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PRODUCTION AND PROPERTIES OF A MEDIUM DENSITY WOOD-CEMENT BOARDS PRODUCED WITH ORIENTED STRANDS AND SILICA FUME

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ABSTRACT

Wood-cement board (WCB) is a panel product that has the advantages of inorganic and organic materials. However, the main problems affecting the manufacture and use of WCB are the inhibitory effects of wood on the setting of cement and the high specific gravity of the final product. This paper examines the potential of strand orientation and the use of silica fume (SiO_2) to facilitate the production of a medium density WCB from *Pinus taeda*. Oriented wood-cement boards (OWCB) were manufactured with wood/cement (w/w) ratio of 1:1, specific gravity 850 kg/m^3; and SiO_2 content as cement replacement of 0%, 10% and 20%. The OWCB were tested for static bending (MOR and MOE) properties in parallel (//) and perpendicular (⊥) directions; internal bond (IB); compression strength parallel to surface (CP); thickness swelling (TS) and water absorption (WA). The results showed that replacement of cement with 10% of SiO_2, increased MOE (//), MOR (//) and CP and, decreased WA and TS, and most importantly eliminated the inhibitory effect of wood on cement setting. The principle of strand orientation was effective to produce boards with anisotropy in the flexural properties ranging form 2.1 to 2.8 for MOR and 2.6 to 3.8 for MOE. However, boards had very low IB strength and this shortcoming must be addressed in future research.

Keywords: wood-cement board, particle orientation, silica fume, *Pinus taeda.*

1. INTRODUCTION

Wood-cement boards (WCB) are already used thoroughly in Europe, United States, Russia and S.E. Asia, mainly for roofs, floors and walls. They possess countless advantages compared to panels produced with organic resins: high durability, good dimensional stability, acoustic and thermal insulation properties and low production cost.

In recent years, several research groups have been evaluating the suitability of different lignocellulosic materials for the manufacture of WCB including cypress (Okino *et al.* 2005), rubberwood (Okino *et al.* 2004), eucalyptus (Okino *et al.* 2004; Evans *et al.* 2000; Del Menezzi and Souza, 2000; Latorraca, 2000), pines (Cabagon *et al*. 2002; Teixeira and Pereira, 1987), acacia (Eusebio *et al.* 2002; Teixeira and Guimarães, 1989), agricultural residues (Almeida *et al.* 2002) and fiber (Del Menezzi *et al.* 2001). In spite of these studies there is no industrial plant in Brazil yet.

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There are obstacles to the utilization of these materials for WCB. The main problems are the inhibitory effect caused by wood on the cure of cement and the high density of the final product. Wood component, mainly extractives and polysaccharides, affects reactions between wood and cement resulting in boards of low quality. Jorge *et al.* (2004) argued that the nature of the extractives also has influence on this inhibitory effect.

To solve inhibition problems, it is common to add inorganic chemicals, known as accelerators, to accelerate the cure of cement or use pretreatments such as aqueous extraction to remove inhibitory substances from wood. Cement chemicals accelerators usually improve the properties of WCB (Jorge *et al.* 2004). There are many papers concerning the use of cement curing accelerators such as $SnCl_2$, $FeCl_3$, $AlCl_3$ and $CaCl_2$ (Zhengtian and Moslemi, 1985; Moslemi *et al.*, 1983) and pre-treatments of wood particles to improve the properties of WCB (Lee and Short 1989; Simatupang *et al.* 1987; Lee, 1984; Moslemi *et al.*, 1983).

According to Lange *et al.* (1989), one of the most promising additives for the WCB industry is silica fume (SiO_2). Silica fume is a pozzolana material based on silica and aluminum with little cementious property. Silica is an industrial by-product of the metallic silicon, iron-silicon leagues and other silicon based products obtained from the quartz and coal produced in electric ovens. In fine powder form and in the presence of water, it reacts chemically with calcium hydroxide to form cement (Metha, 1987). During the hydration process of cement, calcium hydroxide (lime) is formed as a by product and is a weak and soluble material which does not contribute to the strength of the cementious material. Ordinary Portland cement produces about 20% calcium hydroxide. Silica fume reacts with the calcium hydroxide, and creates an additional amount of valuable calcium silicate hydrate, the same type of binder produced during the hydration of Portland cement.

