

Effect of Maguey Sawdust and Sugarcane Bagasse Ash on the Physico-Mechanical Properties of Mortar

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ABSTRACT

This study assessed the influence of maguey sawdust (MS) and sugarcane bagasse ash (SCBA) on the physico-mechanical properties of mortar through a 3×3 factorial design with a control group. MS (5–15%) and SCBA (2–6%) were incorporated as partial cement replacements. Results showed statistically significant improvements ($p < 0.001$) across all variables. Bulk density increased to over 2630 kg/m³, while porosity and total water absorption decreased to 9% and below 4.0%, respectively. Mechanically, compressive strength reached a maximum of 21.1 MPa, and bond strength rose to 0.36 MPa both outperforming the control group (17.3 MPa and 0.26 MPa). ANOVA, Tukey, and Dunnett tests confirmed the individual and interactive significance of the additives. The synergistic effect of MS and SCBA enhanced microstructural compactness, reduced voids, and improved the paste–substrate interface without compromising cohesion. These findings support the technical and environmental viability of using MS and SCBA in mortar production, offering a sustainable alternative aligned with Sustainable Development Goals (SDGs 9 and 12). Their implementation contributes to the valorization of agro-industrial residues and to lowering the environmental footprint of the construction sector.

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1. INTRODUCTION

The use of agro-industrial waste in construction materials has become a viable strategy to improve the technical performance of mortar and reduce environmental impacts. In Peru, self-construction and poor mix proportioning affect

the durability of buildings. The incorporation of maguey sawdust (AM) and sugarcane bagasse ash (CBCA) into mortar is presented as an innovative solution, leveraging abundant and underutilized materials. Construction, guided by the principles of the circular economy, evaluates agro-industrial wastes (AM, CBCA) and plant by-

products as partial replacements for Portland cement to maintain or improve the physico-mechanical properties of mortar without compromising its durability or structural strength [1]. Therefore, sugarcane bagasse, a by-product of the sugar industry, generates millions of tons of lignocellulosic waste annually [2]. Its incineration produces CBCA, rich in amorphous silica, which makes it a material with pozzolanic potential [3]. Recent research has shown that CBCA, used as a partial replacement for cement (up to 20%), improves mortar microstructure and its mechanical strength at later ages due to more efficient secondary hydration [4]. However, its impact on mortar workability can be negative, which requires the complementary use of plasticizing admixtures [5]. CBCA can reduce density and improve the thermal insulation of mortar, but inadequate treatment decreases strength; nonetheless, its combination with sawdust has shown synergies in panels at certain mix percentages [6].

Several studies have highlighted that the optimal mixture of these wastes can result in materials with characteristics comparable to international construction standards, as established by ASTM D1037, UNE-EN 196-1, and COVENIN [7]. The joint use of CBCA and plant residues not only promotes the sustainability of the construction process but also significantly reduces the carbon footprint associated with cement production, one of the largest industrial emitters of CO₂ [8]. Moreover, the valorization of agro-industrial waste aligns with the Sustainable Development Goals (SDGs), promoting innovation in infrastructure, sustainable cities, and responsible production [9]. This approach has gained particular relevance in Latin America, where the availability of these by-products is abundant and housing needs demand low-cost, high-efficiency solutions [10].

On the other hand, maguey sawdust contains plant fibers with insulating properties and good adhesion within cementitious matrices, although with adverse effects on workability and early strength if not pre-treated [11]. Multiple investigations are aligned with global sustainability policies, especially in countries with high sugarcane and agave production, such as Mexico, Peru, Brazil, and Colombia [12, 13].

From an international perspective, according to [14], masonry mortar for traditional buildings is prepared so that the addition of calcium oxide and hydrated calcium sulfate can improve quality. Similarly, in Colombia, studies show a lack of resilience and toughness in mortars, which motivates the search for alternative materials [15]. In Ecuador, the research gap regarding mortar proportioning and composition leads to traditional, uncontrolled preparation that is not regulated, resulting in low mortar quality [16]. Furthermore, it should be noted that sugarcane bagasse is an extremely abundant resource that is often available in places where it is not used properly, becoming a mere waste instead of realizing its potential [17]. Likewise, [18] indicates that countries such as Mexico have recognized the limited use of sugarcane bagasse. As stated in [19], the presence of certain components can slow down the setting and hardening of mortar. On another note, there is limited research on the use of maguey sawdust to reinforce mortars in order to improve their tensile strength and toughness [20].

Regarding the description of the national problematic reality, according to [21]—a study carried out in the city of Trujillo—one of the pressing problems is the self-construction of housing, which includes mortar proportioning. This leads to strength problems and efflorescence due to incorrect mix application. Similarly, in Cajamarca, studies by [22] show that the mortars used have low compressive strength and poor adhesion in masonry walls. In Chimbote as well, the limited knowledge of mortar properties undermines strength, durability, and proper proportioning [23]. Additionally, it is important to point out that poor management of maguey waste and sugarcane bagasse ash is a major environmental concern: as [24] states, sugarcane bagasse is produced at a rate of approximately 264 kg per ton of cane processed. Similarly, [25] notes that current, frequent problems with mortars include cracks and fissures due to lack of homogenization, adhesion affected by contaminated surfaces, and deterioration due to adverse weather. According to [26, 27], their research established that the addition of CBCA to mortar substantially improves its physical and mechanical characteristics. As noted in [28], the chemical composition of CBCA varies according to factors such as the soil where cane is grown, specific varieties, age, and applied fertilizers.

