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Influence of partial replacement of cement by biomass ashes on cement-wood composites properties

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Abstract
The aim of this work was to evaluate the physical and mechanical properties of cement-wood composites with the addition of biomass ashes at different levels (0, 5, 10, 15, 20, and 25%). The composites were produced using Portland cement CPII, Eucalyptus grandis particles, and ashes from eucalyptus wood. The tests followed the NBR 7215 (2019) and ASTM E1876 (2022) standards, density, 24-hour thickness swelling, 24-hour water absorption, dynamic modulus of elasticity from non-destructive testing, static modulus of elasticity, and compressive strength at 28 days tests were carried out. After the tests, statistical analysis was performed to verify if there were statistically differences between the means at a 5% level of significance. The partial replacement of cement with ashes shows potential, especially with a 5% replacement, due to better physical and mechanical properties.

Keywords: cementitious composite; mechanical properties; physical properties; residues use.

Influencia de la sustitución parcial de cemento por cenizas de biomasa en las propiedades de compuestos de cemento y madera

Resumen
El objetivo del presente estudio fue evaluar las propiedades físico-mecánicas de compuestos cemento-madera con la incorporación de cenizas de biomasa en diferentes proporciones (0, 5, 10, 15, 20 y 25%). Estos compuestos se fabricaron utilizando cemento Portland CPII, partículas de Eucalyptus grandis y cenizas procedentes de la combustión de madera de eucalipto, siguiendo las normativas NBR 7215 (2019) y ASTM E1876 (2022). Se realizaron pruebas de densidad, expansión en espesor a las 24 horas, absorción de agua a las 24 horas, módulo de elasticidad dinámico mediante ensayos no destructivos, módulo de elasticidad estático y resistencia a la compresión a los 28 días. Posteriormente, se efectuó un análisis estadístico para determinar si existían diferencias entre las medias con un nivel de significancia del 5%. La sustitución parcial del cemento por cenizas demostró tener potencial, destacándose especialmente el tratamiento con una sustitución del 5% debido a sus mejores propiedades físico-mecánicas.

Palabras clave: compuesto de cemento; propiedades mecánicas; propiedades físicas; aprovechamiento de residuos.

1. Introduction

Cement-wood composites are produced by combining wood particles with a mineral binder. The first cement-wood industries emerged in the 1930s in Austria, with significant development occurring in the late 1940s. Large-scale production began in 1976 in Germany. Currently, cement-wood boards are widely used in the United States, Japan, Russia, and Mexico [1,2].

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Cement-wood composites are used as ceiling and wall coverings, as well as in structural applications such as floors and walls. In these composites, wood contributes to increased rupture resistance, while cement provides enhanced durability, fire resistance, and dimensional stability [3].

Some advantages of cement-wood composites include lower density, approximately 15% lower, compared to traditional cement boards, good thermal and acoustic properties, as well as resistance to weathering and wood-destroying agents, the possibility to use small-diameter trees or timber industry residues, reducing environmental impact, due to its renewable nature, and the good mechanical properties, such as high impact resistance, flexural strength, and hardness [4-6].

The construction industry is one of the most significant contributors to the economy. However, it also causes major environmental impacts, particularly in cement production, which is highly polluting due to limestone extraction and carbon dioxide emissions during its calcination [7,8]. An alternative to reducing cement usage is the partial substitution of cement with biomass ash in cement-wood composites.

Ashes are industrial solid waste originating from the incomplete combustion of biomass. Recycling and reusing ashes mitigate environmental impact and reduce transportation and landfill costs [9]. Currently, this waste is used for soil fertilization in agriculture and forestry [10-12]. However, other applications are being explored, including their use in cementitious composites.

The incorporation of ashes in cementitious products meets the construction industry's need for materials with high durability, strength, and cost-effectiveness [13]. The addition of ashes to cement mortar increased its normal compression and flexural strength [14]. In concrete, ash addition yielded favorable results in terms of water absorption and freeze-thaw resistance [15].

Therefore, the aim of this study was to assess the physical and mechanical properties of cement-wood composites with partial cement replacement by biomass ash at different proportions.

2. Methodology

For the production of the composites were used Portland cement type II, Eucalyptus grandis wood particles and biomass ash from the burning of eucalyptus wood. Table 1 presents the chemical composition of the ash used, based on three samples.

First, the wood pieces were processed using a drum chipper and a Wiley mill, followed by classification through a set of vibrating sieves with three different mesh sizes. The particles used were those that passed the 9-mesh sieve and were retained on the 16-mesh sieve. After the sieving, these particles were dried in an oven at 103±2° C for 24 hours.

