

Mechanical Properties and Dimensional Stability of Wood-Cement Particleboard from Tree Prunings Residues of Some Wood Species as Affected by The Panel Density

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ABSTRACT

The possibility of using tree prunings residues from four wood species grown in Saudi Arabia to create cement-bonded particleboards (CBPs) was studied. The properties of the produced CBPs at different board densities were evaluated. Panels were made using three different board densities (1100, 1200 and 1300 kg/m³) at a constant wood/cement ratio (1/2 by weight). The mechanical properties and dimensional stability characteristics of the CBP panels were determined. It was found that the tree prunings from the four wood species are suitable raw material to create CBPs after pretreating the particles in either cold or hot water and by using chemical additives. The results indicated that the panels produced from these tree prunings meet the mechanical and dimensional stability requirements of commercial CBP panels. CBP panels with good mechanical properties, good dimensional stability and a high level of board density (1300 kg/m³) should be used.

Keywords: Board density, cement-bonded particleboard, dimensional stability, mechanical properties, pretreatment, tree prunings, wood species.

INTRODUCTION

There is a growing wood demand from forest industries because the rapid development of the industry has decreased the wood supply. Many regions around the world have an acute shortage of wood. Saudi Arabia is similar to many developing countries in that there are not adequate forest reserves within the country to satisfy their needs for fuel wood, industrial wood, sawn wood, and wood composite panels. In the wood-based composite panel industry, which includes the manufacture of wood-cement particleboards, efforts are being intensified to determine other suitable wood substitutes. Apart from using tree thinnings, fast-growing trees and agricultural residues have been attempted (Almeida et al, 2002, Mohamed, 2004, Çöpür et al, 2007).

The cement-bonded particleboard (CBP) is one type of mineral-bonded product that has evolved as a high-density, smooth board with promising characteristics for

exterior use or where fire resistance is required. These panels contain 30-70% (by weight) of wood particles and 30-60% of a mineral binder (Vaickelioniene and Vaickelionis, 2006). Wood-wool slabs using magnisite as a binder were first produced; however, later Portland cement was introduced. The most important binder is cement because of its high quality and availability virtually all over the world. CBPs have excellent sound insulation, high resistance to water, termites and fungi, and excellent long-term weather durability in outdoor conditions. CBPs are used in roofing, wall and flooring parts, and noise absorbing partitions.

Many processing factors affect the mechanical properties and dimensional characteristics of CBP panels. The most important factors that affect CBP properties are the wood species and the particle size of the wood. Previous studies have revealed that not all wood species react favourably with cement due to the adverse effects of certain extractives during cement setting. These species are not suitable to manufacture CBPs (Miller and Moslemi, 1991, and Al-Mefarrej and Nasser, 2008; Nasser et al. 2011). Many investigators have performed a series of tests to enhance the compatibility of wood and cement by using different pretreatments and chemical additives. Cold and hot water extraction are among the common pretreatments used to extract the inhibitory substances in wood (Mohamed, 2004, and Olorunnisola, 2008). Calcium chloride is one of the chemical additives that is widely used as an accelerator for cement setting (Fernandez and Taja-on, 2000, and Olorunnisola, 2007). These treatments are relatively inexpensive and simple to use. To overcome the wood shortage and to meet the future demand of wood products, several countries have conducted studies to investigate the use of non-wood materials, agricultural residues, fast-growing trees, low-grade wood species and/or underused wood species as raw material to create CBPs. Examples of such alternative materials include vine stalks (Nasser et al., 2011), date palm midribs (Nasser and Al-Mefarrej, 2011 and Nasser 2014), arhar stalks (Aggarwal et al., 2008), sisal (Roma et al., 2008), wheat straw

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Received July 8, 2014, Accepted August 28, 2014

(Soroushian et al., 2004) and the shell of the babaçu (Almeida et al., 2002). Generally, these studies have shown the viability of using these materials for use in CBP composites. Saudi Arabia is a poor country in terms of timber resources, where tree prunings from trees on the streets and ornamental trees could be an inexpensive and adequate secondary resource.

Athel (*Tamarix aphylla*) is a forest tree planted throughout Saudi Arabia and is fast-growing, drought-resistant and salt-tolerant. Athel wood is a renewable resource that could be used as necessary raw material for several local uses. In the last three decades, many multi-purpose tree species, i.e., *Acacia salicina* and *Pithecellobium dulce*, were imported into the country and planted as fast-growing tree species to produce biomass (Aref et al., 2003). These trees are used to supplement fuel wood and fibrous raw materials. The suitability of these tree prunings as raw material for CBP manufacturing has not yet been explored. There is no accurate estimate in Saudi Arabia regarding the wastes accumulated from pruning *Ficus altissima* trees. However, annually, there are huge quantities of biomass due to seasonal pruning of this wood species as a regular agricultural practice in public gardens and streets. Most of these residues in developing countries are plowed into the soil or burned in fields; however, in developed countries, the residues are used to manufacture different types of wood products, i.e., pulp and paper (Abdel-Aal, 2013, Al Mefarrej et al. 2013), particleboards and fibreboards (Nasser 2012 and Hegazy and Aref, 2010). El-Juhany et al. (2003) stated that most of the tree prunings in Saudi Arabia are eliminated by incineration or discarded as waste by costly conventional methods, which can be considered as environmental pollution.

