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Cement-Wood Composites: Effects of Wood Species, Particle Treatments and Mix Proportion

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Abstract The aim of this research was to investigate the effects of wood species, particle treatments and mix proportion on the physical (density) and mechanical (compressive strength and dynamicmodulus of elasticity) properties of cement-wood composites. Different mix proportions were investigated, based on the cement: wood ratio of 0.3:0.7, in volume, with *Pinus elliottii* and *Eucalyptus grandis* sawdust percentages of 0-100, 25-75, 50-50, 75-25 or 100-0. Sawdust particles were pre-treated with either lime or cement coating to improve cement and wood compatibility. Results show that wood species, particle treatments and mix proportions may influence the physical and mechanical properties of cement-wood composites. In general, results confirm that Eucalyptus sawdust and cement are naturally compatible and do not require any previous particle treatment to avoid compatibility problems.

Keywords *Pinus elliottii, Eucalyptus grandis,* Lime, Cement, Sawdust, Waste

1. Introduction

Brazil is one of the five largest producers of industrial round wood with USA, Russian Federation, China and Canada. These countries produced in 2013 54% of total global production [1]. As consequence, huge quantities of wood waste are produced annually by sawmills, whose improper disposal can lead to environmental damage and economic concerns for wood companies.

Plant biomass has already being used to produce engineering materials, encompassing technological and scientific aspects as well as economic, environmental and social issues [2]. The use of wood in cement matrix, in particular, has been investigated for more than one hundred years, whereas its industrial utilization has started later. Initially, small wood particles were embedded in cement matrixto produce low-density boards mainly used for insulating purposes [3]. However, recent studies have also investigated the use of wood waste as raw material for manufacture of many other composites such as wood-based panels, cement slabs and plastic-wood [4].

Wood waste in form of fibers, particles or strands have the potential to be used as reinforcing agent or filler in cement composites [3, 5-9].Cement-wood composites have many advantages over other conventional wood materials, including better insulation and fire performance, better resistance to water soaking, better bactericidal properties and higher stiffness [5].

Wood fibers, as natural fibers, are composed by three major components: cellulose, hemicellulose and lignin. The relative portion of these components may vary based on the types of fibers and the plant source [2]. For some specific applications, certain chemical elements may have to be removed [10].

Due to the chemical morphology of cement and cellulose, hydrogen bonding and/or hydroxyl bridges may play a major role in the bonding of these components [3]. On the other hand, hemicelluloses, starches, sugars, phenols and acids existing in wood fibers, at different levels for each wood specie, tend to inhibit cement hydration, not only leading to a longer setting time but also limiting the strength of the cementitious composite due to micro-fracturing of the matrix during cement hydration [3, 6].The complex system of cement hydration reactions itself is influenced by the concentration of $Ca(OH)_2$, pH and temperature. Different conditions determine different yields for the reactions and different stabilities for the final products [11]. Inhibition of cement hydration occurs when the calcium silicate hydrate (C-S-H) nucleation sites, which are originally positively charged surfaces, are poisoned by the sugar-acid anions. The wood-fiber surface is probably the most likely place to find the inhibitory effects, related cement hydration [7].

Variability in properties of natural fibers, in general, depends on the growing environment (temperature, humidity, soil composition, air and age) but also depends on the way the plants are harvested and processed [2]. Therefore, physical and mechanical properties of cement-wood composites are strongly influenced by the wood species used in the manufacture, as well as by wood

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content [3], wood particle size [3, 4] and particle treatments [3, 5, 7, 8].

The main purpose of this study was to investigate the effects of two wood species, three particle treatments and fifteen different mix proportions, on the physical and mechanical behavior of cement-wood composites, through the analysis of density, compressive strength and dynamic modulus of elasticity.

2. Materials and Methods

2.1. Materials

Brazilian cement CPV-ARI [12] similar to Portland cement Type III – HESC - High Early Strength Cement (ASTM C150-12) was used as binder.