Table 1.
Ash chemical composition.

		Mean
Composition (%)	Nitrogen (N)	0,27
	Phosphorus pentoxide (P2O5)	0,38
	Potassium oxide (K2O)	0,88
	Calcium (Ca)	4,20
	Magnesium (Mg)	0,89
	Sulfur (S)	0,13
	Total organic carbon	1
Composition ($mg * kg^{-1}$)	Sodium (Na)	3669
	Copper (Cu)	86
	Iron (Fe)	14602
	Manganese (Mn)	1005
	Zinc (Zn)	149
pH		12

Source: Adapted from Hansted et al., 2023 [16].

Table 2.
Evaluated treatments.

Treatment	Mixture ratio (Cement: Ash: Wood: Water)
CP II 0%	1,00 : 0,00 : 0,20 : 0,80
CP II 5%	0,95 : 0,05 : 0,20 : 0,80
CP II 10%	0,90 : 0,10 : 0,20 : 0,80
CP II 15%	0,85 : 0,15 : 0,20 : 0,80
CP II 20%	0,80 : 0,20 : 0,20 : 0,80
CP II 25%	0,75 : 0,25 : 0,20 : 0,80

Source: Authors.

Six different treatments were evaluated, varying the replacement of cement with biomass ash, as shown in Table 2. In studies using cementitious composites with ash and concrete with ash, the authors presented different levels as ideal for improving the properties of the material, varying between 5 and 25% [16-20]. In this way, treatments from 0 to 25% in cement-wood composites with partial ash replacement were evaluated. The mixture was used based on the mass of the materials, representing the amount of cement, ash, wood, and water, respectively.

The production of the composites followed the standard recommendations [21]. Mixing and compaction were done manually. For the mechanical and apparent density tests, cylindrical PVC molds with a diameter of 50 mm and a height of 100 mm were used. For thickness swelling and water absorption tests, prismatic wooden molds with a square cross-section of 50 mm and a height of 25 mm were used.

A thin layer of vegetable release agent was applied to the molds before adding the cement mixture, and a plastic sheet was placed in the prismatic molds to prevent adhesion. Six specimens of each model were produced for each treatment.

After compaction, the composites cured in an air-conditioned environment at 25°C for 28 days. Fig. 1 shows the production stages.

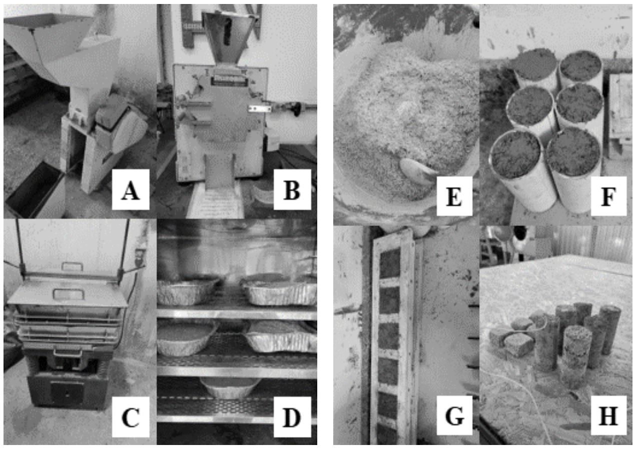

Figure 1. Production of composites, where (a) Drum chipper. (b) Wiley mill. (c) Set of vibrating sieves. (d) Oven drying. (e) Mixing of materials. (f) Molded cylindrical composites. (g) Molded prismatic composites. (h) Finished composites.
Source: Authors.

To determine the apparent density, the specimens were measured with a digital caliper with a resolution of 0.01 mm and then weighed on a semi-analytical balance with a resolution of 0.01 g. Density was calculated using the ratio of mass to volume.

To determine the swelling in thickness and water absorption, the prismatic specimens were measured caliper and weighed on a semi-analytical balance. They were then immersed in water for 24 hours and then weighed and measured again.

The thickness swelling was determined according to eq. (1).

$$TS = \frac{t_f - t_i}{t_i} * 100 \quad (1)$$

Where: TS is the thickness swelling 24h (%); t_i is the initial thickness of the specimen (mm) and t_f is the final thickness of the specimen (mm).

Water absorption was determined according to eq. (2).

$$WA = \frac{m - m_i}{m_i} * 100 \quad (2)$$

Where: WA is the water absorption 24h (%); m_i is the initial mass of the specimen (g) and m_f is the final mass of the specimen (g).