The substitution of cement with silica fume in concrete minimizes exudation and increases cohesion (Sellevold and Nilsen, 1987) and resistance to compression up to 15% (Duval and Kandri, 1998). Simatupang *et al.* (1987) evaluated the use of silica fume in the production of wood-cement panels. The authors concluded that silica at a ratio between 25 and 45% presented the most satisfactory results and that smaller amounts demand the simultaneous application of other additives. Moslemi *et al.* (1995) also produced WCB with addition of 10% silica and 5% calcium hydroxide. Their results showed that the use of silica fume did not affect the linear expansion and the thickness swelling of the boards. Miyafuji and Saka (2001) argued that SiO_2 improves the fire-resistant properties of wood-inorganic composites.

Some wood cement composites, for example cement-bonded particleboard utilize large amounts of cement in comparison to wood (cement:wood ratio higher then 3:1), so the final product has a high density (>1300 kg/m^3), because cement is denser than wood. These high-density boards are difficult to handle, cut, nail and transport (Zhou and Kamdem, 2002). Therefore it would be desirable to develop a low-density board composite using larger amounts of wood, reducing the cement:wood ratio. Zhou and Kamdem (2002) also argued that wood is less expensive than cement, so larger amounts of wood can reduce the cost of the boards. Rim *et al.* (1999) observed a reduction of the density of a clay-cement-wood composite as the weight percentage of wood in the composite increases.

For most forest products, density is an important physical attribute because it is correlated with most mechanical properties. Therefore, low density boards should be produced taking this into account and strategies need to be developed such as altering the type and geometry of the particles and the type of mat forming to increase the mechanical properties of the boards. Some authors present satisfactory results with low-density panels produced with flake-type particles (Semple and Evans, 2004; Teixeira and Pereira, 1987) as well as with excelsior-type particles (Cabangon *et al.* 2002; Miller *et al.* 1989). Excelsior seems ideal for the production of low density WCB, because it is a long and thin type of

´particle´, which is ideal for the production of stronger and stiffer boards, as argued by Badejo (1988). Strand-type particles have also been used for production of medium density WCB (≅ 1000 kg/m^3) (Ma *et al.* 2002) as well as for denser boards (> 1500 kg/m^3) (Miyatake *et al.* 2002).

The strand-type particle geometry and its cross-layered structure are responsible for the improved mechanical properties of oriented strandboard (OSB). This geometry promotes better inter-particle contact and improves adhesive bonding. The strands in OSB production are distributed in layers, usually three, oriented and forming a transversal angle between them as observed in plywood panels. OSB has a density ranging between 500 - 750 kg/m^3, is produced with water-resistant adhesive in thicknesses varying from 9 to 38 mm. These characteristics, together with others, have permitted the utilization of OSB for structural end-uses (ex. roof and floor sheeting) often as a substitute for plywood. The principle of orienting particle in mats that is used in OSB has been adapted to produce WCB with improved mechanical properties. Cabangon *et al.* (2002) manufactured WCB with oriented strands of boards and showed that strand orientation greatly increased the flexural properties in comparison to boards with randomly oriented particles. Ma *et al.* (2002) produced oriented cement-bonded boards from sugi (*Cryptomeria japonica*) with a great anisotropy (stiffness/strength ratio for parallel and perpendicular direction), up to 3.5 for MOE and up to 8 for MOR.

