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Effects of tree species and wood particle size on the properties of cement-bonded particleboard manufacturing from tree prunings

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Abstract

This study investigated the possibility of using the prunings of six locally grown tree species in Saudi Arabia for cement-bonded particleboard (CBP) production. Panels were made using four different wood particle sizes and a constant wood/cement ratio (1/3 by weight) and target density (1200 kg/m3). The mechanical properties and dimensional stability of the produced panels were determined. The interfacial area and distribution of the wood particles in cement matrix were also investigated by scanning electron microscopy. The results revealed that the panels produced from these pruning materials at a target density of 1200 kg m^{-3} meet the strength and dimensional stability requirements of the commercial CBP panels. The mean moduli of rupture and elasticity (MOR and MOE) ranged from 9.68 to 11.78 N mm^2 and from 3952 to 5667 N mm^2, respectively. The mean percent water absorption for twenty four hours (WA24) ranged from 12.93% to 23.39%. Thickness swelling values ranged from 0.62% to 1.53%. For CBP panels with high mechanical properties and good dimensional stability, mixed-size or coarse particles should be used. Using the tree prunings for CBPs production may help to solve the problem of getting rid of these residues by reducing their negative effects on environment, which are caused by poor disposal of such materials through direct combustion process and appearance of black cloud and then the impact on human health or the random accumulation and its indirect effects on the environment.

Key words

Cement-bonded particleboard, Dimensional stability, Mechanical properties, Target density, Wood/cement ratio

Introduction

The natural forest area in Saudi Arabia covers approximately 2.1 million ha equivalent to 1.3% of the area of the Kingdom (El Atta and Aref, 2010). The Kingdom depends on imported wood and wood products to meet the demands of the population, which puts great strain on the government budget. The value of imported panels was USS 476.8 million in 2010, of which approximately USS20.5 million are due to particleboard (FAO, 2011). The increasing population and growing concern about the environment have led to changes in forest management practices, resulting in a significant reduction in wood harvesting from national forests despite growing demands. In the meantime, a constantly increasing population has resulted in an escalating demand for wood in the forest products.

Cement-bonded particleboard (CBP) is one of the most important mineral-bonded wood composites, a molded panel comprised of 10-70 wt% wood particles and 30-90 wt% Portland cement binder. Unlike resin-bonded particleboards, CBP boasts excellent sound insulation, high resistance to water, termites and fungi, and excellent long-term weather durability in outdoor conditions. These advantages suggest its potential application as a replacement for traditional building materials and conventional wood composites in roofing, wall and flooring parts and noise absorbing partitions. CBP panel production provides attractive

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possibilities for using wood wastes and agricultural residues, which are otherwise environmentally problematic. In addition they have a low production cost. However, several problems have hindered the development of these composites, including species sensitivity and heavy weight.

The ability of wood to combine with Portland cement is termed compatibility. It can be measured either by exothermic behavior during hydration processing or by measuring some strength properties of the resulted CBP panels. Hydration characterised include the maximum hydration temperature (T_2), time to reach maximum temperature (t_2), inhibitory index (I) and compatibility factor (C_A). Inhibited reactions caused by species are characteristics by lower T_2 or by a longer t_2 and higher inhibitory index (Moslemi *et al*., 1983, Sample *et al*., 2002 and Okino *et al*., 2004). Cold and hot water are among the common pretreatments used to extract inhibitory substances in wood (Moslemi *et al*., 1983). Calcium and magnesium chloride are widely used accelerators of cement setting. These treatment methods were used in this work (both pretreatments and accelerators).