The dynamic modulus of elasticity was determined using the non-destructive method with the SONELASCTIC® system, following the standard recommendations [22]. For the test, the specimens were weighed on a semi-analytical balance and measured using a digital caliper.

Next, a non-destructive test conducted, where the specimens were placed in a horizontal position and impacted with a device, while a microphone was placed at the other end to capture the longitudinal resonance frequency. The dynamic modulus of elasticity was calculated using eq. (3).

$$Ec_d = 16 * m * fl^2 * (\frac{L}{\pi * d^2 * K}) * 10^{-6} \quad (3)$$

Where: Ec_d is the dynamic compression modulus of elasticity (MPa); fl is the mean of three consecutive measurements of the longitudinal resonance frequency (Hz); d is the mean diameter of the specimen (mm); L is the mean height of the specimen (mm); K is the correction factor calculated using eq. (4).

$$K = 1 - (\frac{\pi^2 * \mu^2 * d^2}{8 * L^2}) \quad (4)$$

Where: μ is Poisson's ratio, the value of 0.15 was used, referring to concrete [19].

The compression test was conducted to determine the static modulus of elasticity and strength [23]. The EMIC DL300 universal testing machine with a capacity of 300 kN was used, and the machine's loading speed was set at 0.25 ± 0.05 MPa * s^{-1}. The test specimens were compressed until failure. Fig. 2 shows the tests procedure.

After the tests, statistical analysis was performed. First, the Shapiro-Wilk test was performed to verify data normality, and the Bartlett test was used to verify variance homogeneity. Subsequently, analysis of variance was performed to determine if there was a statistical difference among means at a significance level of 5%. In cases where necessary, the Tukey test was applied to identify which means differed. A regression analysis was also carried out to investigate the correlation between properties and the variation in cement replacement. All statistical tests were conducted using R software version 4.3.1.

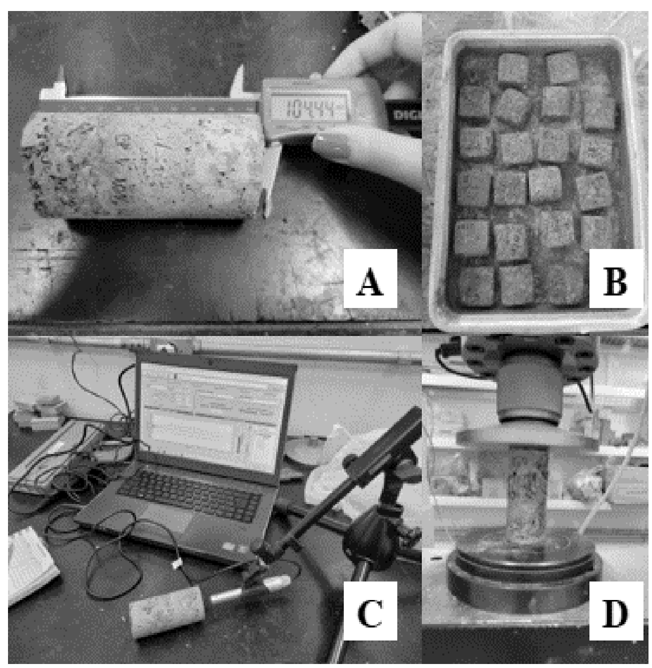

Figure 2. Physical-mechanical tests, where (a) Measurement of the test piece; (b) Test specimens immersed in water; (c) Non-destructive test; (d) Compression test.
Source: Authors.

3. Results and discussion

Table 3 presents the results of the physical tests containing the mean, standard deviation, in parentheses, and statistical analysis, where identical letters vertically do not differ at the 5% level of significance.

Table 3.
Results of the physical tests.

Treatment	Density (kg/m^3)	Thickness swelling (%)	Water absorption (%)
CP II 0%	1119 A (34)	2.28 A (1.68)	27.95 B (0.83)
CP II 5%	1075 A (18)	2.15 A (0.83)	27.94 B (1.72)
CP II 10%	1145 A (254)	1.70 A (0.60)	31.44 B (1.17)
CP II 15%	1034 A (20)	1.81 A (1.95)	31.56 B (3.34)
CP II 20%	1090 A (12)	1.64 A (1.46)	31.01 B (1.89)
CP II 25%	972 A (36)	2.61 A (1.52)	43.24 A (3.46)

Source: Authors.

