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# The Effect on the Compressive Strength of Concrete Produced by the Incorporation of Boiler-Calcined Biomass Ash into Sand from the Maule River, Chile

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**Abstract:** The pulp industry generates large amounts of wood biomass ash (WBA) as waste, which causes economic and environmental problems. However, WBA has pozzolanic and cementing properties that can complement cement in concrete production. Many studies have been published on the replacement of cement by WBA, but few discuss the replacement of other concrete components such as sand. The objective of this research is to determine the effect of volume replacement of sand with ash on the mechanical resistance of concrete. A reference concrete was made with a specified strength of 30 MPa at 28 days. Samples with 5%, 10%, 13%, 15% and 20% WBA were compared. A water-cement ratio of 0.49 was maintained, plasticizer was added to maintain an acceptable workability, and compression tests were conducted at 7, 28 and 63 days. The results indicate that WBA decreases the workability of the fresh concrete mixture. However, the compressive strength increases in most cases, thus demonstrating the possibility of using WBA as an addition to the concrete to improve its mechanical properties, and at the same time reduce the environmental impact of this waste material.

## 1. Introduction

The search for more sustainable materials and methods for production is a constant in the concrete industry given its high demand for energy and resources. Some alternatives include the use of waste from other productive areas, or recycled materials as additions in concrete mixtures (seashells [1], recycled concrete aggregates [2], rubber [3] and plastic [4]) in order to reduce the environmental impact of concrete production, maintain or improve its mechanical properties, and increase the value of waste materials.

A residue widely studied in concrete mixtures is vegetal biomass ash from the combustion of waste from the food or wood industries, which stands out due to its large scale of production and renewable nature. Its components are varied and depend on the combustion temperature and the type of resource used, such as tree wood, grasses, straw, fruits, and algae, among others. For example, CaO (56.83%) is usually found in pine bark, while SiO<sub>2</sub> is present in pieces of pine wood (68.18%) [5]. The effect biomass ash has on the properties of concrete also depends on the chemical composition of the ash. Ash from Miscanthus, a grass frequently used as fuel, has a high content of amorphous silica with a porous structure, which prevents the rapid desiccation and contraction of mixtures thanks to its ability to retain



water and slowly release it during cement hydration [6]; similar results have been obtained with rice husk ash [7]. Other studies, such as those by Chen et al. [8], show the effect of cattle manure ash on the development of alkaline reactions in mortars. These reactions are expansive and occur between alkaline ions, such as  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ , and the  $\text{CaOH}$  produced from the setting of cement. Sunflower seed husk ash can also have adverse effects: due to its high alkaline ion and sulfate content, it can produce ettringite, an expansive mineral generated in the later stages of setting that causes cracks and weakens the concrete. Hence, a maximum weight replacement of 5% of the cement is recommended [9].

Wood biomass ash (WBA) is one of the most important waste materials in the lumber industry on account of the sustained growth of pulp production in the world during the last decade, led principally by the United States, Canada, Finland, Sweden and Japan. The growth pattern of this industry reveals an increasing trend of expansion in Asian, African and Latin American countries [10]. This expansion has produced negative effects such as waste from this industry, which includes the WBA generated by boiler calcination. In the European Union alone, it is estimated that  $7.3 \times 10^7$  tons of WBA are produced annually [11]. In Chile, pulp production has also been growing and with it, ash as a waste product. As with other vegetal wastes, the possibility of using WBA as an addition in concrete has been studied. For example, Carrasco et al. [12] analyzed the effect of WBA on the properties of concrete. The various tests indicated that an increase in WBA content as a weight replacement for cement increases the porosity of the material and therefore decreases compressive strength and thermal conductivity. This results in materials that can be used to produce insulating blocks for construction since they meet European Standards (ENs). However, more studies are necessary to determine the effect on concrete regarding the rest of its components. In a similar vein and taking into account such a large scale of production and potential use, the objective of this research is to characterize and evaluate wood biomass ash as a replacement for sand by volume in concrete and determine its effect on the mechanical properties of the mixture and hardened concrete.

## 2. Materials and Methods

### 2.1. Materials used

Ordinary Portland cement; rounded sand and crushed gravel from the Maule River Basin, Chile; and tap water were used, as well as an SMF superplasticizing additive (known by its brand name Melment F-10), which was added on a percentage basis according to the weight of the cement. The ash was obtained from the combustion boiler in a pulp mill in the Maule Region of Chile, which runs on heterogeneous wood waste materials to produce the facility's energy.