As commented above, the cement:wood ratio has significant effects on WCB properties, mainly by affecting board density. Improvements of the flexural properties of WCB have been observed when a higher cement:wood ratio is used (Latorraca and Iwakiri, 2000). This effect is evident up to a ratio of about 2.6-3.0, as observed by Zhou and Kamdem (2002), but higher cement:wood ratios do not result in further property increase. However, lower cement:wood ratio (up to 1:1) have been used to produce WCB with satisfactory properties (Papadopoulos *et al.* 2006; Cabangon *et al.* 2002).

The objective of this project was to assess whether it is possible to manufacture a medium density WCB with suitable mechanical properties. Three factors were varied during the manufacture of boards to produce composites with desired properties: low wood:cement ratio to reduce board density, silica-fume to reduce negative effects of wood on cement hydration and use of OSB´s particle geometry and distribution to improve board strength/stiffness and offsett the effect of low board density.

2. MATERIAL AND METHODS

2.1 Wood Material

Five loblolly pine trees (*Pinus taeda* L.) from Arapoti (Paraná State, Brazil) were felt. They were from 21 to 23 years old and were about 25 cm in diameter at breast height (DBH). The first two logs were transported to the Forest Products Laboratory (LPF) of the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) where this research was conducted.

2.2 Particle Preparation and Board Production

Initially the logs were sawn and resawn into small pieces of lumber measuring 100 x 160 x 62 mm *(w x l x t)*. The pieces were then shredded parallel to grain in a rotary disk flaker, to produce strands measuring 18 x 62 x 0.8 mm *(w x l x t)*. After processing, the material was air dried to 12% moisture content to prevent fungal attack. Three concentrations of silica fume 0%, 10% and 20% were used as substitutes for cement. There were four replications for each treatment, i.e 12 boards in total. The cement: wood:water ratio used was 1:1:0.25 and 4% of $CaCl_2$ by weight of cement was used as an additive.

Initially, the particles were wetted with a mixture of water and additive, and then the inorganic materials (silica and cement) were added. The final mixture was divided into three parts, using the mass ratio 37.5:25:37.5 (surface/core/surface) to form a 3-layer panel. The core layer of boards had the strands oriented perpendicular to the surface layers (Figure 1). The mat obtained was pressed (4 MPa) using a flat press for 8 hours at room temperature. The boards were then kept in a conditioned room (20±1 ºC, 65±2% RH) for an additional 28 days to allow the cement to cure. The target density of oriented wood-cement boards (OWCB) was 800 kg/m^3 and their dimensions were 550 x 550 x 13 mm (*w, l, t*).

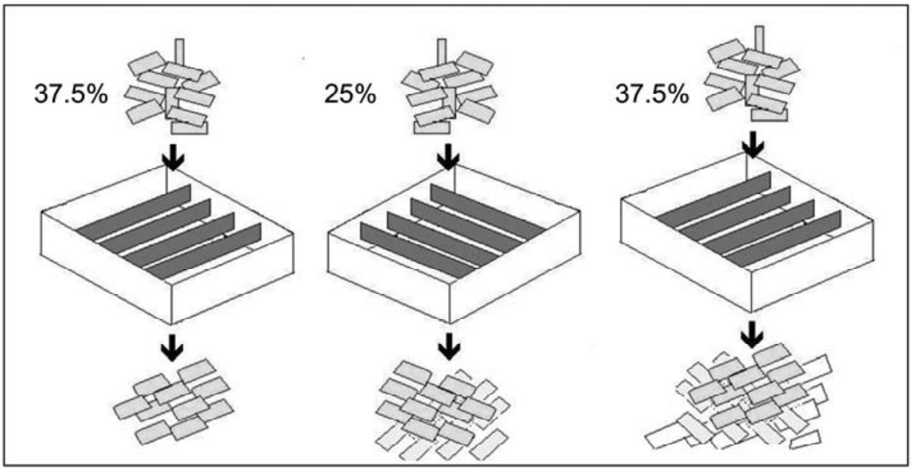


Figure 1. *Method used to orient and distribute strands during board production.*

