (Wet compressive strength)

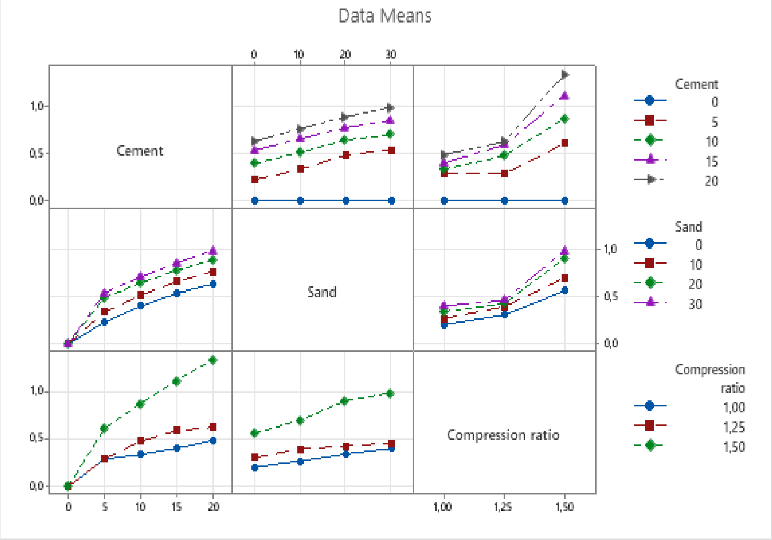

Fig -22: Interaction plot for Means (Wet compressive strength)

Figure 21 shows that the effects of each factor on the means are significant. It can be seen that an increase in cement content appears to have a positive effect on wet compression as the mean increases with cement content. Cement was the dominant factor with an optimum level of 20%. The compression ratio has a significant effect. There is a clear increase in the mean values as the compression ratio increases, with the optimum level for this factor being 1.50. For the sand ratio, the effect was less marked, but a variation in this factor showed a slight tendency to influence the response, with an optimum level of 30%.

Figure 22 shows that the cement and sand ratios exhibit some dependence, but the effect is not strongly nonlinear. The interaction between the cement content and compression ratio is more significant, indicating that the effect of cement depends on the level of compression applied. The interaction between the sand and compression ratios is also notable, although it is less marked. These interactions show that optimizing the performance requires a specific combination of the levels of the three factors.

The results of Taguchi's analysis of compressive strength in the wet state indicate that the cement and compression ratio are the factors that most influence this response. To maximize this response, the highest level of each factor should be applied.

5. DISCUSSIONS

5.1. Application of PCA in the evaluation of parameters influencing papercrete performance

The results confirmed that PCA is a powerful tool for assessing papercrete performance by reducing the dimensionality of the data while preserving most of the information. In this study, the three components accounted for 94.5% of the total variance.

- **Influences of mechanical properties**

The compressive strength, flexural tensile strength, and density make a significant contribution to the first principal component (PC1), highlighting their importance in optimizing the performance of papercrete. In line with previous studies [20] [21], the performance of materials is strongly influenced by their mechanical properties.

- **Influences of water absorption capacity and proportions of ingredients**

Water absorption capacity and ingredient proportions contributed significantly to the second main component (PC2). Badaruzzaman *et al.* (2022) [22] showed that water absorption capacity is a critical variable for materials used in humid environments, such as solar stills (a proposed application for papercrete). This study also stated that, to optimize the performance of the material, its absorption capacity must be reduced to a minimum. In addition, the proportions of sand and cement play an important role by directly influencing the microstructure, porosity, and density of papercrete. An excess of cement can improve homogeneity at the expense of durability, whereas an excess of sand can reduce handleability and cohesion [23]. Optimization of this dimension is essential for maximizing the performance of papercrete.