Pinus elliottii and *Eucalyptus grandis* wastes were obtained from a wood processing industry, located in Southern Brazil. Two particle treatments were used:

Cement coating [13], which consisted in mixing wet sawdust and cement, with a sawdust: cement ratio of 8:1in volume;

Immersion of sawdust particles in a saturated lime solution [5]prepared with Calcium Hydroxide type CH II [14] with a sawdust: water: $Ca(OH)_2$ ratio of 1:1:0.05 in mass, for 24 hours, followed by a brief washin running tap water.

Figure 1 shows *in natura* and pre-treated sawdust particles, namedaccording to the wood specie and particle treatment: P_{nat} (ρ_{un}0,21g/cm^3), P_{cem} (ρ_{un}0,29g/cm^3), P_{alk}(ρ_{un}0,21g/cm^3), E_{nat}(ρ_{un}0,22g/cm^3), E_{cem}(ρ_{un}0,30g/cm^3) and E_{alk}(ρ_{un}0,23g/cm^3), for *Pinus elliottii* and *Eucalyptus grandis* species with natural, cement and alkaline treatments, respectively.

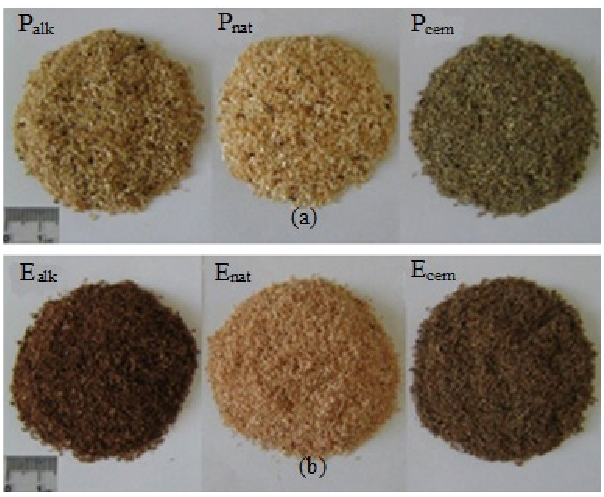

Figure 1. *In natura* and pre-treated sawdust particles: (a) *Pinus elliottii*; (b) *Eucalyptus grandis*

Table 1 shows chemical composition of pre-treated sawdust samples, obtained by X-Ray fluorescence (XRF).

Table 1. Chemical composition of Sawdust

Chemical Elements	XRF quantitative analysis (%)					
	P_{nat}	P_{cem}	P_{alk}	E_{nat}	E_{cem}	E_{alk}
Ca	51.11	85.42	90.91	43.25	83.51	94.14
Mn	24.03	0.44	5.71	16.92	0.24	3.03
Fe	7.70	7.10	3.38	13.88	7.45	2.34
K	9.58	0.60	-	-	1.60	-
Cu	7.59	-	-	10.43	-	-
Er	-	-	-	15.52	-	-
Si	-	4.23	-	-	4.40	-
S	-	1.21	-	-	1.58	-
Sr	-	1.04	-	-	1.23	-

Figure 2 shows sawdust waste particle size distributions, after sieving to obtain the dense gradation [15].

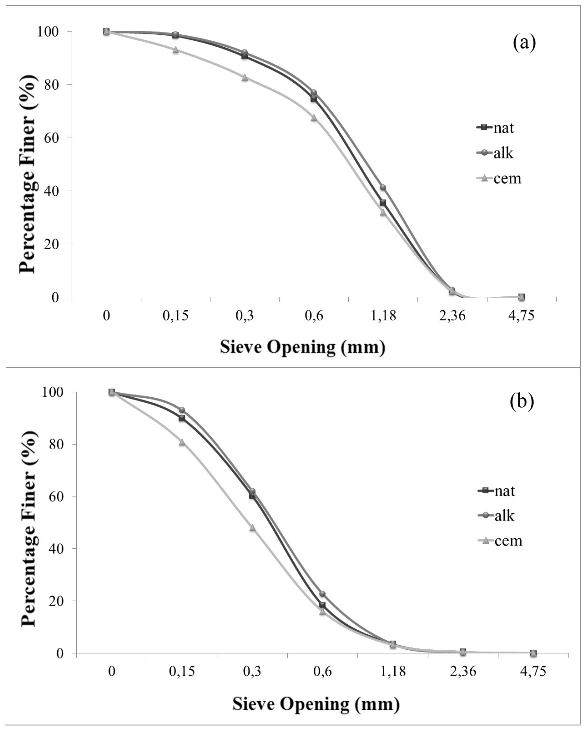

Figure 2. Particle size distribution: (a) *Pinus elliottii*; (b) *Eucalyptus grandis*

2.2. Mix Proportions and Manufacture

Mix proportions were defined, based on the cement:wood ratio of 0.3:0.7, in volume, with *Pinus elliottii* and *Eucalyptus grandis* sawdust percentages of 100-0, 75-25, 50-50, 25-75 and 0-100, as shown in Table 2.