### 2.2. Characterization tests

Aggregate and ash granulometric characterization tests were performed according to the standard NCh 165 [13] to determine particle size and distribution. In the case of the ash, the same procedure described for the aggregates was used, with a homogeneous sample dried in an oven at  $60^\circ\text{C}$  to avoid incinerating the organic material, until a constant weight was obtained. Once dry, the ash was sifted with the ASTM sieves No. 16, No. 30, No. 50, No. 100 and No. 200, and the percentage retained in each was recorded. The density, relative density and absorption of gravels and sands were determined according to the standards NCh 1117 [14] and NCh 1239 [15] respectively. The ash density was calculated empirically by means of the Archimedes principle, by submerging a dry sample in a container with water and recording the displaced volume of water and the dry ash weight. The moisture content of aggregates was determined according to the standard NCh 1515 [16] and the workability of the concrete mix in accordance with the standard NCh 1019 [17]. Lastly, the Materials and Thermomechanical Processes Institute at the Universidad Austral de Chile determined the structural characterization of the ash based on a sample sifted with sieve No. 30, using the Bruker x-ray diffraction (XRD) system D2 PHASER with DIFRAC SUITE software.

### 2.3. Design and production of the mixture

A 30 MPa reference concrete was prepared based on the Faury-Joisel method [18], which determines aggregate proportions using an ideal granulometric curve for a specified resistance. Mixtures were made for comparison in which the fine sand material was replaced with WBA by volume. The experimental design involved 6 different dosages of WBA: 0%, 5%, 10%, 13%, 15% and 20%. For each, 7 test cubes (20 x 20 cm) were made: 1 to test at 7 days, and 3 to test at 28 and 63 days, for a total of 42 test specimens. To maintain a similar consistency, the plasticizer was added to each sample in different percentages with respect to cement weight. The proportions of the materials for each WBA dosage are presented in table 1.

**Table 1.** Dosages for 1 m<sup>3</sup> of concrete.

	WBA-0%	WBA-5%	WBA-10%	WBA-13%	WBA-15%	WBA-20%
Material	Amount	Amount	Amount	Amount	Amount	Amount
Cement (kg)	386.05	386.05	386.05	386.05	386.05	386.05
Sand (kg)	926.15	879.84	833.54	805.75	787.23	740.92
Gravel (kg)	980.92	980.92	980.92	980.92	980.92	980.92
Ash (kg)	-	32.67	65.35	84.95	98.02	130.70
Water (l)	189.44	189.44	189.44	189.44	189.44	189.44
Plasticizer additive (%)	-	-	0.70	0.90	1.00	2.00
Total (kg)	2482.56	2468.92	2455.29	2447.11	2441.66	2428.02

The concrete mix was prepared according to standard NCh 1018 [19] by combining the coarse aggregate and part of the water in a mixer. After mixing was started, sand + WBA (0%, 5%, 10%, 13%, 15%, 20%) was added until a homogeneous mixture was achieved. With the mixer off, cement was added together with the plasticizer, and the rest of the water was incorporated gradually with the mixer turned on. The concrete was mixed for 5 minutes and then allowed to stand for 2 minutes.

### 2.4. Specimen preparation and compression tests

Test specimens were created according to standard NCh 1017 [20], using 20 x 20 cm metal molds with an inner non-stick coating. The concrete was carefully placed in the molds in 2 layers and was vibrated with an immersion vibrator (Makita, 12,500 rev/min). After filling, each mold was evened out with a trowel to obtain a smooth surface. Curing of the concrete was carried out in a flat place protected from the sun, at a room temperature of between 16 and 27°C to avoid water evaporation. The specimens were demolded after 24 hours and immediately immersed in water saturated with lime for the remaining test days (7, 28, and 63 days). Upon completing the curing time, the specimens were removed from the water and dried at room temperature for 10 minutes. Then compression tests were carried out in accordance with standard NCh1037 [21].

## 3. Results and Analysis

### 3.1. Granulometry and physical properties of the materials

The maximum nominal size of the gravel was 1" (25 mm), thereby complying with the acceptable grading limits for concrete manufacturing specified in Table No. 6 of standard NCh 163 [22]. The sand had a maximum nominal size of 1/2" (12.5 mm), varying slightly in the percentages that passed through the 3/8 and No. 4 sieve in Table No. 5 of standard NCh 163. No organic impurities were detected. The maximum size of the ash was 0.63 mm and was concentrated in sieve No. 200. The results are detailed in table 2 and table 3 respectively. Lastly, the results of material density, absorption and moisture content are presented in table 4.