Fig. 3 shows the physical property graphs for each treatment, containing the linear regression curve.

The linear function for the density property is indicated in eq. (5).

$$\rho = 1130{,}32 - 4{,}61 * AC \tag{5}$$

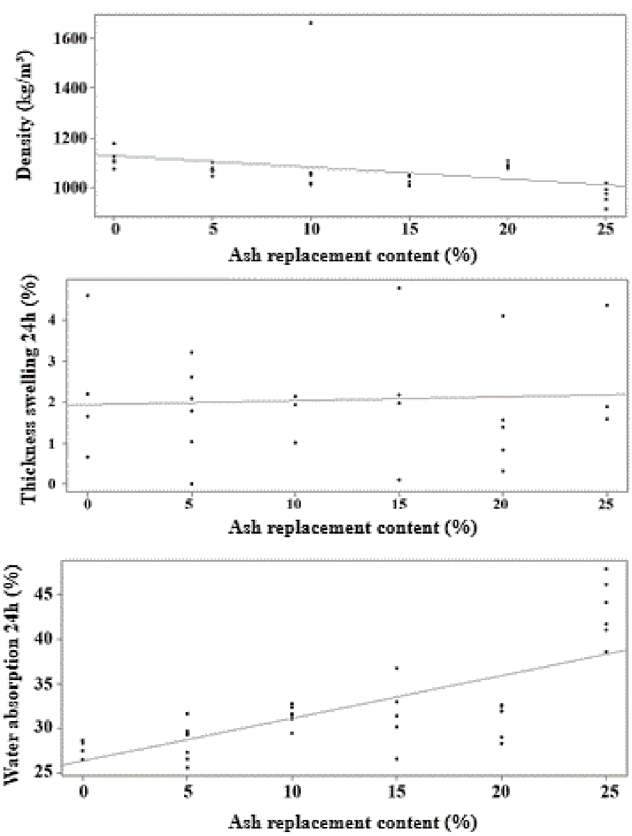

Figure 3. Chart of physical properties as a function of ash replacement content.
Source: Authors.

Where: ρ is the density (kg/m^3) and AC is the ash content (%). The correlation between the density and the ash content is 34,99%

In the density test, there was no statistical difference among the means. However, a decreasing trend in the property is noticeable with the increase in the percentage of ash replacement, as observed in the linear function, whose angular coefficient is negative. This is because the density of ashes is slightly lower than that of the cement paste. This reduction has also been observed in concrete and mortar with partial cement replacement by wood ashes [14,24].

The linear function for the thickness swelling 24h property is indicated in eq. (6).

$$TS = 1{,}930 + 0{,}01 * AC \tag{6}$$

Where: TS is the thickness swelling 24h (%). The correlation between the TS and the ash content is 3,64%. The thickness swelling did not exhibit statistical variation due to the high standard deviation. However, it showed a trend of reduction with an increase in the amount of ashes.

This is a favorable factor and is justified by the smaller particle size of the ashes, which reduces the voids in the composite due to the increased surface area of the particles, resulting in better interaction between the materials [16].

The tendency towards reduced thickness swelling indicates that the C-S-H gel formed in the reaction of ash with calcium hydroxide contributes to the durability of the composites, even with a reduced amount of cement added [25].

The linear function for the water absorption 24h property is indicated in eq. (7).

$$TS = 26{,}29 + 0{,}48 * AC \tag{7}$$

Where: WA is the water absorption 24h (%). The correlation between the WA and the ash content is 74,62%.

Water absorption increased as the content of cement replaced by ash increased, presenting a high correlation index. The ash contains a significant amount of calcium, which is hydrophilic, and less silica, a hydrophobic element [26].

This occurs because, with the decrease in the amount of added cement, the hydration reaction is reduced, causing water to evaporate more quickly, leading to the formation of a greater number of pores in the composite, which in turn facilitates water penetration [27].

Table 4.
Results of the mechanical tests.

Treatment	Ec_d (MPa)	Ec (MPa)	fck (MPa)
CP II 0%	1798 A (524)	115 A (39)	2.39 AB (0.38)
CP II 5%	1573 A (108)	132 A (46)	2.373 A (0.53)
CP II 10%	1562 A (548)	100 A (42)	2.05 AB (0.35)
CP II 15%	1399 AB (166)	131 A (33)	2.01 AB (0.34)
CP II 20%	1637 A (71)	187 A (130)	2.27 AB (0.61)
CP II 25%	982 B (118)	89 A (39)	1.64 B (0.28)

Source: Authors.