Regardless, [29] affirms that CBCA improves mortar strength.

There are multiple investigations related to the use of sugarcane bagasse ash (CBCA). For instance, [30] experimented with mortars mixed at 1:3:0.60 (cement:sand:water) and 0%, 10%, and 20% CBCA as a cement replacement; at 28 days, owing to the pozzolanic activity of the material, compressive strength increased from 20.78 MPa to 23.64 MPa, concluding that CBCA can be used as a supplement in mortar due to its mechanical characteristics. Reference [31] studied three different CBCA biomasses and reported notably higher compressive strengths, with increases of more than 11%, evidencing a moderate influence that improved mortar structure at 28 days. Reference [32] evaluated the use of CBCA as a structural filler or pozzolanic material for producing cement mortars and found that the ashes improved the rheological, mechanical, and durability properties of cement grouts. Reference [33] determined the physical, mechanical, and microstructural properties of binary and ternary cement mortars containing CBCA and showed lower densities, while those containing fly ash exhibited higher densities; furthermore, the use of USBA and fly ash improves mortar properties and performance. In the same vein, [34] determined mortar strength by replacing cement with sugarcane ash (*Saccharum officinarum*) and clam powder (*Semele* sp.); mortars achieved a compressive strength of 397.5 kg/cm² at 7 days, surpassing the control of 371.4 kg/cm² at 28 days, where substituting 15% of cement with CBCA and clam powder increased mortar strength. Additionally, [35] determined the effect of partial cement replacement by CBCA on slump and compressive strength of mortar, where the 5% mix showed the highest slump, but as CBCA increased, strength decreased; agglomeration and fusion were related to specific surface area, specific gravity, and combustion temperature. Reference [36] evaluated the physical-mechanical properties of mortar using CBCA and rice husk; they concluded that incorporating CBCA and rice husk ash (RHA) favorably improves mortar properties. Reference [37] investigated the efficiency of mortar by replacing sugarcane bagasse ash in cement and sand; they concluded that crushed stone waste can completely substitute coarse sand, using less water in the production process. Additionally, [38] determined the influence of CBCA and rice

husk on the compressive strength of modified mortar, concluding that to prepare a mortar, an optimal 7.5% of rice husk ash should be added.

The theoretical basis holds that sugarcane bagasse ash (CBCA)—the product of burning sugarcane bagasse in boilers—is a potentially pozzolanic material; key factors in ash reactivity include the crystallinity of silica and the presence of impurities such as carbon and unburned material [39]. Researchers have used sugarcane residues as an alternative cementitious material [40]. Sugarcane yields 270 kg of bagasse per ton, which, when burned, produces 25 kg of ash. Sugarcane bagasse ash is used as an alternative material for eco-friendly concrete [41]. The use of CBCA in construction greatly helps partially replace cement, which positively reduces CO₂ emissions and offers economic and environmental benefits [42]. According to DICYT, CBCA contains silicon oxide, which improves the mechanical properties and durability of concrete and stabilizes compressed earth blocks, increasing their strength. Sugarcane waste is a pozzolanic material, and CBCA calcined at 800–1000 °C has high pozzolanic activity [43]. As with other assessments that evaluate pozzolanic activity, the tests performed clearly reveal the influence of different factors on the activation processes of these volcanic ashes [44]. For its part, [45] notes that CBCA contains between 63.2% and 76.3% silica and is classified as a pozzolan when it exceeds 75% in mechanical strength (ASTM C618). Reference [46] found that sugarcane leaf ash contained 81% silica, confirming its suitability as a pozzolanic additive. Other studies focus intrinsically on the behavior of the pozzolanic material CBCA and, similarly, on determining the appropriate percentage of this specific component within the concrete mix; for example, [47] studies sugarcane ashes as a cement substitute, finding good mechanical properties and that they can replace 15%–30% of cement. Reference [48] investigated the pozzolanic behavior of CBCA and concluded that this secondary material should only be used to replace inert components of cement, not added as a pozzolan. Reference [49] states that sawdust can be added to mortars without prior treatment, reducing both density and thermal conductivity. Ashes can act as natural cement, behaving as binders in the mix; moreover, CBCA contains silica as a mineral and would therefore be suitable for use in mortars [50, 51]. Additionally,

CBCA could be used as a material for horizontal and vertical adhesion of masonry units [52].

Following the review of the state of the art, there remains a need for a comparative, systematic study under standardized norms that quantifies the dose-response effects and interactions of maguey sawdust (AM) and sugarcane bagasse ash (CBCA) on the physico-mechanical properties of mortar, and relates them to the microstructure to define optimal dosages and technical feasibility.