- **Inverse relationships between factors and properties**

The loading plot (Figure 2) revealed an inverse relationship. The opposite was observed between the cement and sand. This observation is consistent with the work of Amer *et al.* (2020) [24], who showed that increasing sand in a mixture generally reduces the proportion of active cement, which can negatively affect certain mechanical properties while increasing porosity.

An opposition between water absorption capacity and mechanical properties was also observed. This is because of the increased porosity, which promotes absorption but weakens the internal structure of the material. This is confirmed by several studies that have shown that an increased water absorption capacity is often associated with a decrease in the overall density and mechanical performance [25] [26].

5.2. Application of Taguchi analysis in the optimization of papercrete properties

The Taguchi papercrete analysis revealed important information on the effects of cement, sand, and compression ratio on the mechanical properties of the material. This information is valuable for optimizing these properties.

- **Cement**

This study showed that cement content has a significant effect on density and that an increase in cement dosage improves density and strength. This was also observed in studies on mortar and concrete [27]. Cement is the dominant factor in reducing the water absorption capacity of papercrete. An increase in the cement level reduces the porosity by forming a dense and compact matrix that is capable of limiting water infiltration. Cement is essential, as it acts as a binder that fills gaps between particles, thus reducing the number of connected voids within the structure. These observations highlight that optimizing the cement rate is a priority for effectively controlling water absorption capacity. These results are consistent with those of Ayanladun and Oke (2021) [28], who found that water absorption was mainly influenced by the type and proportion of reinforcements used and that matrix-related factors (cement) had a dominant influence. This factor also plays a crucial role in maximizing the flexural tensile strength of the paper by ensuring adhesion between solid particles to form a rigid matrix. A moderate increase in cement content contributed to a better resistance. In fact, a study [29] showed that increasing the percentage of cement increases the compressive strength of the material to a certain limit before decreasing the yields are observed. This is consistent with the dominant role of the cement in this analysis.

- **Sand**

According to our results, sand plays a crucial role in increasing the density of papercrete, as it directly influences its structure and compactness. This increase may be explained by the better filling of voids in the material. This finding is consistent with the results of previous studies. Sing *et al.* (2011) [30] showed that adding 25% sand to cemented mixtures significantly increases the density by acting as a filler and stabilizer. Candra *et al.* (2018) [31] also noted that the use of specific aggregates (such as granite) in geopolymer mixtures optimizes density by reducing voids. Sand also contributes to the reduction of water absorption in papercrete by increasing its overall density. The influence of this factor on the flexural tensile strength was less marked but still relevant. Indeed, sand improves the strength of the material by affecting the granulometry and compactness of papercrete. This is in line with a study on earth-sand-cement mixtures, which found that a moderate proportion of sand improves the compactibility without compromising the adhesion between particles.

- **Compression ratio**

Although significant, the effect of the compression ratio on the density maximization was less than that of sand and cement. This may be explained by its limited role in reducing voids compared with the direct addition of dense materials such as sand or cement. This observation is corroborated by Candra *et al.* (2018) [31], who showed that other parameters, such as aggregate type, have a greater impact on density than mechanical factors such as compression. Its impact on the water absorption capacity is also limited. This is owing to the intrinsic quality of the matrix and the composition of the papercrete. However, it is the factor that has the most significant influence on the flexural tensile strength of papercrete because it directly determines its density and internal cohesion. High compression reduces the voids and improves the interaction between particles, which enhances the ability of the material to withstand tensile and bending forces. These results are consistent with those of other studies that used the Taguchi method to optimize the mechanical properties of composites or cementitious materials. For example, Fazita *et al*. (2021) [32] showed that the particle load had a dominant effect on the mechanical properties, similar to the dominant effect of the compression ratio in this study. In addition, research on compressed materials indicates that an increase in the pressure applied during molding significantly improves the mechanical properties by reducing the porosity [33] [34]. Our results confirmed this observation.

- **Optimization of the papercrete mechanical properties**

Table 3 summarizes the main results of the Taguchi analysis.