Table 2. Mix proportion, in volume

Composites	Cement (%)	Wood (%)	Type of sawdust (%)					
			P_{nat}	P_{cem}	P_{alk}	E_{nat}	E_{cem}	E_{alk}
$P100E0_{nat}$			100	-	-	-	-	-
$P100\ E0_{cem}$			-	100	-	-	-	-
$P100\ E0_{alk}$			-	-	100	-	-	-
$P75E25_{nat}$			75	-	-	25	-	-
$P75E25_{cem}$			-	75	-	-	25	-
$P75E25_{alk}$			-	-	75	-	-	25
$P50E50_{nat}$			50	-	-	50	-	-
$P50E50_{cem}$	30	70	-	50	-	-	50	-
$P50E50_{akl}$			-	-	50	-	-	50
$P25E75_{nat}$			25	-	-	75	-	-
$P25E75_{cem}$			-	25	-	-	75	-
$P25E75_{alk}$			-	-	25	-	-	75
$P0E100_{nat}$			-	-	-	100	-	-
$P0E100_{cem}$			-	-	-	-	100	-
$P0E100_{alk}$			-	-	-	-	-	100

Manufacture process consisted in mixing cement, water and sawdust contents (Table 3) in a planetary mortar mixer, placing five samples of each composite in cylindrical ϕ20mmx40mmmetallic molds. After seven curing days, samples were demolded and conditioned in a laboratory room, protected from air currents and direct insulation, for 21 days.

Table 3. Mix proportion, in mass

Composites	Cement	Water	Sawdust					
			P_{nat}	P_{cem}	P_{alk}	E_{nat}	E_{cem}	E_{alk}
$P100E0_{nat}$			0.483	-	-	-	-	-
$P100\ E0_{cem}$			-	0.667	-	-	-	-
$P100\ E0_{alk}$			-	-	0.483	-	-	-
$P75E25_{nat}$			0.362	-	-	0.127	-	-
$P75E25_{cem}$			-	0.500	-	-	0.173	-
$P75E25_{alk}$			-	-	0.362	-	-	0.132
$P50E50_{nat}$			0.242	-	-	0.253	-	-
$P50E50_{cem}$	1	0.6	-	0.334	-	-	0.345	-
$P50E50_{akl}$			-	-	0.242	-	-	0.265
$P25E75_{nat}$			0.121	-	-	0.380	-	-
$P25E75_{cem}$			-	0.167	-	-	0.518	-
$P25E75_{alk}$			-	-	0.121	-	-	0.397
$P0E100_{nat}$			-	-	-	0.506	-	-
$P0E100_{cem}$			-	-	-	-	0.690	-
$P0E100_{alk}$			-	-	-	-	-	0.529

2.3. Physical and Mechanical Properties

Cement-wood composites performance, regarding wood species, particle treatments and mix proportions, were evaluated through physical and mechanical properties.

Density

Density was determined by measuring the mass and volume of each sample, according toEquation1, where M_0 is the weight (g), V_0 is the volume (cm^3) and ρ is the density (g/cm^3). Results were reported as the average of five measurements.

$$\rho = \frac{M_0}{V_0} \tag{1}$$

Compressive strength and Dynamic Modulus of Elasticity

Compressive strength tests were carried in a universal testing machine, following a procedure adapted from the Brazilian Technical Standard for Compressive Strength of Cement[16], considering a loading speed of 0,05MPa/s and reported as the average of five samples.