The objective of the study is to determine the effect of incorporating maguey sawdust (AM) and sugarcane bagasse ash (CBCA) on the physical and mechanical properties of mortar, such as apparent density (kg/m^3), porosity (%), total absorption (%), compressive strength (MPa), and bond strength (MPa).

2. MATERIALS AND METHODS

2.1. Type and research design

This study corresponds to an applied and experimental research, aimed at improving mortar properties through the incorporation of agro-industrial residues. A completely randomized factorial design (3×3) with a control group was employed, evaluating the individual and combined effects of maguey sawdust (5%, 10%, 15%) and sugarcane bagasse ash (2%, 4%, 6%) on variables such as density, porosity, absorption, compressive strength, and bond strength.

2.2. Materials

Materials used were selected based on their specific properties to evaluate their impact on mortar. SCBA, calcined at $800\text{ }^\circ\text{C}$, provides amorphous silica content with pozzolanic potential, while maguey sawdust, a lignocellulosic residue, influences density and absorption due to its porosity and organic content. Portland cement Type I was used in accordance with NTP 334.009, washed sand according to ASTM C33, and potable water for mixing and curing, ensuring standardized conditions throughout the process.

2.3. Experimental procedure

Preparation of maguey sawdust (MS)

The process began with cutting maguey pieces using a circular saw to obtain sawdust, which was manually collected and stored in plastic bags to prevent contamination. The material was then dried and sieved as part of its pre-conditioning prior to use as an additive, a crucial stage to ensure its effect on the density, workability, and strength of the mortar.

Preparation of sugarcane bagasse ash (SCBA)

Sugarcane bagasse, collected from Trapiche Espinoza (Abancay, Apurímac), was manually selected to remove impurities and subsequently air-dried if moisture was present. It was then calcined in the open field through controlled burning until complete carbonization, yielding an ash rich in amorphous silica with pozzolanic potential. After cooling, the ash was collected, stored in dry conditions, and sieved, enabling its use as a sustainable additive in mortar mixes.

Mix design and specimen preparation

The mix design sought a balanced proportion of cement, sand, and water to achieve mortar with good workability, bond strength, and compressive strength, using a water/cement ratio of 0.6. The dosage consisted of 435.49 kg/m^3 of cement, 1570.79 kg/m^3 of sand, and 281.82 kg/m^3 of water, with a volumetric ratio of 1:3.04:0.78. For practical use on-site, this was adjusted per 42.5 kg cement bag, yielding 0.3629 m^3 of mortar per batch. The specimens were prepared with homogeneous mixtures in a 3 ft^3 mixer, cast into cylindrical molds of $15 \times 30\text{ cm}$ for compression, and into refractory brick walls for bond strength testing. After initial setting, the specimens were cured for 28 days in water at $23 \pm 2\text{ }^\circ\text{C}$, according to technical standards for mechanical testing.

Tests performed

After 28 days of curing, physical and mechanical tests were carried out to characterize the mortar. Density, porosity, and water absorption were evaluated according to ASTM C642 / NTP 334.078, while permeability was measured following DIN 1048 Part 5 / EN 12390-8.

Compressive strength was determined based on ASTM C109 / NTP 334.061, and bond strength was assessed according to UNE-EN 1015-12 and ASTM C952. All tests were performed at 28 days to ensure standard material maturity conditions.

2.4. Experimental design

This study was designed under a completely randomized 3×3 factorial scheme, with the objective of evaluating the combined effect of maguery sawdust (MS) and sugarcane bagasse ash (SCBA) as additives in mortar formulation. The factors considered were: Factor A (MS) with three levels (1%, 2%, and 3%) and Factor B (SCBA) with three levels (5%, 10%, and 15%), in addition to a control sample corresponding to conventional mortar without additives. Each of the nine factorial combinations, along with the control treatment, was evaluated in triplicate, for a total of 30 experimental units (9×3 + 1×3).

2.5. Statistical analysis

The statistical treatment was structured in three stages: descriptive analysis (mean, standard deviation, coefficient of variation), normality verification with the Ryan–Joiner test, and inferential analysis through linear regression and

3×3 ANOVA, considering a significance level of 5% in Minitab v.22.1. The control sample was compared with the optimal treatments using Dunnett’s test. Furthermore, when significant differences were found ($p < 0.05$), Tukey’s HSD test was applied to identify differences among treatments. The following statistical model was used:

$$Y_{ijk} = \mu + A_i + B_j + (AB)_{ij} + \epsilon_{ijk} \quad (1)$$

Where:

- A_i : Effect of maguery sawdust (MS),
- B_j : Effect of sugarcane bagasse ash (SCBA),
- $(AB)_{ij}$: Interaction between both factors,
- ϵ_{ijk} : Random experimental error.

3. RESULTS

3.1. Descriptive statistical test

Before the inferential analysis, a descriptive statistical characterization of the treatments and the control group was carried out by calculating measures of central tendency and dispersion. This allowed for the identification of preliminary differences among treatments and the evaluation of data homogeneity. Table 1 summarizes the main statistics obtained.