The objectives of this study were to investigate the effects of wood species and board target density on the properties of CBP panels from tree prunings from four hardwood species grown throughout Saudi Arabia.

MATERIALS AND METHODS

Raw materials

Tree prunings residues of four different tree species growing in Riyadh city were collected during 2011 and used as lignocellulosic raw materials to manufacture wood-cement particleboards (WCPs). The species were *Acacia salicina*, *Ficus altissima*, *Pithecellobium dulce* and *Tamarix aphylla*. The characteristics of these species are listed in Table 1. After being collected and air-dried, the woody materials were cut into small pieces or discs using a band saw and fed through a laboratory hammer mill using a 5-mm screen. Two particle sizes were used in the current study: particles that were passed through a 0.8-mm sieve and retained on a 0.4-mm sieve (-20/+40 mesh) were used to manufacture WCP panels. Particles that were passed through 0.4-mm sieve and retained on a 0.27-mm sieve (-40/+60 mesh) were used to perform the chemical analysis of the wood. The wood particles (-20/+40 mesh) were pretreated by either cold water soaking or hot water extraction before manufacturing the WCP panels according to Nasser (1996) and Moslemi et al. (1983).

Commercial Portland cement (Type I), which met the ASTM specification (ASTM C150, 1984) and was manufactured by Yamama Saudi Cement Company Limited, Riyadh Saudi Arabia, was used in this study as a binder. A list of several of its chemical composition is shown in Table 2 as provided by the supplier.

Chemical Analysis of the Woody Materials

The percentages of the woody extractives based on the oven-dried weight was determined according to ASTM D1105 (1989). The contents of the three primary chemical components of wood i.e., cellulose, hemicelluloses, and lignin, were then determined using extractive-free wood meal and based on the oven-dried weight according to the standard methods described in the ASTM designations (ASTM, 1989) D1103, D1104 and D1106, respectively. In addition, the ash content was determined according to ASTM-D1102 (1989).

Table 1. Characteristics of the pruning residues of the four wood species

Wood Species	Height (m)	Diameter (cm)	Age (year)	SG	MC* (%)
<i>Acacia salicina</i>	9.65	13.5	10-12	0.561	8.45
<i>Ficus altissima</i>	19.3	26.5	20-25	0.460	9.65
<i>Pithecellobium dulce</i>	12.8	14.3	10-12	0.532	8.79
<i>Tamarix aphylla</i>	32.2	35.7	30-35	0.600	15.16

Each value is an average of 3 trees.

SG is the basic specific gravity, and MC is the moisture content. Each value is an average of 10 samples.

* After being air-dried and before processing. Date palm required additional drying to decrease the MC.

Table 2. Properties of ordinary Portland cement (Type I).

	Chemical composition (%)						Setting time (min)		C _{max} (MPa)
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	Initial	Final	
Cementused	20.46	5.69	3.88	64.82	0.72	2.55	105	165	29.9
ASTM*	(-)	(-)	(-)	(-)	Max 6.0	Max 3.5	Min. 45	Max. 375	Min. 19.7

Reported by the supplier (Yamama Saudi Cement Company Limited).

(-) limit is not specified.

Time of setting was performed by the Vicat test method.

C_{max} is the compressive strength of cement after 7 days.

According to standard specification for Portland cement (ASTM C150, 1997).

Hydration test

Twelve treatments were performed for each species: every combination between pre-treatment (untreated, cold water and hot water) and the addition of four different chemicals (none, CaCl₂, Al₂(SO₄)₃ or MgCl₂) was tested. Hydration data was obtained, and the inhibitory index was calculated according to Moslemi *et al.* (1983). Wood materials mitigate the temperature increase that occurs during the setting process of cement.

Treatment selection for WCP manufacturing

The hydration data (not included) revealed that the four wood species cannot be used directly as raw materials for WCPs. The wood species must first be pre-treated by either cold or hot water with an addition of 3 wt% CaCl₂ or MgCl₂. As seen in Table 3, the best treatment differed depending on the wood species. Using the best treatment, the four wood species were all suitable for WCP production according to Sandermann and Kohler (1964) and Hachmi *et al.* (1990). The results showed that the time to reach the maximum temperature (t_{max}) ranged from 2.5 to 4.0 h; therefore, the panels were pressed in an automatic hydraulic press for at least 4 h and then clamped for 20 h before being removed from the mould. These results agree with the results from previously published reports (Olorunnisola, 2007).