Dynamic modulus of elasticity was determined [17] through the measurement of ultrasonic pulse velocity using aTICO Proceq testing device with transducers of 54 Hz. Results were reported as the average of five samples, based on Equation 2, where V is the ultrasonic pulse velocity (mm/μs), ρ is the density (kg/m³) and μ is the Poisson ratio.

$$Ed = V^2 \rho \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \qquad (2)$$

2.4. Statistical Analysis

Analysis of variance (ANOVA) was performed using the Statgraphics commercial software. Fisher´s Least Significant Difference (LSD) test was used to compare the difference among the mean values for the properties at the level of 0.05.

3. Results and Discussion

Trends in the average properties of cement-wood composites values are difficult to ascertain, mainly because wood fibers are a biological material and had inherent variability in fiber length and properties [7]. Apart from that, treatments of each wood fiber may not be uniform over the fiber surface. However, wood specimens, treatments and mix proportions, proposed in this experimental program, resulted in a data set that allowed an examination of apparent trends in the average physical and mechanical properties of cement-wood composites, as discussed in this section.

3.1. Density

Figure 3 shows results of density for cement-wood composites, whose values are presented in Table 3. Results agree with others reported by literature [3, 4, 8, 11, 19].

The importance of studying physical properties of cement-wood composites, in particular density, refers to the fact that, in general, the wood incorporation leads to a composite with lower density and, consequently, lower compressive strength [11, 18]. Cement-wood composites with higher densities also present higher values of modulus of elasticity and modulus of rupture [19]. On the other hand, reduction of density results on lighter elements that could be an advantage regarding handling and transporting.

In this study, density of cement-wood composites was significantly influenced by particle treatments. Composites with sawdust treated by cement coating showed higher density, followed by the ones with *in natura* sawdust and the ones in which sawdust was immersed in alkaline solution.

Regarding P100E0 that contains only *Pinus elliottii* sawdust, test results indicate that values of density are higher for cement coating, decreasing when immersion in alkaline solution or *in natura* sawdust are applied.

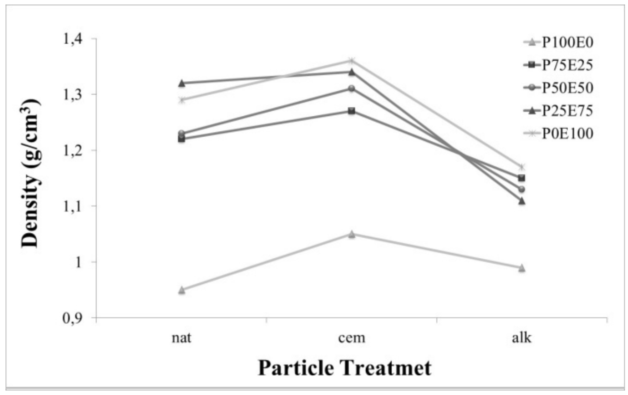

Figure 3. Density of cement-wood composites

Table 3. Density of cement-wood composites

Composite	Density (g/cm³)		CV (%)
$P100E0_{nat}$	0.95	a	3.53
$P100\ E0_{cem}$	1.05	c	3.88
$P100\ E0_{alk}$	0.99	b	0.97
$P75E25_{nat}$	1.22	f	2.06
$P75E25_{cem}$	1.27	g	2.36
$P75E25_{alk}$	1.15	de	0.83
$P50E50_{nat}$	1.23	f	3.38
$P50E50_{cem}$	1.31	hi	1.83
$P50E50_{akl}$	1.13	de	2.54
$P25E75_{nat}$	1.32	hi	0.72
$P25E75_{cem}$	1.34	ij	1.49
$P25E75_{alk}$	1.11	d	4.09
$P0E100_{nat}$	1.29	gh	1.10
$P0E100_{cem}$	1.36	j	1.59
$P0E100_{alk}$	1,17	e	1.41

CV = Coefficient of variation. Same letters imply treatments with equivalent means.

On the other hand, composites with *Eucaliptus grandis*, P0E100, P25E75 P50E50 e P75E25, show a different behavior: density is higher for cement coating, decreasing when *in natura* sawdust and immersion in alkaline solution particle treatments are applied.

Mix proportions in which blends of both wood species were used (P25E75 P50E50 e P75E25) and sawdust particles were immersed in alkaline solution showed the lowest values of density and no statistic difference among means.