2.3 Board Properties and Statistical Analysis

The consolidated OWCB were trimmed to a final size of 530 x 530 mm to eliminate low density regions on the edge of boards. Two samples were cut for static bending parallel (//) and perpendicular (⊥) to the surface (MOR, MOE); and four samples for internal bond (IB) and compression strength parallel to the surface (CP). For the physical properties four samples were cut to evaluate thickness swelling (TS), water absorption (WA) after 2 and 24 hours of immersion, respectively, and density (D). The samples were tested according to ASTM D 1037-96a (1998), however, with a modification for physical properties: samples measured about 76 x 76 mm. The results obtained were subjected to an analysis of variance (ANOVA) to identify the effect of the silica fume on the property of interest and a Duncan test was applied to compare treatment means. For the properties for which silica fume had a significant effect, a regression analysis was used to explain the variation observed.

3. RESULTS AND DISCUSSION

3.1 Oriented Wood-Cement Board Properties

Figure 2 shows the results obtained for the mechanical and physical properties of the oriented wood-cement boards (OWCB). It can be observed that the addition of 10% of silica fume improved all the mechanical properties (2a-c) and the dimensional stability (2e-f) of the boards. However, when the proportion of silica fume was increased to 20% (T20), the properties of the boards were similar to those of the controls that did not contain silica. The anisotropy in the flexural strength and stiffness (parallel/perpendicular direction ratio) ranged from 2.6 to 3.8 for MOE and from 2.1 to 2.8 for MOR, as the amount of silica fume in the matrix increased. However, these values were lower than those observed by Ma *et al.* (2002) who observed values ranging from 3 to 3.5 for MOR and 6 to 8 for MOE. On the other hand, our results are more similar to those obtained by Cabangon *et al.* (2002). They produced oriented wood-wool cement board and found anisotropy values from 2.2 to 2.5 for MOR and from 2.8 to 3.1 for MOE depending on the species used.

Data presented in Figure 2 were analyzed statistically and the results of the analyses are summarized in Table 1. It can be observed that the addition of 10% silica fume had no significant effect on board density. The addition of 10% of silica fume to the matrix, however, improved all mechanical properties of boards, but particularly MOR (//) and MOE (//) and PC, where the differences between treatments were significant (Table 1). The trend seen in Figure 2a-f is similar to that observed by Lange *et al.* (1989) and Simatupang (1987), but the optimum silica fume content for the composites manufactured by these researchers was between 30 to 40% and 25 to 45%, respectively.