Scanning electron microscope (SEM) imaging technique has been used to identify the interfacial area between the wood particles and the cement matrix of the fracture surface of the CBP samples (Ahn and Moslemi, 1981 and Tonoli *et al*., 2010). Davies *et al*. (1981) investigated that wood fiber reinforced cement composites by SEM. They concluded that the fiber break at fracture interfaces for the pre-treated composite while the fibers pull out from the cement matrix for untreated composites. Ahn and Moslemi (1981) examined the wood-cement bonds by using SEM. They concluded that specimens containing calcium chloride exhibited cone-shaped, well-formed crystals in the cement and their strength was greater than that of the controls, while the specimens containing D-glucose or sucrose had very poor strength, with long thin fibers.

Lignocellulosic materials, including wood species from different countries, have been screened, tested and classified according to their suitability for CBP production. The next step involves experiments to improve this compatibility by using various pretreatments and/or chemical additives to manufacture wood-cement panels. Finally, the properties of the resulting panels must be determined to gauge their suitability for various applications. Studies have been conducted to utilize non-wood materials, agricultural residues, fast-growing trees, low-grade wood species and/or underutilized wood species as raw materials for CBP production in several countries to overcome the wood shortage and to meet the future demand of wood products. Some of these raw materials include vine stalks (Nasser *et al*., 2011), arhar stalks (Aggarwal *et al*., 2008), sisal (Roma *et al*., 2008), wheat straw (Soroushian *et al*., 2004) and shell of babaçu (Almeida *et al*., 2002). Overall these studies have shown the viability utilizing of these materials for use in CBP composites. In Saudi Arabia, with its poor timber resources, the pruning of street trees could be an inexpensive and adequate secondary resource.

The properties of CBP panels are affected by many processing factors. The types of raw material used and the particle size of the wood are the most important factors affecting the properties of CBP. Species is one of the most important factors affecting the compatibility of wood-cement mixtures and the properties of CBP panels. Previous studies revealed that not all species react favorably with cement (Hachmi *et al*., 1990, Sample *et al*., 2002 and Aggarwal *et al*., 2008). Badejo (1988) reported that the effects of particle size and geometry on the mechanical properties of CBP are similar to those observed in resin particleboards. Semple and Evans (2004) stated that CBP requires a larger particle size than resin particleboard, as there is no chemical bonding between cement and wood. Shorter fibers means that there are more individual fibers per unit volume, which may lead to an increase in the void space per unit weight due to the cell lumens of the fibers (Pehanich *et al*., 2004).

Although there are no accurate estimates in the Kingdom concerning residues accumulated from the pruning of trees, enormous quantities of *Conocarpus erectus*, *Ficus altissima* and *Pithecellobium dulce* yields a large amount of biomass annually through seasonal pruning as a regular agricultural practice in public gardens and streets. In developing countries, most of these residues are plowed into the soil or burned in the field; however, in developed countries these residues are used to produce wood composites such as pulp, particleboard and medium density fiberboard. In Saudi Arabia, most of these residues are eliminated by incineration or discarded as waste by costly conventional methods that could be considered environmental pollution (El-Juhany *et al*., 2003). No data are currently available in this field regarding these residues.

Tamarix aphylla (locally named Athel) is a species of forest trees planted throughout the kingdom that is fast-growing, drought resistant and salt-tolerant. This species of wood is a renewable resource that could be used as a source of necessary raw material for several local uses. During the last three decades, many multi-purpose tree species, i.e., *Acacia salicina* and *Leucaena glauca* were imported into the country and planted as fast-growing tree species for biomass production (Aref et al., 2003). These trees are used to supplement fuelwood and fibrous raw materials. However, the suitability of wood prunings of these trees in the manufacturing of CBP panels has not been explored.

The objective of this study was to investigate the effects of wood species, particle size and pretreatments on the physical and mechanical properties of cement-bonded particleboard made from tree pruning residues of six hardwood species grown throughout Saudi Arabia.