Table 1. Descriptive statistical analysis.

Variable	Mean	Std. Dev.	Variance	Coeff. of Variation	Rango
Bulk density (g/cm ³)	2612.37	19.5827	383.482	00.75	66.00
Porosity (%)	10.82	1.2628	1.5947	11.67	4.00
Total absorption (%)	4.6533	0.6447	0.4156	13.86	2.00
Compressive strength (MPa)	19.1604	1.2789	1.6356	06.67	3.9149
Bond strength (MPa)	0.3138	0.0322	0.0010	10.27	0.1157

According to Table 1, the descriptive analysis revealed that bulk density was the most stable variable (CV = 0.75%), while porosity (CV = 11.67%) and total absorption (CV = 13.86%) showed greater variability. The mechanical properties presented moderate dispersion, with CV = 6.67% in compressive strength and 10.27% in bond strength, suggesting a homogeneous behavior with slight structural variations among samples.

3.2. Normality test

Data normality was verified through tests applied to all evaluated variables, obtaining p-values >

0.05 in all cases: bulk density ($p = 0.088$), compressive strength ($p = 0.094$), and the rest with $p > 0.100$, in addition to correct alignment in the plots. These results confirm that the data follow a normal distribution, which justifies the use of parametric analyses, such as ANOVA, in the inferential treatment.

3.3. Inferential statistics

Inferential statistics with parametric tests, supported by the normality of the data, were applied to identify significant differences among treatments and to draw objective conclusions from the sample results.

Regression analysis for bulk density

Regression equation:

$$\text{Bulk density (kg/m}^3\text{)} = 2552.19 + 504.4 \cdot \text{MS} + 744 \cdot \text{SCBA} + 4000 \cdot (\text{MS} \times \text{SCBA}) \quad (2)$$

Table 2. Analysis of variance for bulk density.

Source	DF	Adj SS.	Adj MS.	F Value	P Value
Regression	3.00	6385.10	2128.37	161.34	0.000
Maguey sawdust (MS)	1.00	1635.80	1635.84	124.01	0.000
Sugarcane bagasse ash (SCBA)	1.00	570.00	570.03	43.21	0.000
MS × SCBA	1.00	192.00	192.00	14.55	0.001
Error	23.00	303.40	13.19		
Lack of fit	5.00	158.10	31.61	3.92	0.014
Pure error	18.00	145.30	8.07		
Total	26.00	6688.50			

From Table 2, the analysis of variance showed highly significant effects of both main factors, maguey sawdust (MS) and sugarcane bagasse ash (SCBA), on the response variable (p-value = 0.000 in both cases), as well as a significant interaction between them (p = 0.001). This indicates that the effect of one factor depends on the level of the other. The regression model was globally significant (p = 0.000), with a high F-value (161.34), demonstrating a strong explanatory capacity of the model.

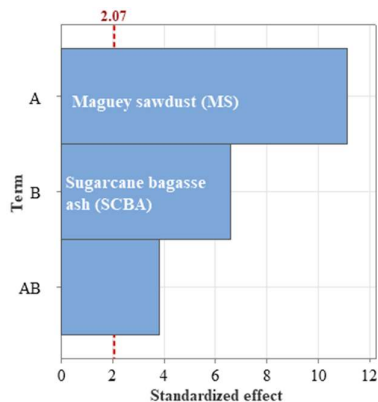


Fig. 1. Pareto chart for bulk density (kg/m³).

The Pareto chart for bulk density in Fig. 1 shows that maguey sawdust (A), sugarcane bagasse ash (B), and their interaction (AB) exceed the significance threshold ($\alpha = 0.05$), being statistically significant. Factor A has the greatest effect, followed by B, and although the interaction

is smaller, it also exerts a significant influence, demonstrating that both individual and combined effects impact bulk density.

Regression analysis for porosity

Regression equation:

$$\text{Porosity (\%)} = 14.656 - 32.22(\text{MS}) - 41.39(\text{SCBA}) + 200.0(\text{MS} \times \text{SCBA}) \quad (3)$$

Table 3. Analysis of variance for porosity.

Source	DF	Adj SS.	Adj MS.	F Value	P Value
Regression	3	30.1761	10.0587	1098.76	0.000
Maguey sawdust (MS)	1	6.6746	6.6746	729.10	0.000
Sugarcane bagasse ash (SCBA)	1	1.7620	1.7620	192.47	0.000
MS × SCBA	1	0.4800	0.4800	52.43	0.000
Error	23	0.2106	0.0092		
Lack of fit	5	0.1039	0.0208	3.51	0.022
Pure error	18	0.1067	0.0059		
Total	26	30.3867			

Table 3 of the analysis of variance reveals highly significant effects of maguey sawdust (MS), sugarcane bagasse ash (SCBA), and their interaction on the response variable (p = 0.000), demonstrating a notable influence both individually and in combination. The regression model is globally significant (F = 1098.76; p = 0.000), with little unexplained variability.