**Table 2.** Gravel and sand granulometry used in the 30 MPa reference concrete mix.

Gravel						Sand			
Total dry weight of the sample						1300 g			
Sieve	Weight retained (g)	Weight retained (%)	Cumulative weight retained (%)	Percentage passing (%)	Weight retained (g)	Weight retained (%)	Cumulative weight retained (%)	Percentage passing (%)	
mm	US								
25	1"	-	-	-	100.000				
20	3/4"	42.0	0.416	0.416	99.584				
12.5	1/2"	5333.0	52.802	53.218	46.782	-	-	-	100.000
10	3/8"	3114.0	30.832	84.050	15.950	3.0	0.231	0.231	99.769
5	No. 4	1514.0	14.990	99.040	0.960	123.0	9.462	9.692	90.308
2.5	No. 8	41.0	0.406	99.446	0.554	100.0	7.692	17.385	82.615
1.25	No. 16	-	-	-	-	76.0	5.846	23.231	76.769
0.63	No. 30	-	-	-	-	283.0	21.769	45.000	55.000
0.315	No. 50	-	-	-	-	552.0	42.462	87.462	12.538
0.16	No. 100	20.3	0.201	99.647	0.353	150.0	11.538	99.000	1.000
Remainder		8.2	0.081	99.728		10.0	0.769	99.769	
Total (g)		10072.5				1297			
Fineness modulus				5.3	2.8				

**Table 3.** WBA granulometry used in the concrete mix.

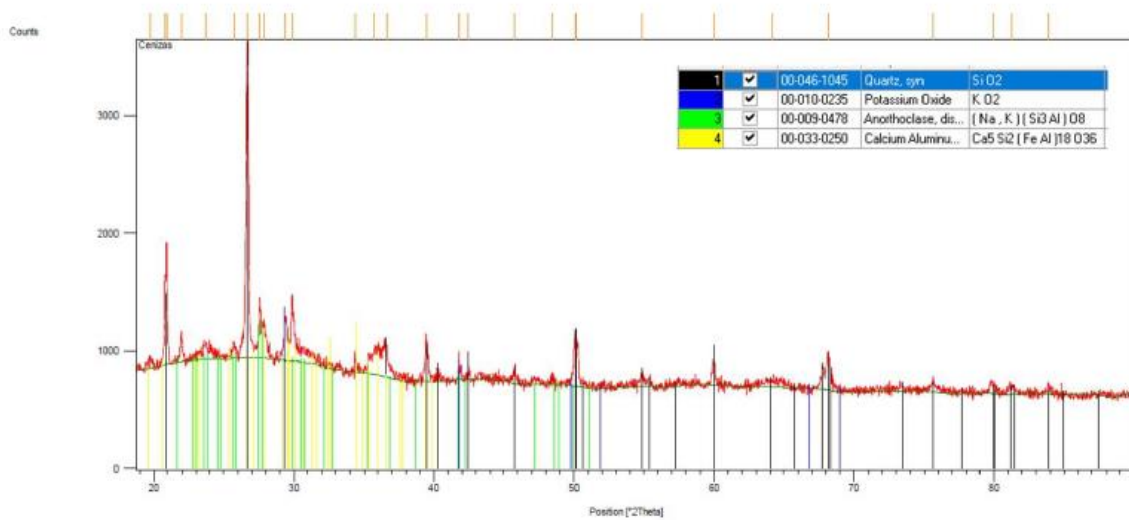
WBA							
Total dry weight of the sample = 500 g							
Sieve	Weight retained (g)	Weight retained (%)	Cumulative weight retained (%)	Percentage passing (%)			
mm	US						
0.63	No. 30	-	-	-	-	-	100.00
0.315	No. 50	119.2	23.84	23.84	76.16		
0.16	No. 100	98.2	19.64	43.48	56.52		
0.08	No. 200	208.6	41.72	85.20	14.80		
Remainder		68.0	13.60	98.80	1.20		
Total (g)		494					

**Table 4.** Physical properties of aggregates and WBA.

	Gravel	Sand	WBA
Density (kg/m <sup>3</sup> )	2654	2564	1809
Relative density (kg/m <sup>3</sup> )	2719	2686	-
Absorption (%)	0.89	1.77	-
Aggregate moisture (%)	0.39	1.06	-

### 3.2. Chemical composition of the ash

Figure 1 shows the x-ray diffraction results of the WBA sample. The main crystalline phases identified were quartz, potassium oxide, anorthoclase, and iron, calcium and aluminum silicates. In general, the element that was found in the greatest quantity was silica, which commonly comes from pieces of wood without bark.