WCP panels preparation

The WCP panels were manufactured based on the results of the hydration test (Table 3) using the best treatment, which included a pre-treatment (cold or hot

water) and the addition of chemical additives (CaCl₂ or MgCl₂) based on the method described by Papadopoulos (2008). Oven-dried wood particles (278 g) and an aqueous solution (24.3 g of chemical additives dissolved in 383.4 mL of distilled water) were hand-mixed. Then, 810 g of Portland cement (Type I) was added to the wetted particles, and the constituents were thoroughly mixed until the cement paste was completely hydrated. The distilled water quantity was calculated according to the relationship developed by Simatupang (1979). After approximately 15 minutes of hand mixing, an open-top box made of composite wood and coated with a phenolic layer, which had an inside base with dimensions of 30 x 30 cm and a height of 3.1 cm, was used to form the panel. The mat was then cold-pressed using a hydraulic press (Carver Monarch) to a 10-mm thickness, and the panel remained under a constant pressure for 20 h using a press clamp. The panels were carefully extracted from the mould, misted with water, wrapped in cellophane and aligned before conditioning at room temperature and relative humidity for at least 1 month. In total, 36 panels were manufactured, which represented four wood species, three target densities and three panels per combination.

Test specimens preparation

The CBP panels were dried at approximately 70 °C for 8 h after conditioning and before cutting. All the CBP panels were trimmed by cutting approximately 1 cm from each side to the dimensions of 28 by 28 cm.

Table 3. Hydration parameters for the best treatments selected to manufacture WCP panels.

Wood Species	Best treatment		Hydration data and indices				
	Pre-treatment	Chemical additive	T _{max} (°C)	ΔT (°C)	t _{max} (hrs)	I	C _A (%)
<i>A. salicina</i>	CWE	CaCl ₂	74.53 ^C	51.03 ^C	3.00 ^C	-0.81 ^B	84.51 ^B
<i>F. altissima</i>	HWE	MgCl ₂	72.66 ^D	49.00 ^C	4.00 ^A	-0.45 ^B	81.75 ^C
<i>P. dulce</i>	HWE	MgCl ₂	76.80 ^B	53.03 ^B	3.50 ^B	-0.68 ^B	85.13 ^B
<i>T. aphylla</i>	HWE	CaCl ₂	80.20 ^A	57.93 ^A	2.50 ^D	0.79 ^A	89.81 ^A
Net cement	-	-	88.60	65.6	6.25	0	100

CWE: cold water extraction, HWE: hot water extraction.

T_{max}: maximum temperature, ΔT: temperature increase above room temperature,

t_{\max} : time to reach T_{\max} , I: inhibitory index and C_A : compatibility factor.

Test specimens were prepared and cut to determine the mechanical properties of the CBP panels and the dimensional stability properties according to ASTM D-1037 (1989). Two samples for the bending test, three specimens for the IB test and three specimens for the dimensional stability test were cut from each panel.

Mechanical properties of the WCP panels

In accordance with ASTM D-1037 (1989) with several modifications due to the limited size of the panels and by using an Instron Testing Machine (Model 3382), static bending, internal bond, screw withdrawal and Janka hardness tests were performed on the WCP panels. The modulus of rupture, modulus of elasticity, internal bond strength, screw holding power and Janka hardness number were calculated and recorded. After static bending was completed, the specimens were cut near the failure zone to determine the density and moisture content of the WCPs by the displacement method in water and the conventional dry method, respectively.

Dimensional stability characteristics

Dimensional stability characteristics, which include water uptake (WU), thickness swelling (TS) and linear expansion (LE) of the CBP panels, were determined according to ASTM D-1037, 1989. The samples were soaked in a water bath at room temperature for 2 h and then taken out and weighed. The samples were then re-immersed to complete the 24-h soaking time. The percentage of WU, TS and LE after 24 h were expressed based on the original state.

Statistical analysis

A randomised complete design (CRD) with two factors was used to study the differences in the properties of the CBP panels using the analysis of variance (ANOVA). Using the SAS statistical package (2004), the mean values were tested by an LSD test ($p < 0.05$) to detect the significance of the differences between the four species and the different panel target densities of the CBP panels.