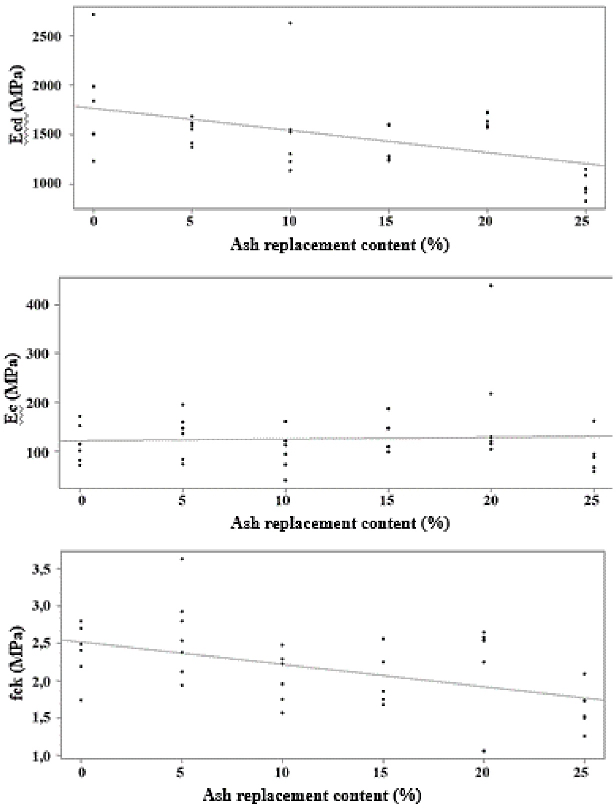

Figure 4. Chart of mechanical properties as a function of ash replacement content.
Source: Authors.

Table 4 presents the results of the mechanical tests containing the mean, standard deviation, in parentheses, and statistical analysis, where identical letters vertically do not differ at the 5% level of significance. Where Ec_d is dynamic modulus of elasticity, Ec static modulus of elasticity and fck is compressive strength at 28 days.

Fig. 4 shows the mechanical property graphs for each treatment, containing the linear regression curve.

The linear function for the Ec_d property is indicated in eq. (8).

$$Ec_d = 1755{,}15 - 22{,}44 * AC \quad (8)$$

The correlation between the Ec_d and the ash content is 49,31%. The linear function for the Ec property is indicated in eq. (9).

$$Ec = 121{,}62 + 0{,}33 * AC \quad (9)$$

The correlation between the Ec and the ash content is 4,24%.

The overall correlation between dynamic modulus of elasticity and static modulus of elasticity is 15.80%, while the correlation between dynamic modulus of elasticity and compressive strength is 57.08%. The properties showed weak and moderate correlation, respectively. A high correlation represents the potential to predict the mechanical properties of composites without the need for rupture.

The linear function for the Ec property is indicated in eq. (10).

$$fck = 2{,}52 - 0{,}03 * AC \quad (10)$$

The correlation between the fck and the ash content is 46,52%.

The compressive strength at 28 days showed a tendency to reduce with the increase in the replacement of cement with wood ash. The same occurred in concrete and cementitious composites with fly ash [28-30].

The reduction in strength with the addition of ash occurs due to the higher number of pores and the formation of a microstructure with greater permeability [31]. In addition to the fact that the use of *in natura* ash compromises the mechanical strength of the material, it is recommended to carry out treatments such as grinding [32].

The CP II 5% treatment presented the highest compressive strength value. The same occurred in cement-wood composites with the addition of biomass ash and fly ash [8,33].

However, treatments with partial replacement of 10, 15 and 20% do not present a statistical difference with the treatment without adding ash, making it possible to replace larger amounts of ash without loss of physical-mechanical performance.

4. Conclusion

The partial replacement of cement by biomass ash in cement-wood composites has potential for use, due to its similar or superior properties to composites without ash, enabling the reuse of a waste product in a higher value-added product.

The density showed a tendency to reduce as the ash content decreased, as well as the dynamic modulus of elasticity and compressive strength at 28 days. On the other hand, 24-hour water absorption increased.

The properties of density, 24h thickness swelling and static modulus of elasticity did not exhibit significant variations with changes in the cement substitution content with ash in the composites.

The 5% replacement treatment exhibited superior overall physical-mechanical performance, but the treatments with 10%, 15%, and 20% replacement did not show a statistical difference compared to the control treatment. Thus, partial substitution of cement with ash is feasible without a reduction in physical-mechanical properties.

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