Table 1 : Characteristics of pruning residues of the six wood species

Wood species	Height (m)	Diameter (cm)	Age (year)	SG	MC* (%)	Remarks
Acacia salicina	9.65	13.5	10-12	0.561	8.45	Branches without bark
Conocarpus erectus	15.7	11.9	10-12	0.653	6.39	Branches with bark (10-12%)
Ficus altissima	19.3	26.5	20-25	0.460	9.65	Branches without bark
Leuceana glauca	13.4	17.6	10-12	0.530	6.41	Branches without bark
Pithecellobium dulce	12.8	14.3	10-12	0.532	8.79	Branches without bark
Tamarix aphylla	32.2	35.7	30-35	0.600	15.16	Branches with bark (7-11%)

Each value is an average of 3 trees; SG is specific gravity and MC is moisture content. Each value is an average of 10 samples; * After air-drying and before processing

Table 2 : Hydration parameters and indices for the best treatments selected to CBP panels manufacture

	Best treatment		Hydration data and indices				
Wood species	**Pre-treatment**	**Chemical additive**	**T_{max} (°C)**	**DT (°C)**	**t_{max} (hrs)**	**I (%)**	**C_A (%)**
A. salicina	CW	$CaCl_2$	74.53^{CD}	51.03^{C}	3.00^{C}	-0.81^{BC}	84.51^{B}
C. erectus	HW	$CaCl_2$	77.13^{AB}	54.93^{AB}	3.00^{C}	-1.42^{CD}	87.70^{A}
F. altissima	HW	$MgCl_2$	72.66^{D}	49.00^{C}	4.00^{A}	-0.45^{B}	81.75^{C}
L. glauca	CW	$CaCl_2$	73.47^{D}	50.40^{C}	3.00^{C}	-1.99^{D}	80.99^{C}
P. dulce	HW	$MgCl_2$	76.80^{BC}	53.03^{B}	3.50^{B}	-0.68^{B}	85.13^{B}
T. aphylla	HW	$CaCl_2$	80.20^{A}	57.93^{A}	2.50^{D}	0.79^{A}	89.81^{A}
Portland cement	**-**	**-**	**88.60**	**65.6**	**6.25**	**0**	**100**

CW: cold water soaking, HW: hot water extraction, T_{max}: maximum temperature, DT: rise in temperature above room temperature, t_{max}: time to reach T_{max}, I: inhibitory index and C_A: compatibility factor

Materials and Methods

Raw materials : Tree prunings of six different tree species, growing in Riyadh city, were collected during 2011 to be used as lignocellulosic raw materials for manufacturing cement-bonded particleboards (CBP). These species were *Acacia salicina, Conocarpus erectus, Ficus altissima*, *Leuceaena glauca*, *Pithecellobium dulce* and *Tamarix aphylla*. The characteristics of these species and their descriptions are listed in Table 1. Commercial Portland cement (Type I) manufactured by Al-Yamama Cement Company, was used in this study as a binder.

Preparation of particles : After collecting tree prunings, they were cut into small pieces or discs using a band saw. The small pieces were then fed through a laboratory hammer mill using a 5 mm screen. Four particle sizes were used: coarse particles (-1.6/+0.8 mm, -10/+20 mesh), medium particles (-0.8/+0.4 mm, -20/+40 mesh), fine particles (-0.4/+0.27 mm, -40/+60 mesh) and mixed particles (-1.6/+0.27 mm, -10/+60 mesh).

Hydration test : Preliminary hydration experiment, by using a two litter Dewar flask, was carried out for each of the six wood species to evaluate its compatibility with cement according to Hachmi *et al*. (1990). Twelve treatments were performed for each species: every combination between pre-treatment (untreated, cold water and hot water) and addition of four different chemicals (none, $CaCl_2$, $Al_2(SO_4)_3$ or $MgCl_2$) was tested. Hydration data was obtained and the inhibitory index was calculated according to Moslemi *et al*. (1983). Wood materials mitigate temperature increase that occurs during the setting process of cement. The extent of this suppression is a measure of the retarding effect of wood materials on cement setting. Types of wood that causes less interference with cement setting process are more likely to be suitable for CBP manufacture.