RESULTS AND DISCUSSIONS

Chemical analysis of the four wood species

The chemical composition of the wood is one of the most important factors that affect the compatibility between wood and cement and the mechanical properties of the produced WCP panels. A comparison of the chemical composition between the four wood species and hardwood is presented in Table 4. There were significant differences for all chemical constituents. These variations might explain the

differences between the produced WCPs. It was evident that, with the exception of the extractives content of *T. aphylla* and the ash content of all the wood species, all chemical constituents fell within the range of hardwood species. The high extractive content and the solubility in cold and hot water of *T. aphylla* may be attributed to the inclusion of bark in the wood meal (Table 1). The last two parameters are the most important factors that influence the compatibility between wood and cement (Moslemi *et al.*, 1983). The pre-treatment of the wood particles most likely removed many extraneous substances that inhibit cement setting, which resulted in a stronger bond between the wood particles and the cement and improved the mechanical properties of the produced WCP panels (Moslemi *et al.* 1983; Nasser 1996; Pehanich *et al.* 2004; Nasser *et al.* 2011). However, in the current work, these components may have had a smaller effect on the properties of the WCP panels because the wood particles were pre-treated by either cold or hot water before manufacturing the panels. The ash content of the wood species appears to be extremely high compared with that of hardwood species and ranged from 1.0% for *A. salicina* to 6.4% for *T. aphylla* (Table 5). Generally, it is known that the ash content of wood is less than 1%; however, many researchers (Al-Mefarrej *et al.* 2011; Abdel-Aal *et al.* 2011) have reported that most wood species grown in Saudi Arabia have a higher ash content, greater than 2%.

Effect of wood species on the CBP panel properties

The mean values and standard deviations of the physical and mechanical properties and the dimensional stability characteristics of the CBP panels are presented in Table 5. The analysis of variance showed that all the CBP panel properties, with the exception of the physical properties (moisture content and density), differed among the four wood species. This result indicates that the type of wood species significantly affects the properties of the produced CBP panels. It is clear that *A. salicina* and *P. dulce* exhibited the highest MOR value, and *T. aphylla* exhibited the lowest MOR value.

As shown in Table 5 and Fig. 1, the MOR and MOE values for all of the CBP panels met the minimum requirements set by the International Organisation for Standardisation (ISO 8335-1987), and these values compare favourably to CBP data published in past studies. The MOR values of the CBP panels made from the coconut shell of babaçu were between 1.6 and 3.8 N/mm², and the MOE values were between 821 to 2650 N/mm² (Almeida *et al.* 2002). The IB values ranged from 1.3 to 1.5 N/mm² and exceeded, by at least three

fold, the requirement set forth by the ISO standard (0.45 N/mm²).

Table 4. Chemical analysis of the four wood species used to manufacture the WCP panels.

Wood species	Percentage content of				
	Extractives*	Holocellulose	Lignin	Ash	CWS
<i>A. salicina</i>	5.2 ^C	68.3 ^B	31.7 ^B	1.0 ^D	3.9 ^D
<i>F. altissima</i>	9.9 ^B	69.7 ^{AB}	30.4 ^{BC}	3.0 ^C	9.2 ^B
<i>P. dulce</i>	6.1 ^C	70.6 ^A	29.4 ^C	4.8 ^B	5.7 ^C
<i>T. aphylla</i>	16.3 ^A	66.4 ^C	33.6 ^A	6.4 ^A	12.7 ^A
Hardwood ⁺	2-8	60-85	23-30	0.2-0.5	4-6

Each value is an average of 5 samples.

* Total extractives by ASTM D1105 (1989).

Means with the same letter in a column are not significantly different at a 0.05 probability level according to the LSD test.

+ Fengel and Wegener (1987).

CWS: cold water solubles.

Table 5. Mean values* and standard deviations of the mechanical and dimensional stability properties of the WCP panels made from the four wood species

Wood species	Mechanical properties			Dimensional stability (%)		
	MOE (N/mm ²)	IB (N/mm ²)	SHP (N)	Water uptake	Thickness swelling	Linear expansion
<i>A. salicina</i>	4850 ^B (1600)	1.45 ^A (0.4)	1601 ^A (312)	14.93 ^C (5.2)	1.00 ^B (0.2)	0.53 ^C (0.2)
<i>F. altissima</i>	4740 ^B (800)	1.32 ^B (0.9)	1201 ^C (430)	19.09 ^B (7.7)	1.29 ^A (0.6)	0.72 ^A (0.3)
<i>P. dulce</i>	6130 ^A (900)	1.28 ^B (0.2)	1290 ^B (187)	18.13 ^B (4.3)	0.68 ^C (0.3)	0.34 ^D (0.1)
<i>T. aphylla</i>	6350 ^A (700)	1.32 ^B (0.3)	1228 ^{BC} (196)	23.28 ^A (5.3)	1.21 ^A (0.3)	0.60 ^B (0.1)
Requirement	3000	0.45	-	-	8	-

* Each value is an average of 27 specimens.

() Values between parentheses are standard deviations.

Means with the same letter in a column are not significantly different at a 0.05 probability level according to the LSD test.

MOE: modulus of elasticity, IB: internal bond, SHP: screw holding power.

Dimensional stability was performed after being soaked in water for 24 h.