3.2. Compressive Strength

Figure 4 shows results of compressive strength for cement-wood composites, whose values are presented in Table 4. Results agree with others reported by literature [3, 4, 7, 8].

Results showed that compressive strength was influenced by wood species. Cement-wood composites with 100% of *Pinus elliottii* sawdust showed better performance regarding compressive strength when sawdust particles were pre-treated by cement coating. Samples with blends of *Pinus elliottii* and *Eucaliptus grandis* follow the same behavior: higher percentages of *Pinus elliottii* and cement coating particle treatment tend to result higher values of compressive strength. Considering samples with 100% of *Eucaliptus grandis*, higher values of compressive strength were reached with *in natura* sawdust.

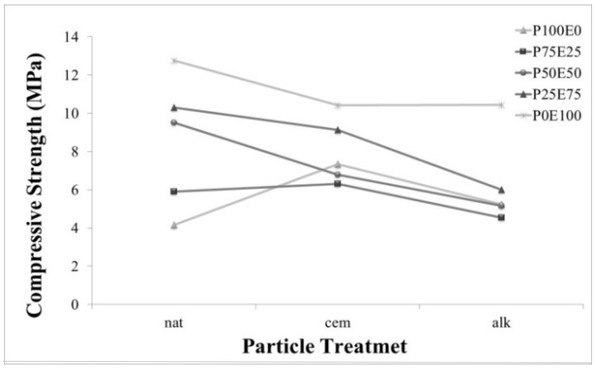

Figure 4. Compressive Strength of cement-wood composites

A previous study of cement-wood composites with *in natura Pinnus sp.* sawdust and cement: wood: water ratio of 1:0.21:0.6 resulted in a compressive strength mean of 5MPa [8], which is compatible to the mean value of 4.16MPa (Table 4), for $P100E0_{nat}$ with cement: wood: water ratio of 1: 00:48:0.60.

As a general trend, this research shows that the highest values of compressive strength are reached in composites with higher percentage of *in natura Eucaliptus grandis* sawdust. On the other hand, high percentages of *in natura Pinus elliottii* decreased the compressive strength.

Experimental results [20] of compressive strength tests performed in cement wood-composites show that *Eucalyptus* sawdust and cement are naturally compatible and do not require any previous particle treatment to avoid compatibility problems. Those results are aligned to the results found in the present study. These results, regarding composites with *Eucaliptus* sawdust are very important for industrial purposes, since the *Eucaliptus* wood is the most important raw material for cellulose and paper industry in Brazil [21] and the wood processing leads to a great amount of waste.

Table 4. Compressive strength of cement-wood composites

Composite	Compressive Strength (MPa)		CV (%)
$P100E0_{nat}$	4.16	a	3.53
$P100\ E0_{cem}$	7.35	e	3.88
$P100\ E0_{alk}$	5.23	abcd	0.97
$P75E25_{nat}$	5.90	bcde	2.06
$P75E25_{cem}$	6.30	cde	2.36
$P75E25_{alk}$	4.55	ab	0.83
$P50E50_{nat}$	9.52	f	3.38
$P50E50_{cem}$	6.78	de	1.83
$P50E50_{akl}$	5.17	abc	2.54
$P25E75_{nat}$	10.30	f	0.72
$P25E75_{cem}$	9.12	f	1.49
$P25E75_{alk}$	6.00	bcde	4.09
$P0E100_{nat}$	12.77	g	1.10
$P0E100_{cem}$	10.42	f	1.59
$P0E100_{alk}$	10.45	f	1.41

CV = Coefficient of variation. Same letters imply treatments with equivalent means.