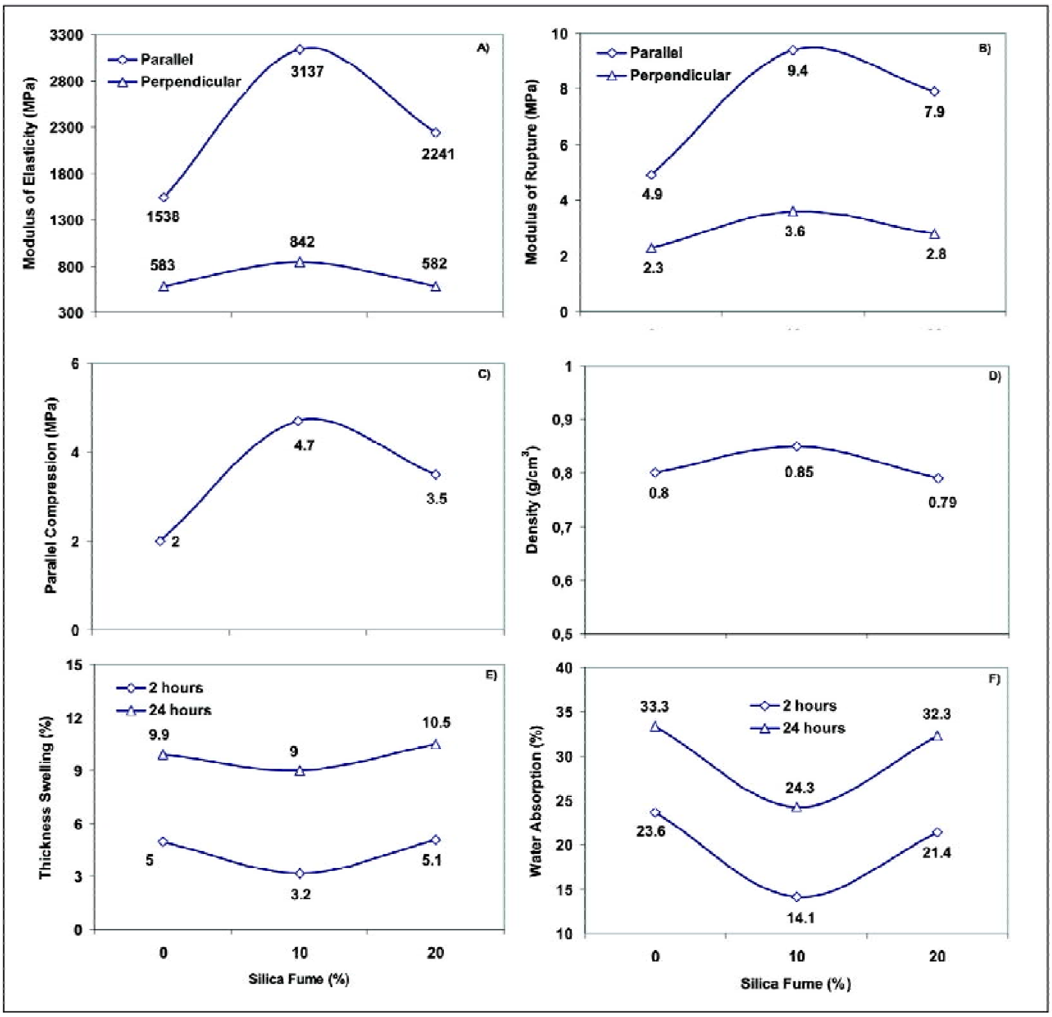


Figure. 2.- *Physical and mechanical properties of the oriented wood-cement board (OWCB).*

Table 1. - Effects of percentage of silica fume on the properties of oriented wood-cement board.

Property	Calc. F-value	Sig. F-value	Duncan Test		
			T0	T10	T20
Modulus of Rupture (//)	4.51*	0.036	a	b	c
Modulus of Rupture (⊥)	1.01^{ns}	0.41	-	-	-
Modulus of Elasticity (//)	6.25*	0.02	a	b	ab
Modulus of Elasticity (⊥)	0.89^{ns}	0.45	-	-	-
Internal Bonding	3.26^{ns}	0.086	-	-	-
Parallel Compression	7.52*	0.012	a	b	ab
Density	0.84^{ns}	0.464	-	-	-
Thickness Swelling (2h)	4.40*	0.049	b	a	b
Thickness Swelling (24h)	1.95^{ns}	0.197	-	-	-
Water Absorption (2h)	4.72	0.04	a	b	ab
Water Absorption (24h)	2.61^{ns}	0.127	-	-	-

- Significant at $\alpha = 0.05$ level. T0 = no silica fume; T10 and T20 = 10% and 20% of silica fume.

Additionally, only boards containing 10% silica fume met ISO 8335 requirements for MOR and MOE, which specifies 9 MPa and 3000 MPa, respectively. The results obtained here differ from those of Moslemi *et al.* (1995). They evaluated the effect of adding silica fume on the properties of a WCB produced by two pressing methods using aspen and larch particles. For both conventionally pressed board and those pressed using CO_2 injection boards, the addition of 10% silica fume reduced flexural properties (MOR and MOE), and only toughness was improved in some cases.