Table -3: Summary of the results of the Taguchi analysis

	Cement		Sand		Compression ratio		Interactions
	Rank	Optimal level	Rank	Optimal level	Rank	Optimal level	
Density	2	20 %	1	30 %	3	1,50	Cement – Sand Sand – Compression ratio
Water absorption capacity	1	20 %	2	30 %	3	1,50	Cement – Compression ratio
Flexural tensile strength	2	20 %	3	30 %	1	1,50	Cement – Sand Cement – Compression ratio Sand – Compression ratio
Dry compressive strength	1	20 %	3	30 %	2	1,50	Cement – Sand Cement – Compression ratio Sand – Compression ratio
Wet compressive strength	1	20 %	3	30 %	2	1,50	Cement – Sand Sand – Compression ratio

Table 3 shows that the best respective levels of the factors are their highest levels studied. The analysis also demonstrated interactions between factors, suggesting that simultaneous application of optimal levels of each would optimize the properties of the papercrete. The optimal formulation of the papercrete is therefore: 20% cement, 30% sand, 50% pulp with a compression ratio of 1.50. The optimized papercrete should meet the mechanical needs of buildings while being economical [35].

5.3. Summary of the combined results for optimization

The results of the ACP and Taguchi analyses converge to identify the critical factors and their optimal interactions in optimizing the papercrete performance.

According to CPA, cement plays a major role in influencing the mechanical properties and reducing the water absorption capacity. According to Taguchi's analysis, with an optimal level set at 20%, this factor allows a compact matrix to be formed, and the maximum mechanical properties to be achieved. This factor appeared to be the dominant factor. This dominance is consistent with the study by Shermale *et al*. (2017) [36], which showed that the cement content was the most important factor influencing the papercrete properties.

The PCA showed that sand contributes to the density and overall structure of the material but requires balance with cement. Taguchi's analysis showed that a proportion of 30% optimizes the density while reducing the water absorption without compromising the manageability of the papercrete. The interrelationship between sand and cement percentages in improving the papercrete properties and their respective importance was confirmed by Chung *et al*. (2015) [37].

Finally, the compression ratio improved the internal cohesion and tensile strength. An optimal level of 1.50 maximizes mechanical performance by reducing voids and increasing the overall density of the material. Its influence was less marked than that of the percentage of ingredients, but it was significant.

The combined ACP-Taguchi approach demonstrates the importance of the balance between the mechanical properties, porosity, and papercrete handling. Both methods confirm that optimizing the interactions between cement, sand, and compression is essential to maximize the material performance while ensuring economical and sustainable applications.

6. PERSPECTIVES

This study provides valuable information on the optimization of the mechanical and physical properties of papercrete. This material can be used for many applications, such as house building, interior and exterior decoration, and as a sound insulation material [38]. We aim for another application of papercrete for use as a building material for the Panorano solar distiller pool [39]. To this end, studies on the thermal characterization of the material are still to be conducted and will be the subject of further research.

7. CONCLUSION

This study was conducted in the context where sustainable construction and waste recovery are crucial issues. In response to these challenges, papercrete, which is composed of recycled paper pulp, sand, and cement, is being explored as an environmentally friendly alternative to traditional materials. The main objective was to optimize the mechanical and physical properties of this material while identifying the factors (cement, sand, and compression ratio) that most influence its performance.

The combined analysis of the ACP and Taguchi methods was effective in optimizing these factors. Cement, the main influencing factor, improves density and reduces water absorption, with an optimal level of 20%. The sand optimizes compactness and reduces porosity to an ideal proportion of 30%. A compression ratio of 1,50 ensures better cohesion and maximizes mechanical strength. These parameters interact synergistically to ensure optimal overall performance.

Papercrete is a promising alternative for sustainable construction applications, helping reduce environmental impacts while recovering waste. However, to broaden its field of use, additional studies, including thermal studies, are required.

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