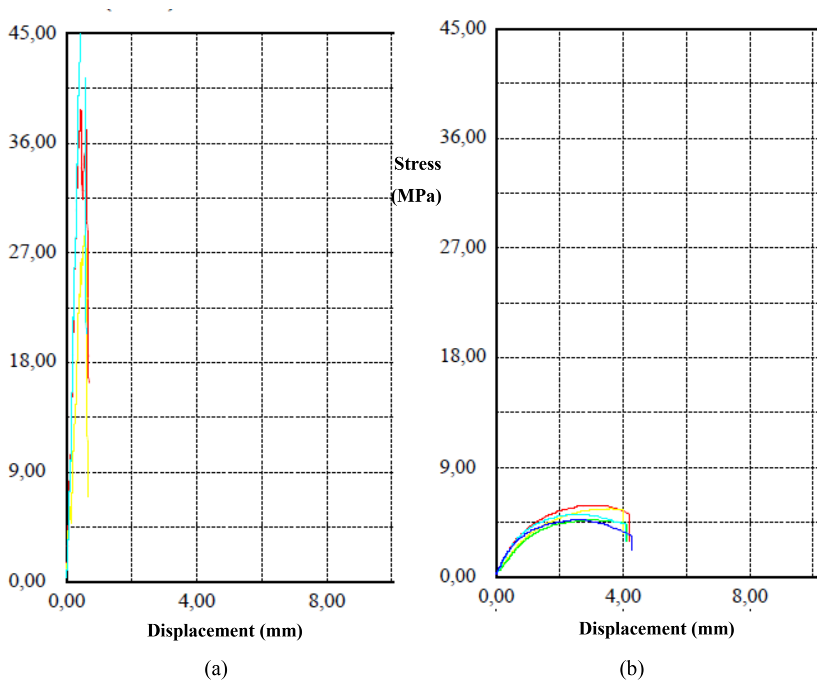

Figure 5. (a) Brittlebehavior of a cement paste; (b) Tough behavior of the $P100E0_{cim}$ cement-wood composite

Eucaliptus grandis sawdust pre-treated by immersion in alkaline solution resulted lower compressive strength values compared to *in natura* sawdust. Mix proportions in which blends of both wood species were used (P25E75 P50E50 e P75E25) and sawdust particles were immersed in alkaline solution showed the lowest values of compressive strength and no statistic difference among means.

The bonding between the wood fiber and the cement may be chemical, physical, or a combination of both. At the interface between the wood fiber and the cement matrix, stress is transferred between the wood fiber and the cement [7]. A strong or weak interfacial bonding influences the mechanical behavior of the composite. If a strong bonding exists, the result is a brittle material with high strength, as shown in Figure 5(a). On the other hand, a weak bonding results in a tougher material, lacking high strength (Figure 5(b)).

Figure 6 shows Stress *versus* Displacement behaviour of cement-wood composites with *in natura Eucaliptus grandis* sawdust, during compressive strength tests, which results are presented in Table 4.