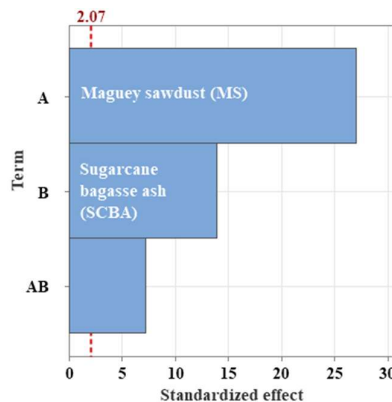


Fig. 2. Pareto chart for porosity (%).

The Pareto chart for porosity (%) in Fig. 2 shows that both maguey sawdust (A) and sugarcane bagasse ash (B) have significant effects ($\alpha = 0.05$), with A standing out as the most influential. The AB interaction had a slight and barely significant

effect, indicating that individual effects predominate over the combined effect.

Regression Analysis for Total Absorption

Regression Equation:

$$\text{Total Absorption (\%)} = 6.6852 - 17.333 (\text{AM}) - 23.06 (\text{CBCA}) + 125.0 (\text{AM}) * (\text{CBCA}) \quad (4)$$

Table 4. Analysis of Variance for Total Absorption.

Source	DF	Adj SS.	Adj MS.	F Value	P Value
Regression	3	7.8347	2.61157	736.34	0.000
Maguery sawdust (MS)	1	1.9314	1.93143	544.57	0.000
Sugarcane bagasse ash (SCBA)	1	0.5467	0.54675	154.16	0.000
MS × SCBA	1	0.1875	0.18750	52.87	0.000
Error	23	0.0815	0.00355		
Lack of fit	5	0.0482	0.00965	5.21	0.004
Pure error	18	0.0333	0.00185		
Total	26	7.9163			

Table 4 shows that the regression model is highly significant ($F = 736.34$; $p = 0.000$), with an excellent overall fit. Both maguery sawdust (AM) and sugarcane bagasse ash (CBCA) exhibited highly significant effects on the response variable ($F = 544.57$ and 154.16 ; $p = 0.000$). Likewise, the AM×CBCA interaction was significant ($F = 52.87$; $p = 0.000$), confirming a relevant combined effect between both factors.

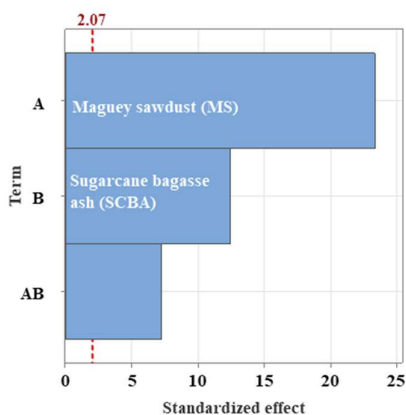


Fig. 3. Pareto Chart for Total Absorption (%).

The Pareto chart for total absorption (%) in Fig. 3 shows that maguery sawdust (A), sugarcane bagasse ash (B), and their interaction (AB) have statistically significant effects, as they all exceed the critical threshold ($\alpha = 0.05$). Factor A exhibits

the greatest effect, followed by B and then the AB interaction, confirming that both individual and combined effects significantly influence the material’s absorption.

Regression Analysis for Compressive Strength

Regression Equation:

$$\text{Compressive Strength (MPa)} = 15.7977 + 29.616 (\text{AM}) + 21.92 (\text{CBCA}) - 64.6 (\text{AM}) * (\text{CBCA}) \quad (5)$$

Table 5. Analysis of Variance for Compressive Strength.

Source	DF	Adj SS.	Adj MS.	F Value	P Value
Regression	3	34.6477	11.5492	7080.24	0.000
Maguery sawdust (MS)	1	5.6386	5.6386	3456.71	0.000
Sugarcane bagasse ash (SCBA)	1	0.4940	0.4940	302.86	0.000
MS × SCBA	1	0.0501	0.0501	30.74	0.000
Error	23	0.0375	0.0016		
Lack of fit	5	0.0102	0.0020	1.34	0.292
Pure error	18	0.0273	0.0015		
Total	26	34.6853			

The regression model was highly significant ($F = 7080.24$; $p = 0.000$), indicating an excellent fit to the data. The factor maguery sawdust (AM) showed a highly significant effect on the dependent variable ($F = 3456.71$; $p = 0.000$), as did sugarcane bagasse ash (CBCA) ($F = 302.86$; $p = 0.000$). A significant interaction between both factors was also observed (AM × CBCA, $F = 30.74$; $p = 0.000$), suggesting a relevant combined effect.

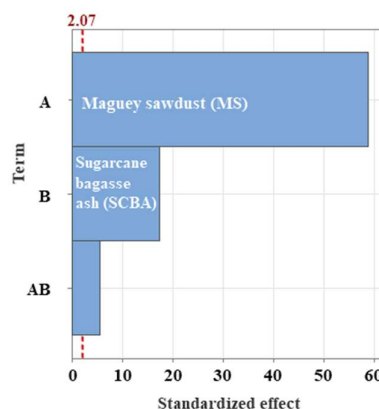


Fig. 4. Pareto Chart for Compressive Strength (MPa).