**Figure 1.** WBA diffractogram.

### 3.3. Mixture workability

The addition of WBA to the mixture reduced workability and complicated component mixing. Spheres of ash formed (Figure 2), which made it impossible to measure the slump of samples with high WBA content using an Abrams cone. This was due to the absorbent property of the ash, which caused low mixture consistency. Since the sample with 5% WBA resulted in a dry consistency, a plasticizer additive was incorporated to improve the workability of the following mixtures. Therefore, plasticizer percentages were added gradually, depending on the ash content added to the mixture. This produced similar consistencies in all mixtures.



**Figure 2.** Appearance of the mixture at different stages of preparation. Left: Ash spheres formed during mixing. Center: Ash spheres during mold filling. Right: Appearance of the mixture after vibration.

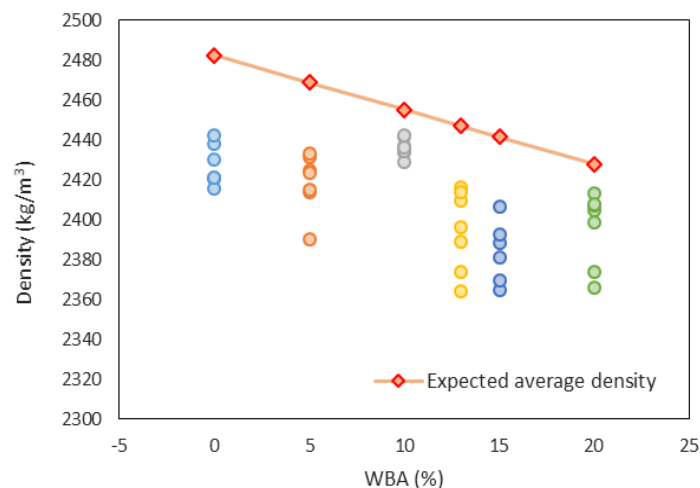
### 3.4. Density of specimens

Table 5 shows the densities of each test specimen for the different preparations and Figure 3 the comparison of averages in relation to the expected density according to Table 1.

**Table 5.** Density of concrete specimens.

WBA dosage (%)	Density (kg/m <sup>3</sup> )							Average (kg/m <sup>3</sup> )
0%	2437.81	2420.86	2420.49	2415.67	2442.02	2430.45	2420.99	2426.90
5%	2431.31	2424.46	2413.75	2415.17	2433.28	2423.73	2389.96	2418.81
10%	2433.96	2436.85	2441.68	2429.05	2434.44	2442.22	2436.49	2436.38
13%	2374.04	2416.15	2396.20	2388.82	2409.71	2413.97	2363.96	2394.69
15%	2364.75	2388.19	2381.11	2406.69	2369.52	2392.67	-	2383.82
20%	2366.21	2413.22	2373.84	2404.71	2407.20	2407.89	2398.77	2395.98

It can be observed that on average, no specimen achieved the expected density; the difference corresponds to the effect of the air trapped in the mixture, which varied between 0.77% and 2.36% of the volume. These differences were compared statistically (using the Kruskal-Wallis non-parametric test,  $\alpha = 0.05$ ) and it was concluded that the amounts of air trapped in the different specimens differ statistically. This could be due to the difference in vibration times due to greater ash content.

**Figure 3.** Density distribution and comparison with the expected density of each concrete specimen.

### 3.5. Compressive strength

The results of the compression tests on each mix with added WBA, performed at 7, 28 and 63 days, are presented in Table 6. The results for 7 days range from 20.71 to 28.13 MPa, with an increasing trend depending on the WBA dosage. At least 3 groups of ranges, 0-5%, 10-13% and 15-20%, can be distinguished (Figure 4). Figure 5 shows the distribution of the results for 28 days of maturation, ranging from 29.24 to 42.9 MPa. Again, an increasing trend of ranges, 0-5%, 10-13% and 15-20% is clearly discernable.

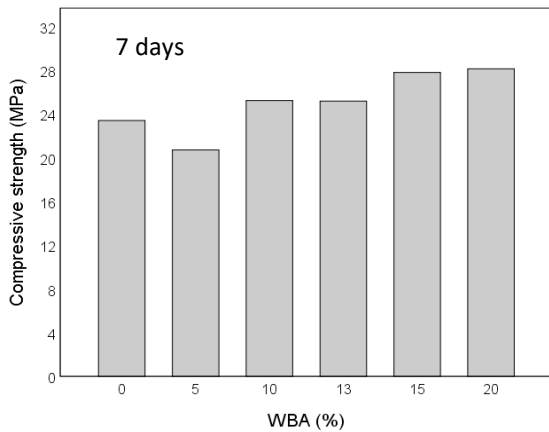


Figure 4. Compressive strength results at 7 days.