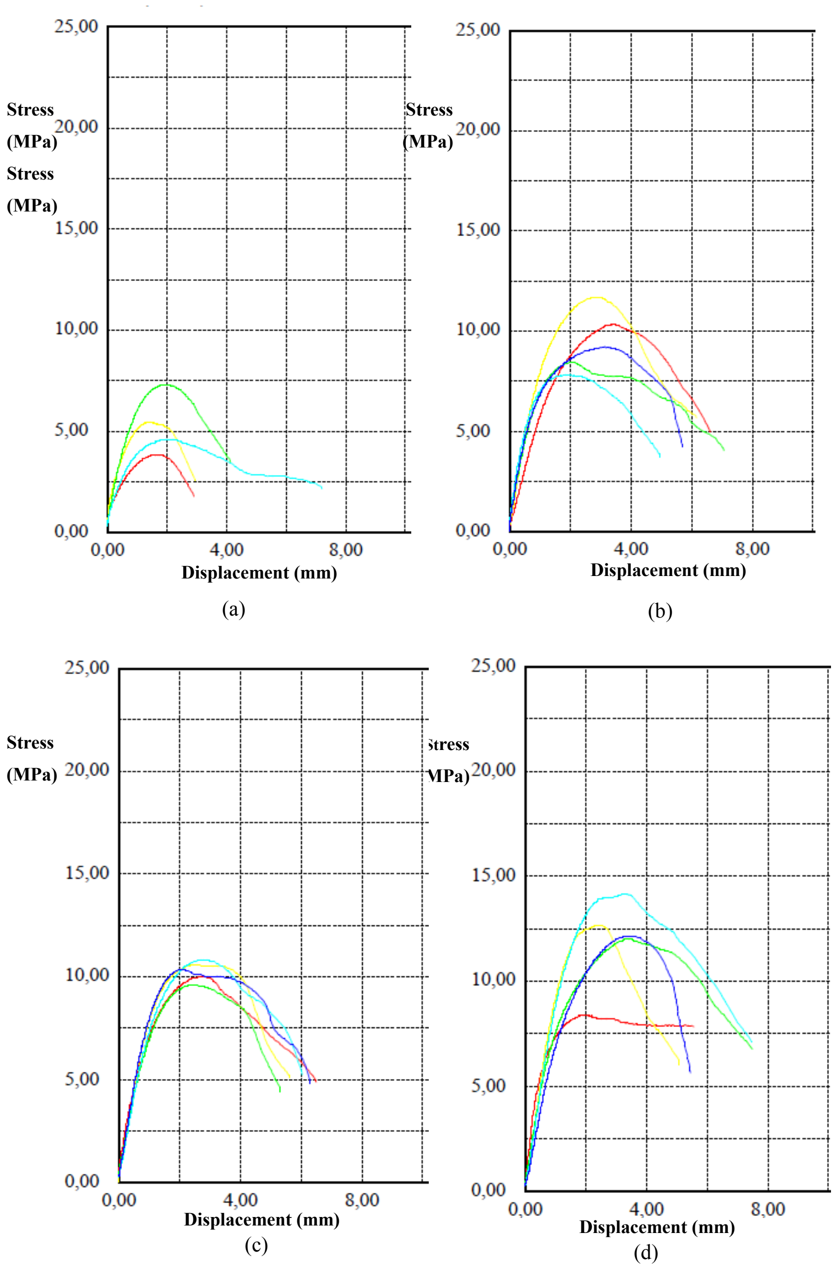

Figure 6. Stress x Displacement behavior of cement-wood composites with different percentage of *in natura Eucaliptus grandis* sawdust: (a) P75E25; (a) P50E50; (a) P25E75; (a) P0E100

The tough material behavior of the cement-wood composites that shows the efficiency of load transfer between matrix and wood fiber can be verified in Figure 6, as well as the increase in the compressive strength with the higher percentage of *in natura Eucaliptus grandis* sawdust.

3.3. Dynamic Modulus of Elasticity

The importance of determining the modulus of elasticity refers to the fact that this mechanical property is directly related to stiffness, deformability and cracking control of cement-wood composites [22]. The modulus of elasticity of a cement paste depends basically on its porosity and water: cement ratio. However, in a cement-wood composite, the proportion between paste and aggregate, the wood specie and wood particle treatments may also be relevant.

Figure 7 shows results of dynamic modulus of elasticity for cement-wood composites, whose values are presented in Table 5. Results agree with others reported by literature [3, 4, 8, 9]

Table 5. Modulus of Elasticity of cement-wood composites

	Dynamic Modulus of Elasticity (MPa)	CV (%)
P100E0$_{nat}$	1356,61 ^{a,b}	9,21
P100 E0$_{cem}$	2548,79 ^{e}	4,61
P100 E0$_{alk}$	1231,58 ^{a}	3,47
P75E25$_{nat}$	2843,76 ^{f}	4,41
P75E25$_{cem}$	3324,74 ^{g}	4,35
P75E25$_{alk}$	2188,59 ^{c,d}	4,05
P50E50$_{nat}$	2108,38 ^{c,d}	8,07
P50E50$_{cem}$	2778,16 ^{e,f}	4,36
P50E50$_{akl}$	1959,85 ^{c}	5,44
P25E75$_{nat}$	3016,93 ^{f}	4,02
P25E75$_{cem}$	2947,05 ^{f}	10,53
P25E75$_{alk}$	1492,32 ^{b}	10,35
P0E100$_{nat}$	2828,18 ^{f}	8,34
P0E100$_{cem}$	2063,79 ^{d}	8,01
P0E100$_{alk}$	1554,89 ^{b}	4,37

CV = Coefficient of variation. Same letters imply treatments with equivalent means.

The modulus of elasticity of *Pinus* and *Eucaliptus* may range from 7GPa-13GPa and 12GPa-19GPa, respectively. As a result of that, the mechanical behavior of cement-wood-composites, especially regarding stiffness and deformability, may vary considerably if blends of woods species are used.