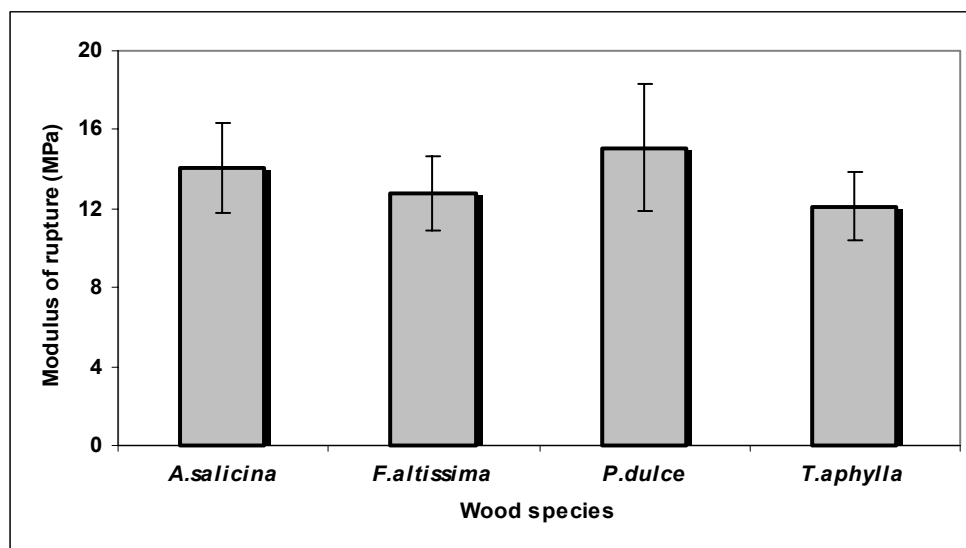


Fig. 1. Modulus of rupture of CBP panels made from the four wood species

These results may be attributed to the use of pre-treated wood particles in manufacturing the CBP panels, which improved the compatibility between the wood particles and the cement. Many researchers have concluded that the water-soluble extractives of wood could potentially inhibit the normal setting and strength development of cement (Olorunnisola, 2007 and Ashori et al., 2011). Researchers have reported IB values between 0.4 and 1.3 N/mm² for a wood-wool cement board made from eucalyptus and poplar.

The results indicate that the lowest water absorption, which was judged based on the 24-h water immersion (WA) values, was observed in panels made from *A. salicina* (14.9%). The CBP panels made from *T. aphylla* had the highest water uptake value (23.3%). The thickness swelling values after the 24-h water immersion ranged from 0.7% (*P. dulce*) to 1.3% (*F. altissima*). These values are well below the maximum limit set by the ISO standard (8.0%). The CBP panels made from the four wood species exhibited a greater dimensional stability compared with previously reported data.

The mechanical properties of the CBP panels made in this study were superior to those of other cement-bonded composites using different raw materials under different manufacturing variables (Almedia et al. 2002; Sudin and Ibrahim 2001; Semple et al. 2002; Ashori et al. 2011). All of the physical and mechanical properties of the CBP panels made from the four wood species surpassed the minimum requirements; the dimensional stability characteristics of the panels were also lower than the maximum limits of particleboard standards. These results agree with (Okino et al., 2004; Olorunnisola, 2007; Aggarwal et al., 2008;

Papadopoulos, 2008; Nasser 2014). According to these results, CBP panels can be made from the tree prunings of the four studied wood species after pre-treating the particles with either cold water soaking or hot water extraction and adding either calcium chloride or magnesium chloride as an accelerator.

Effect of board density on the properties of CBP panels

The analysis of variance indicated that the effect of the target board density of the CBP panels on their properties was significant, with the exception of moisture content. The effect of the target board density on the mean values of the physical and mechanical properties of the CBP panels are presented in Table 6 and Fig. 2. The results indicated that the mechanical properties of the CBP panels increased as the board density increased from 1100 to 1300 kg/m³. However, the inverse trend was reported for water uptake, thickness swelling and linear expansion of the CBP panels; these values decreased as the board density increased. These results agree with the results from (Papadopoulos 2008 and Nasser 2014).

Effect of the interaction between wood species and board density on the CBP properties

The interaction between wood species and board density of the CBP panels was highly significant for all mechanical properties and dimensional stability characteristics, with the exception of moisture content, which was not significant. The mean values and standard deviations of the CBP panel properties made from the four wood species at the three target board densities are presented in Table 7 and Figs. 4-6.

Table 6. The effect of the target density of the CBP panels on the mechanical and dimensional stability of the WCP panels.