It is well-known that cement is stiffer than wood, so low amount of cement reduce the stiffness of the boards. However, despite the low cement:wood ratio (1:1), the flexural values were very satisfactory, probably because strands were oriented in boards. Moslemi and Pfister (1987) argued that when wood occupies more volume in a board (i.e. low cement:wood ratio), the regions of stress concentration around the adjacent particles are diffused, resulting in an increase in the applied stress. Forest Products Laboratory (1999) compiled physical and mechanical properties of several kinds of low density WCB (500 to 1000 kg/m^3). The values ranged from 1.7 to 5.5 MPa for MOR and from 621 to 1,241 MPa for MOE. The values found in the present study are within this range for MOE and above it for MOR. In comparison with other studies the properties of boards manufactured here are satisfactory. Papadopoulos *et al.* (2006) produced a cement-bonded OSB using oriented strand-type particles. For boards produced with cement:wood ratio of 1:1 they found MOR values of about 3.1 MPa and MOE values of about 467 MPa, which are lower then those observed here. Zhou and Kamdem (2002) produced a randomly oriented WCB with cement:wood ratio of 1:1 and the properties of theirs boards were lower than those of boards manufactured here. It can also be argued that it probably happened because they used hammer-milled-type particle which does not have a favorable geometry required to produce stiffer boards, as mentioned by Badejo (1998).

Very low IB values of less than 0.03 MPa were found for all boards This property evaluates tension strength perpendicular to the board surface, in other words the bonding quality of the matrix formed, by the wood and the cement. The possible causes of such low values can be: the strands geometry, the low cement: wood ratio and the low wood: water ratio. The strand-type particles are wider than those utilized in the WCB industry, so the cement can not encapsulate them completely, and good bonding does not occur. In commonly manufactured WCB the cement: wood ratio is higher (4:1 or 3:1) than those used here (1:1), and there is a sufficient quantity of cement compound to encapsulate the wood particles. Then, the IB strength is provided mainly by the cement matrix. The strands used for boards manufactured here were probably not encapsulated by cement and there were only weak mechanical bonds between the particles. Higher IB values have been found for WCB produced with the same strand-type particles and cement: wood ratio by Zhou and Kamdem (2002) - 0.37 MPa - and by Papadopoulos *et al.* (2006) - 0.13 MPa. These findings here suggest that more research is needed to overcome the low IB of the boards, because IB is a very important property and low values severely limit application of boards. Values for parallel compression showed significant differences between the two treatments (Table 1), and again the addition of 10% of silica fume improved board properties.

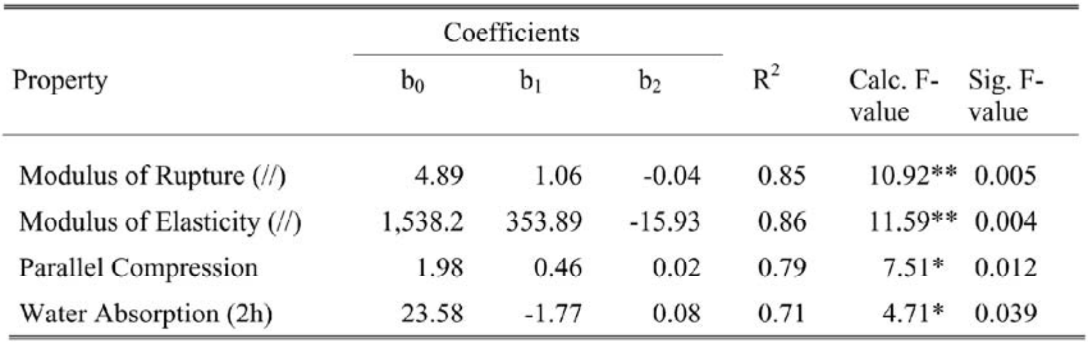
The TS values were very high, but close to those of boards made with the same wood:cement ratio by Fuwape and Oyagade (1993), although they differed from the results of Zhou and Kamdem (2002). None of the boards here, however, met the ISO 8335 requirement for TS, which is <2%. The large TS values can be function of the strand-type particle, which is difficult to compact, so more stress is required during the pressing. This builds into the board more latent compression stress and when the boards are exposed to water, they swell much more. It has been shown that WCB made from particles required lower compression stress than those made from strand or flake-type particles. Semple and Evans (2004) produced WCB from various species using two types of particles and observed that boards made with ordinary particles had TS values lower then those made with flakes. They argued that the rough surface and greater internal-void space of the flakeboards in comparison with particleboards were responsible for the greater thickness swelling of the flakeboards.