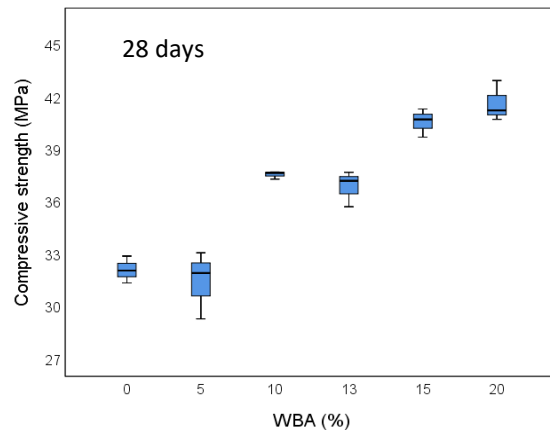


Figure 5. Compressive strength results at 28 days.

Table 6. Results of the compressive strength of the concrete with different WBA dosages and curing times.

Curing time	Compressive strength (MPa)					
	WBA dosages					
	0%	5%	10%	13%	15%	20%
7 days	23.40	20.71	25.22	25.17	27.80	28.13
28 days	32.01	33.03	37.61	37.15	41.27	40.68
	32.84	31.87	37.66	37.64	40.67	41.19
63 days	31.30	29.24	37.25	35.67	39.66	42.90
	40.40	36.72	45.91	44.64	40.40	45.67
	42.11	36.37	47.12	42.04	47.51	48.92
	43.58	36.41	45.37	-	49.53	47.96

Figure 6 shows the distribution of the compressive strength results for 63 days of maturity, which ranges from 36.37 to 49.53 MPa. Although not very clear, a growth trend can be observed, with greater strength in the 15-20% WBA range. The summary of the distribution of compressive strength averages for the different dosages and days of maturity can be seen in Figure 7. These results indicate that the effect of WBA on concrete strength does not vary with the maturity time and tends to increase strength.

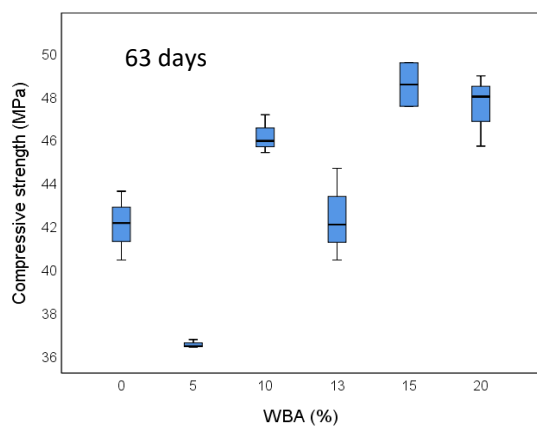


Figure 6. Compressive strength results at 63 days.

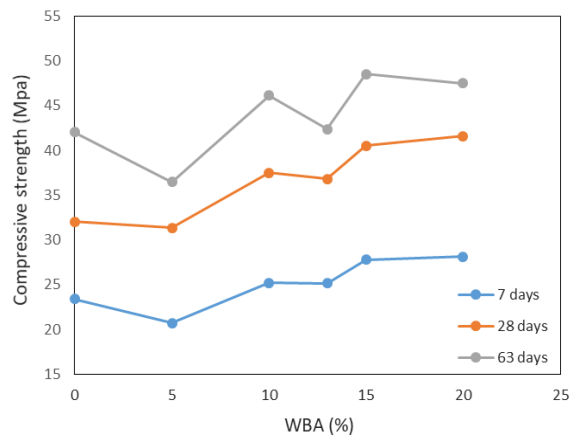


Figure 7. Compressive strength for the different curing times.



#### 4. Conclusions

Based on the results obtained, it is concluded that the addition of WBA as a volume replacement for sand in concrete increases the compressive strength. WBA ranges of from 0-5%, 10-13% and 15-20% were found to have an increasing effect. However, to achieve similar consistencies in the different mixes, a plasticizing additive is necessary, which also has positive effects on the strength of the concrete. In addition, special care must be taken with the volume of air trapped in the mixture, since the differences observed can affect the expected compressive strength results in each case. The combined effect of WBA and plasticizer in the proportions used does not produce any negative effects on the compressive strength of concrete. Thus, WBA waste material can be valorized as a concrete addition that does not damage compressive strength and minimizes the impact it can cause as waste from the lumber industry.

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