Board Density	Mechanical properties			Dimensional stability (%)		
	MOR (N/mm ²)	MOE (N/mm ²)	JHN (N)	Water uptake	Thickness swelling	Linear expansion
1100	10.33 ^C (0.8)	4730 ^B (1100)	4006 ^C (1099)	19.56 ^A (7.3)	1.20 ^A (0.6)	0.63 ^A (0.3)
1200	13.78 ^B (2.8)	5530 ^{AB} (1700)	5142 ^B (703)	19.65 ^A (4.2)	1.06 ^{AB} (0.3)	0.53 ^B (0.2)
1300	16.44 ^A (2.7)	6300 ^A (1000)	5731 ^A (852)	15.96 ^B (6.4)	0.87 ^B (0.3)	0.48 ^B (0.2)
Requirement	Min 9.00	min 3000		-	max 8.0	

Each value is an average of 36 specimens.

() Values between parentheses are standard deviations.

Mean values with the same letter in a column are not significantly different at a 0.05 probability level according to the LSD test.

MOR: modulus of rupture, MOE: modulus of elasticity, JHN: Janka hardness number.

Dimensional stability was performed after being immersed in water for 24 h.

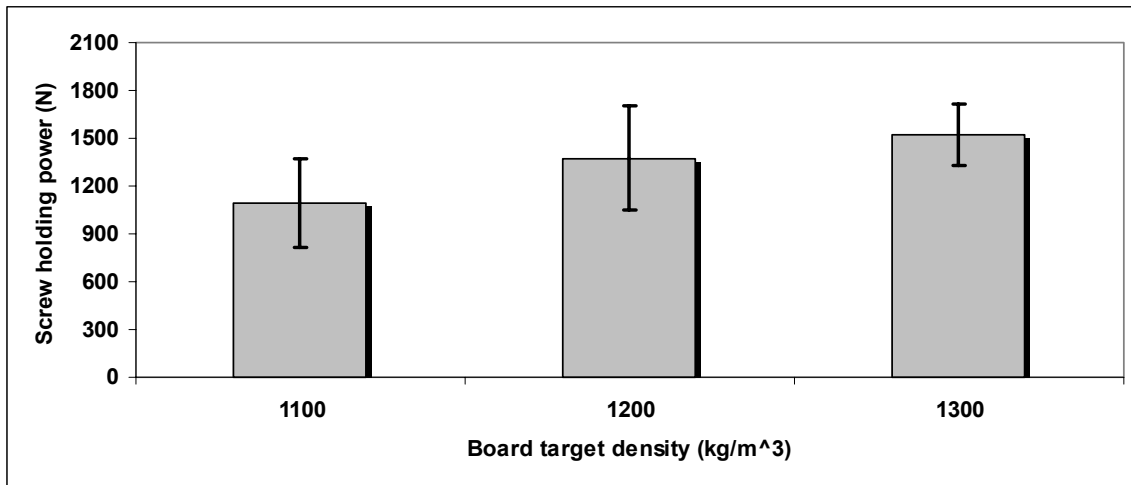


Fig. 2. Effects of board density on the screw holding power of the CBP panels

Table 7. Properties of the WCP panels of the four wood species under the target density of the panels

Wood species	Mechanical properties				Dimensional stability	
	Board density (kg/m ³)	Modulus of rupture (N/mm ²)	Screw holding (N)	Janka hardness (N)	Thickness swelling (%)	Linear expansion (%)
<i>A. salicina</i>	1100	11.0±0.8	1433±129	4098±927	1.03	0.73
	1200	16.7±3.1	1988±117	5227±610	0.81	0.47
	1300	14.5±2.0	1381±141	5878±976	1.15	0.39
<i>F. altissima</i>	1100	9.8±0.6	738±86	4144±799	1.89	1.05
	1200	13.0±0.2	1143±32	4795±966	1.45	0.77
	1300	15.7±2.6	1720±47	5948±707	0.53	0.34
<i>P. dulce</i>	1100	10.7±0.7	1111±53	4634±511	0.51	0.25
	1200	14.4±1.9	1248±47	5853±311	1.01	0.28
	1300	20.1±0.9	1511±110	6454±247	0.52	0.49
<i>T. aphylla</i>	1100	9.8±0.5	1090±68	3147±335	1.38	0.49
	1200	11.1±0.9	1118±74	4694±256	0.97	0.62
	1300	15.5±0.8	1476±70	4642±199	1.29	0.69
LSD _{0.05}		2.8	148	1074	0.29	0.26

Each value is an average of 9 specimens± standard deviations.
 Dimensional stability was performed after being immersed in water for 24 h.
 LSD_{0.05} for the interaction between the species and board density.