The Pareto chart for compressive strength (MPa) in Fig. 4 reveals that the factors maguey sawdust (A), sugarcane bagasse ash (B), and their interaction (AB) are statistically significant, as they exceed the critical significance threshold ($\alpha = 0.05$). Factor A exhibits the greatest standardized effect, making it the main determinant of compressive strength.

Regression Analysis for Bond Strength

Regression Equation:

$$\text{Bond Strength (MPa)} = 0.23304 + 0.7007 \text{ (AM)} + 0.7464 \text{ (CBCA)} - 3.024 \text{ (AM)} \times \text{(CBCA)} \quad (6)$$

Table 6. Analysis of Variance for Bond Strength.

Source	DF	Adj SS	Adj MS	F Value	P Value
Regression	3	0.0166	0.005551	761.20	0.000
Maguey sawdust (MS)	1	0.0031	0.003156	432.80	0.000
Sugarcane bagasse ash (SCBA)	1	0.0005	0.000573	78.59	0.000
MS × SCBA	1	0.0001	0.000110	15.05	0.001
Error	23	0.0001	0.000007		
Lack of fit	5	0.0001	0.000020	5.28	0.004
Pure error	18	0.00006	0.000004		
Total	26	0.0168			

The analysis of variance for bond strength (MPa) in Table 6 shows that the regression model is highly significant ($F = 761.20$; $p = 0.000$), indicating an excellent overall fit. The factors maguey sawdust (AM), sugarcane bagasse ash (CBCA), and their interaction (AM × CBCA) are statistically significant ($p < 0.01$), with F values of 432.80, 78.59, and 15.05, respectively, confirming that all of them have a relevant influence on the material’s strength.

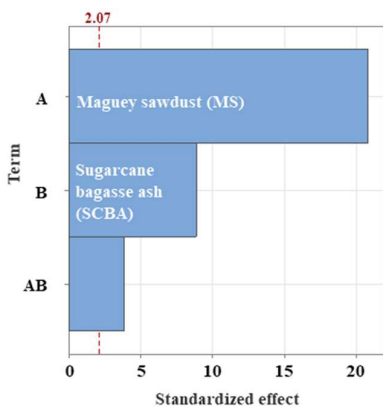


Fig. 5. Pareto Chart for Bond Strength (MPa).

The Pareto chart for bond strength (MPa) in Fig. 5 indicates that the three evaluated terms maguey sawdust (A), sugarcane bagasse ash (B), and their interaction (AB) are statistically significant, as they exceed the significance threshold ($\alpha = 0.05$). Factor A exhibits the greatest standardized effect, followed by B, while AB shows a smaller but still significant effect.

3.4. Tukey Tests

Density

The Tukey analysis with 95% confidence and an individual level of 99.80% reveals statistically significant differences among several treatments, highlighting that treatments T15_4, T15_6, and T15_2 present the highest mean values and form group A, being significantly superior to the Control, which shows the lowest mean value and belongs to group E. The differences between these extremes reach up to 55.33 units, with adjusted p-values of 0.000, indicating high statistical significance.

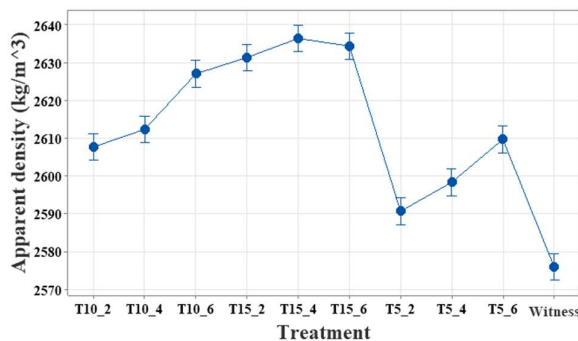


Fig. 6. Apparent Density Intervals (kg/m³).

Fig. 6 on apparent density intervals (kg/m³) shows that treatments T15_4, T15_6, and T15_2 reached the highest mean values, all above 2630 kg/m³, with narrow confidence intervals, indicating good measurement precision. In contrast, the Control exhibits the lowest value (approximately 2576 kg/m³), with a clear separation from the superior treatments, evidencing significant differences.

Porosity

The Tukey analysis shows highly significant differences among treatments, highlighting that the T15 group treatments (T15_4, T15_6, T15_2) differ significantly from the Control and from the

T5 treatments, with differences of up to 3.83 units ($p = 0.000$). In contrast, comparisons within the T15 group show no significant differences ($p > 0.05$), confirming their statistical homogeneity. These results indicate that the T15 group has a notably distinct effect on the evaluated variable compared to the other treatments.

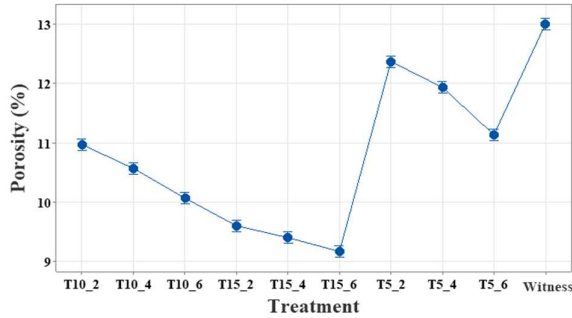


Fig. 7. Porosity Interval Graph (%).