Experimental results (Table 5) showed the influence of the wood species in the modulus of elasticity. Although composites with high amount of *Eucaliptus grandis* sawdust (P25E75 and P0E100) showed the highest values of compressive strength (Figure 4), such composites did not present the same behavior regarding modulus of elasticity.

The high coefficient of variation (Table 5) may result from the heterogeneity of the cement-wood samples but also may occur because several factors such as path length, moisture content, temperature, shape and size of specimen may affect ultrasonic measurements.

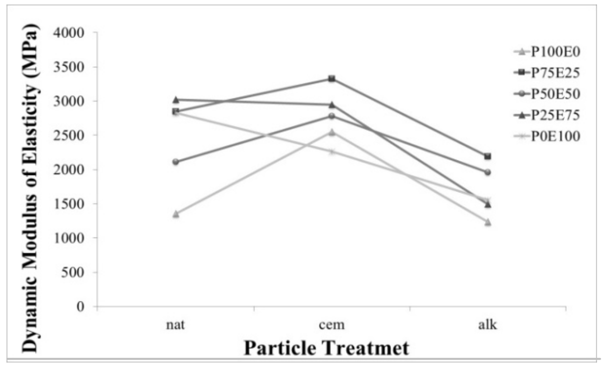

Figure 7. Dynamic modulus of elasticity of cement-wood composites

The influence of the aggregate in the modulus of elasticity sometimes may be more relevant than strength or age. For composites with different types of aggregate this influence may be even more complex [23]. In this research, it was found that different composites with same range of strength may present very different modulus of elasticity and it is assumed that these results come from aggregate influence.

Figure 8 shows dynamic modulus of elasticity of cement-wood composites with statistical data of comparison between means, where same letters imply treatments with equivalent means. Composite P75E25 with particles pre-treated by cement coating showed the highest value of modulus of elasticity.

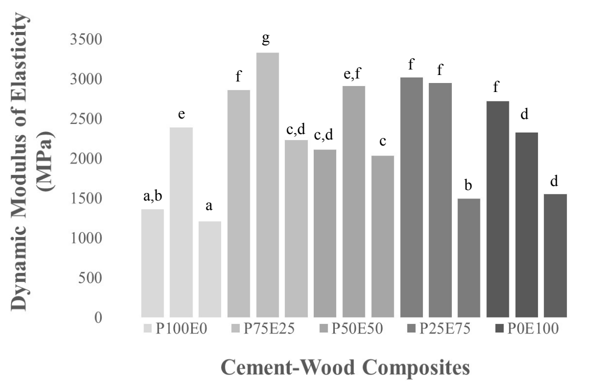

Figure 8. Dynamic modulus of elasticity of cement-wood composites with statistical data of comparison between means

Cement-wood composites with 100%, 75% and 50% of *Pinus elliottii* sawdust and particles pre-treated by cement coating showed better performance regarding modulus of elasticity. Composites P100E0 and P50E50 showed no statistic difference among means for particles pre-treated by immersion in alkaline solution.

Composites with 100% of *Eucaliptus grandis* sawdust showed best results regarding modulus of elasticity for *in natura* sawdust, followed by cement coating and immersion in alkaline solution treatments.

The interfacial bond strength between the fiber and the cement matrix is influenced by the moisture content due to the reduced bending strength of wet fiber, making it more flexible and less likely to inhibit cracking in the cement matrix [3]. Thus, considering the hygroscopic behavior of wood, the modulus of elasticity of a cement-wood composite is lower than the one of the cement paste itself, and tends to decrease the higher the percentage of wood.

4. Conclusions

Results showed that, wood species, particle treatments and mix proportions might influence the physical and mechanical properties of cement-wood composites.

Blends of *Eucalyptus grandis and Pinus ellioti* sawdust led to intermediate values of density, intermediate to lower values of compressive strength and intermediate to higher values of dynamic modulus of elasticity. Composites with 100% of *Eucalyptus grandis* showed higher values of compressive strength. Lighter composites were obtained with *Pinus ellioti* sawdust.

In general, results confirm that *Eucalyptus* sawdust and cement are naturally compatible and do not require any previous particle treatment to avoid compatibility problems.

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