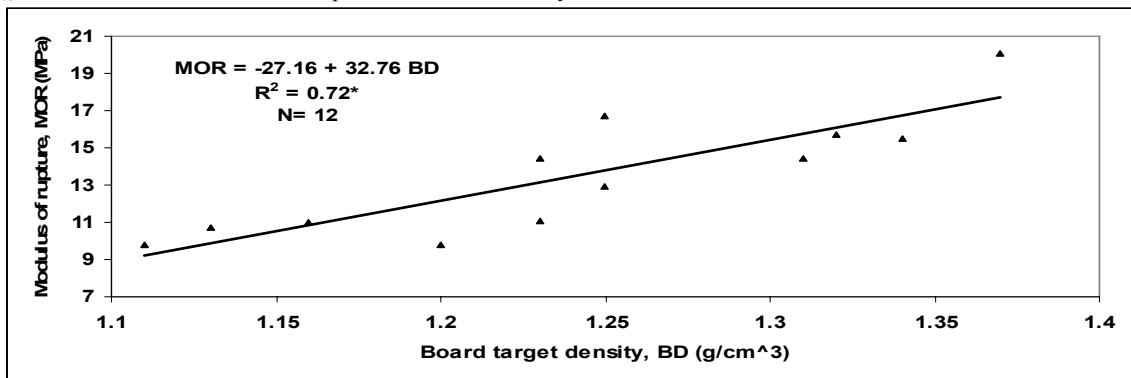


Fig. 3. Relationship between MOR and the density (oven-dry bases) of the WCP panels

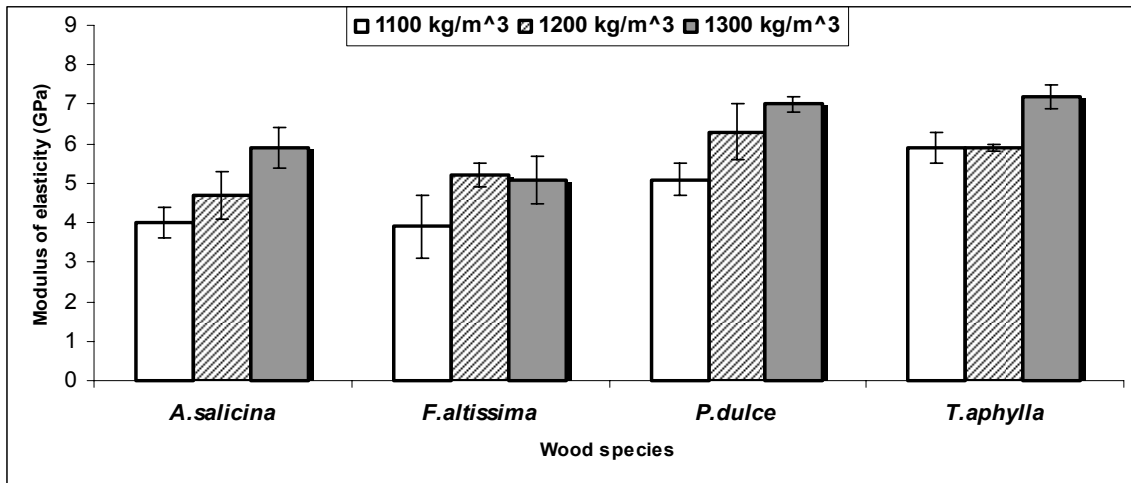


Fig. 4. Effect of the board density of the panels on the MOE of the WCP panels from the four wood species

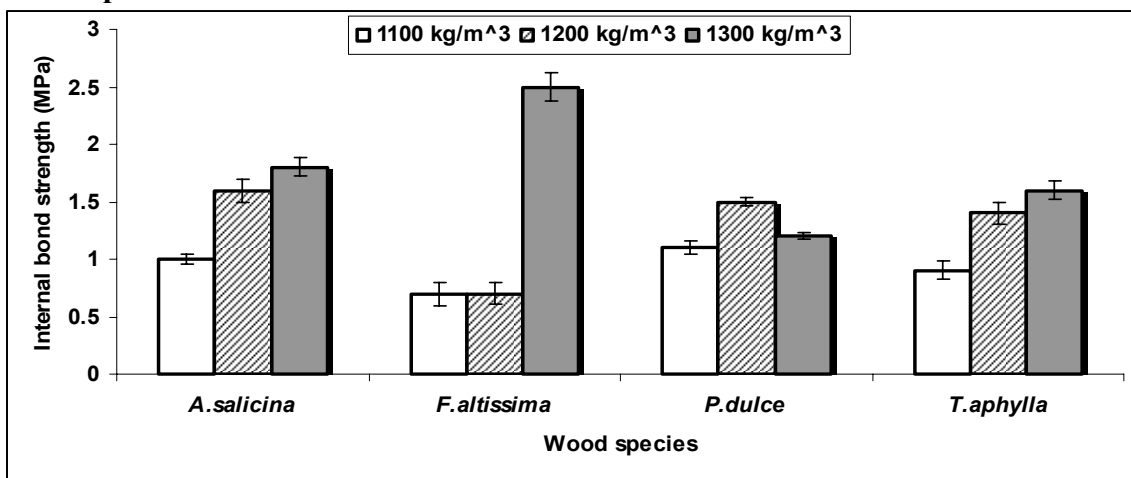


Fig. 5. Internal bond strength of the WCP panels of the four species at the board target density.