Fig. 7 of porosity intervals (%) shows that the treatments in the T15 group (especially T15_4 and T15_6) exhibit the lowest porosity values (around 9%), which indicates better physical properties of the material, since lower porosity implies higher compactness and potentially greater strength. In contrast, the Control exhibits the highest porosity, close to 13%, followed by treatments T5_2 and T5_4, which also show elevated values.

Total Absorption

The Tukey multiple comparison test, with an individual confidence level of 99.80%, indicates highly significant differences among the treatments, particularly between the T15 group and the Control or the T5 treatments, with differences reaching up to 1.90 units ($p = 0.000$). Comparisons within the T15 group (e.g., T15_6 - T15_4) are not significant ($p = 0.994$), reaffirming their statistical homogeneity.

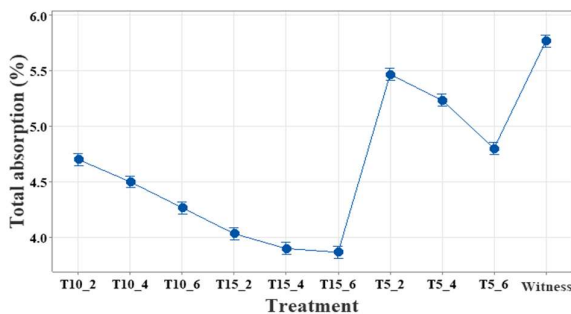


Fig. 8. Total Absorption Intervals (%).

Fig. 8 of total absorption intervals (%) shows that the T15 group treatments (especially T15_4 and T15_6) exhibit the lowest absorption values (below 4.0%), suggesting greater resistance to water penetration and better physical performance. In contrast, the Control reaches the highest absorption (around 5.8%), followed by the T5 group treatments, which also present high levels (above 5%).

Compressive Strength

The Tukey test at 99.80% confidence shows highly significant differences among treatments, where the T15 group treatments exhibit the highest values and differ markedly from the Control, with differences exceeding 3.27 units ($p = 0.000$). Comparisons between T15 and treatments such as T5_2, T5_4, and T5_6 also reveal significant differences, reaffirming the superior performance of the T15 group.

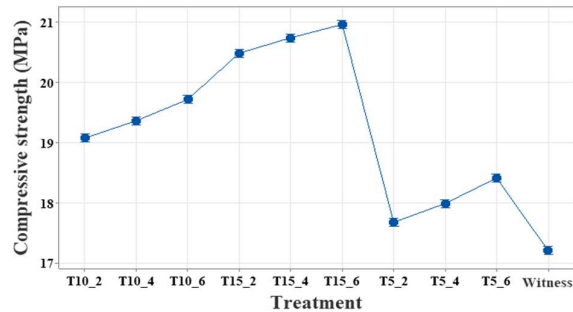


Fig. 9. Compressive Strength Intervals (MPa).

Fig. 9 of compressive strength intervals (MPa) reveals that the T15 group treatments achieve the highest strength values, with T15_6 being the maximum at over 21 MPa, followed by T15_4 and T15_2, all showing notable differences compared to the other treatments. In contrast, the Control presents the lowest strength (approximately 17.3 MPa), along with T5_2 and T5_4, which also show low performance.

Bond Strength

The Tukey multiple comparison test with an individual confidence level of 99.80% shows that the T15 group treatments (T15_2, T15_4, T15_6) present statistically significant differences compared to the Control and the T5 treatments, with mean differences exceeding 0.09 units ($p = 0.000$). Comparisons within the T15 group, such

as T15_6 – T15_4, are not significant ($p = 0.170$), confirming their statistical similarity.

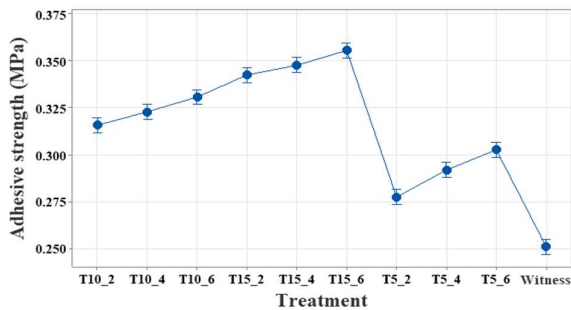


Fig. 10. Bond Strength Intervals (MPa).

Fig. 10 shows that the T15 group treatments exhibit the highest bond strength, with T15_6 standing out at up to 0.36 MPa, demonstrating a better bonding capacity of the material. T15_4 and T15_2 follow with similarly high values. In contrast, the Control and T5_2 show the lowest values (around 0.26 MPa), placing them significantly below the overall average.