There is a direct correlation between TS and IB values for resin bonded particleboards. Panels with higher IB values can resist the stress due to wood expansion and press opening, resulting in lower TS. It is believed that wood-cement boards show the same behavior, and hence stronger panel should be able to resist TS when exposed to water (Zhou and Kamdem, 2002; Lange *et al.* 1989). To test this, the Pearson correlation was estimated between 2h TS and mechanical properties. A negative, but significant, correlation was found for MOR (//) ($r=-0.633; p<0.05$) and for PC ($r=-0.673; p<0.05$) however, for IB was not significant. It means that higher MOR and PC are associated with lower TS, which partially confirms the statement above.

The WA values were also higher than commercial WCB. The possible cause was the low cement:wood ratio used in the treatments. Large quantities of exposed wood and free internal spaces could be the possible cause for the high WA and, consequently, for a higher TS. Although the oriented wood cement boards were dimensionally unstable, the presence of silica reduced WA. Silica fume fills the pores in the cement-wood matrix, thus reducing the permeability of the board (i.e. water absorption) as observed by Moslemi *et al.* (1995). Fan *et al.* (2000) argued that for WCB this property has a linear correlation with TS as a first stage, indicating that water is absorbed primarily by the cell walls of the wood and then by the colloidal spaces of the cement paste. After particle fiber saturation, the moisture was not correlated with changes in board dimensions. The same behavior has been observed here. For the 2h test, a strong positive correlation was found between WA and TS ($r=0.775; p < 0.01$) which, however, was not significant for the 24h test.

For the properties affected by the silica fume (Table 2) a simple regression analysis was performed to model the effect of silica fume content on board properties. It can be observed in Figure 2 that the data has a polynominal trend. From the evaluated regression models it was determined that a polynominal-quadratic model fitted the data. This model had a higher R^2 coefficient and more significant F-values than the others. The coefficients for this model are show in Table 2. It can be observed that the linear coefficient (b_1) for the mechanical properties shows positive values, which means that the addition of the silica increases their values.

Table 2. - Coefficients of the quadratic model for the effect of the percentage of silica fume (PS) on board properties.



Property	Coefficients			R^2	Calc. F-value	Sig. F-value
	b_0	b_1	b_2			
Modulus of Rupture (//)	4.89	1.06	-0.04	0.85	10.92**	0.005
Modulus of Elasticity (//)	1,538.2	353.89	-15.93	0.86	11.59**	0.004
Parallel Compression	1.98	0.46	0.02	0.79	7.51*	0.012
Water Absorption (2h)	23.58	-1.77	0.08	0.71	4.71*	0.039

*,** significant at
$\alpha = 0.05$ and 0.01 levels respectively.
Quadratic model: Property = $b_0 + b_1 PS + b_2 PS^2$

4. CONCLUSION

It is possible to produce medium density (<1000 kg/m^3) cement bonded strandboard to meet modulus of rupture and modulus of elasticity requirements by orienting strands and using silica fume (SiO_2) as an additive. Ten percent of silica fume based on the cement weight was the best level of additive to improve mechanical properties. However, the boards were unstable dimensionally, with high values for thickness swelling possibly due to low wood:cement ratio and the particle geometry in the boards. Very low values for internal bonding were observed for all boards. More research is needed to overcome these limitations.

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