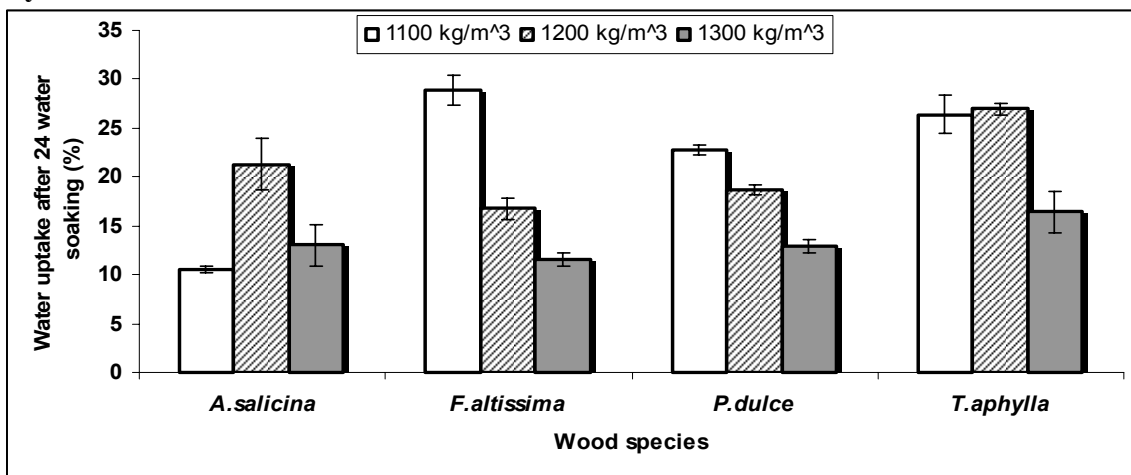


Fig. 6. Water uptake of the WCP panels of the four wood species as affected by the board target density

The results showed that for each species, the values of the mechanical properties (MOR, MOE, IB, SHP, and JHN) increased as the board density increased from 1100 to 1300 kg/m³. The highest values were recorded for panels from a high board density (1300 kg/m³), and the lowest value was recorded with panels made from a low board density (1100 kg/m³). These results agree with the findings by Ajayi and Badejo (2005), which showed that it may be possible to produce stronger, heavier WCP panels by increasing the board density. The mechanical properties of the WCP panels made in this study met the minimum requirements set by the International Organisation for Standardisation (ISO 8335-1987) and compare favourably with data published using different lignocellulosic materials under different manufacturing variables (Semple *et al.* 2002; Ashori *et al.* 2011 and Nasser 2014). The results indicated that all the mechanical properties of the WCP panels were directly related to the board target density, as shown in Fig. 3. These results conform with the fact that the density of all types of wood-based panels normally exerts a significant influence over the mechanical properties of the panels and to the previously published studies on cement-bonded particleboards (Badejo, 1988, Ajayi and Badejo 2005, Nasser 2014).

The dimensional stability characteristics of the panels produced from each species increased as the board density of the panels increased from 1100 to 1300 kg/m³ (Table 7), which can be noted by the decrease in all measured parameters, i.e., water uptake (WU), thickness swelling (TS) and linear expansion (LE) after 24 h of being soaked in water. These results agree with (Papadopoulos 2008), which attributed these results to the greater volume of material consolidated into the higher-density mat, which resulted in a higher board compaction ratio and consequently, fewer void spaces within the boards. Denser panels, which contain less void spaces in the structure, were expected to absorb less water.

CONCLUSIONS

Four wood species residues were used in the current work as raw material for CBP panels and could be used to manufacture CBPs after pre-treated by either cold or hot water and by adding either CaCl₂ or MgCl₂ as an accelerator. Under these conditions, the tree prunings residues of the four wood species are suitable to manufacture high-quality CBP panels. The CBP panels meet the mechanical and dimensional stability requirements of commercial CBP panels. The results indicated that the board density of the CBP panels had a significant effect on the properties of the panels

produced. The mechanical properties and dimensional stability characteristics of the panels increased as the board density increased from 1100 to 1300 kg/m³. To produce CBP panels with good mechanical properties and dimensional stability, a high board density should be used. These tree prunings residues could be used an alternative wood source for cement-bonded particleboards by the wood composite industry.

ACKNOWLEDGEMENTS

With sincere respect and gratitude, I would like to express deep thanks to NPST program, King Saud University, Saudi Arabia for the financial support (project no 08-ENV 517-02), sponsorship and encouragement. My deep thanks to Dr. Ramadan A. Nasser, Assistant Professor of Forestry and Wood Technology, Faculty of Agriculture, Alexandria University, Alexandria, Egypt for his assistance.

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