3.5. Dunnett Test

Regarding apparent density, the Dunnett multiple comparison test with a 99.20% confidence level indicates that all treatments differ significantly from the Control ($p = 0.000$), showing positive effects on the evaluated variable. The T15 group treatments stand out with the largest differences, especially T15_4 (60.33) and T15_6 (58.33), evidencing performance significantly superior to the Control.

For porosity, the Dunnett test with a 99.20% confidence level shows that all treatments present statistically significant and negative differences compared to the Control ($p = 0.000$), indicating an effective reduction of the evaluated variable. The T15 group treatments stand out for having the most pronounced differences, particularly T15_6 (-3.8333) and T15_4 (-3.6000), demonstrating their greater effectiveness in decreasing the variable compared to the control.

Total absorption, with a 99.20% confidence level, confirms that all treatments present negative and statistically significant differences compared to the Control ($p = 0.000$), implying an improvement in the evaluated variable. The T15

group treatments, especially T15_6 (-1.9000) and T15_4 (-1.8667), show the largest reductions, indicating their superior effectiveness. Although the T5 group treatments are also statistically different from the Control, their effects are smaller.

In terms of compressive strength, the Dunnett test with a 99.20% confidence level reveals that all treatments show positive and statistically significant differences compared to the Control ($p = 0.000$), indicating an effective increase in the evaluated variable. The T15 group treatments, particularly T15_6 (3.7518) and T15_4 (3.5302), show the largest increases compared to the Control, standing out as the most effective. The T10 treatments also substantially surpass the Control, although to a lesser extent.

Finally, for bond strength (MPa), the Dunnett analysis with a 99.20% confidence level shows that all treatments present positive and highly significant differences compared to the Control ($p = 0.000$), indicating a statistically solid improvement in the evaluated variable. The T15 group treatments, especially T15_6 (0.10461) and T15_4 (0.09676), obtained the highest differences, consolidating themselves as the most effective compared to the Control.

4. DISCUSSIONS

The incorporation of CBCA and AM generated a significant increase in the apparent density of the mortar, exceeding 2630 kg/m^3 in the T15 treatments, due to void filling by CBCA and better compaction provided by the vegetable fibers. This finding is consistent with previous studies on the pozzolanic effect of CBCA [3, 4, 32]. The regression model was highly significant ($p = 0.000$), with relevant individual and interaction effects.

With respect to total porosity, a significant reduction was observed, with the T15 group showing values close to 9% compared to 13% for the Control. This result aligns with studies indicating that CBCA improves the microstructure of mortar [30, 33], while AM, in low proportions, contributes to sealing fine voids.

Total water absorption decreased significantly, with values below 4.0% in treatments with CBCA and AM, due to lower porosity and greater

compaction. This supports research highlighting the densifying role of CBCA [32, 33]. Despite being porous, AM did not negatively affect performance at low doses, achieving a technical balance between both residues.

Compressive strength increased significantly in the T15 mixes, exceeding 21 MPa compared to 17.3 MPa for the Control. This behavior is consistent with studies conducted in India and Brazil, where CBCA improved mechanical strength through more efficient secondary hydration [30, 31, 33]. AM showed a positive synergy when used in controlled proportions [6].

Finally, bond strength reached values close to 0.36 MPa, with T15_6 standing out, representing a significant improvement over the Control. This finding is key in self-construction contexts and agrees with research showing deficiencies in bond strength of conventional mortars [21, 23]. The combination of CBCA and AM strengthened the paste-substrate interface without compromising the material's cohesion.

5. CONCLUSION

The combined incorporation of CBCA and AM significantly improved the properties of the mortar. Treatment T15 showed the best results, with increases in apparent density (2612.37 kg/m³), compressive strength (19.16 MPa), and bond strength (0.314 MPa), consistently outperforming the control. In terms of physical properties, total porosity (10.82%) and water absorption (4.65%) were reduced, evidencing greater compactness and durability. These effects are attributed to the pozzolanic behavior of CBCA and the contribution of AM in sealing fine voids without compromising the mortar structure.

Regarding mechanical performance, compressive strength reached a maximum of 19.16 MPa, representing an increase of 3.75 MPa compared to the control. Bond strength also improved, registering a maximum value of 0.36 MPa against the general average of 0.314 MPa. Furthermore, the interaction between AM and CBCA was statistically significant across all evaluated variables, confirming a positive synergistic effect when both residues are jointly and proportionally used in mortar formulation.

The regression, Tukey, and Dunnett statistical tests robustly validated that the residue-based treatments largely outperform conventional mortar, with highly significant models ($p < 0.001$) and high F-values. Nevertheless, some signs of lack of fit were identified in certain models, suggesting that future studies could explore the influence of other variables, such as particle size of the residues, their pretreatment, or the use of complementary additives.

Finally, this study supports the technical and environmental feasibility of using AM and CBCA as additives in mortars, providing concrete evidence for their implementation in sustainable construction contexts. Beyond improving material performance, their application contributes to the valorization of agro-industrial residues and to reducing the environmental impact of the construction sector, in line with the Sustainable Development Goals (SDGs 9 and 12).

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