Construction and specifications of the wood-cement panels

The board construction specifications were as follows:

- Panel dimensions (mm): 300 x 300 x 10,
- Target density ($kg.m^{-3}$): 1200,
- Wood to cement ratio (by weight): 1/3,
- Wood particle size (mesh): -10/+20, -20/+40, -40/+60 and -10/+60 (-: pass and + retained),
- Total pressure: 3.5 to 4.5 MPa for 4.0 h and clamped for 20 h.

Water requirements for CBP manufacturing : There are four components used to manufacture the CBP panels: wood, Portland cement, water and chemical additives. The quantity of water used to manufacture the panels were determined by the formula developed by Simatupang *et al*. (1979) with some modification, previously used by other researchers (Moslime and Pfister, 1987 and Papadopoulos, 2008). The water requirement in this formula is divided into two parts, one for wood and the other for cement. According to Simatupang (1979), the water requirement of each gram of oven-dried wood is 0.30 ml to attain

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Table 3 : Physical and mechanical properties of CBP panels from six wood species

Wood species	BD (g cm^{-3})	MC (%)	MOR (N mm^{-2})	MOE (N mm^{-2})	IB (N mm^{-2})	SHP (N)	JHN (N)	WA (%)	TS (%)	LE (%)
A. salicina	1.258^{AB}	8.58^{B}	9.92^{CD}	4543^{C}	1.69^{B}	1785.6^{B}	6000.9^{C}	15.98^{D}	0.84^{B}	0.39^{B}
C. erectus	1.264^{A}	8.27^{B}	11.78^{A}	5678^{A}	1.73^{A}	1473.7^{C}	5532.9^{C}	17.78^{C}	0.79^{BC}	0.32^{B}
F. altissima	1.249^{AB}	8.86^{B}	9.68^{D}	3952^{D}	1.49^{D}	1528.8^{C}	7437.2^{B}	12.93^{E}	0.62^{C}	0.38^{B}
L. glauca	1.251^{AB}	9.11^{B}	10.64^{BC}	4891^{BC}	1.62^{C}	1741.5^{B}	7103.3^{B}	23.39^{A}	0.65^{BC}	0.39^{B}
P. dulce	1.222^{C}	10.33^{A}	10.30^{B-D}	4967^{B}	1.70^{AB}	2252.5^{A}	8477.7^{A}	17.33^{CD}	1.53^{A}	0.63^{A}
T. aphylla	1.241^{BC}	8.40^{B}	10.91^{B}	5474^{A}	1.71^{AB}	1448.2^{C}	5641.9^{C}	21.41^{B}	0.85^{B}	0.38^{B}
Requirement	1.200	6-12	9.00	3000	0.45			-	8	-

Each value is an average of 12 specimens; Means sharing the same letter in the column are not significantly different according to LSD test; BD: board density based on oven-dry weight ant volume at test measured by dimensions method; MC: moisture content, MOE: modulus of elasticity, WA: water absorption, TS: thickness swelling, LE: linear expansion

Table 4 : Effect of wood particle sizes on the physical and mechanical properties of CBP panels

Wood particle size	MOR (N/mm^{-2})	MOE (N/mm^{-2})	IB (N/mm^{-2})	SHP (N)	JHN (N)	WA (%)	TS (%)	LE (%)
Coarse	10.54^{B}	5114^{A}	1.94^{A}	1438.3^{C}	5946.2^{C}	17.21^{BC}	1.200^{A}	0.383^{A}
Medium	10.08^{BC}	4906^{A}	1.52^{B}	1670.0^{B}	6516.5^{B}	19.08^{B}	0.792^{B}	0.416^{A}
Fine	9.89^{C}	4526^{B}	1.30^{C}	1768.4^{AB}	6675.1^{B}	21.76^{A}	0.702^{B}	0.482^{A}
Mixed	11.65^{A}	5117^{A}	1.87^{A}	1932.4^{A}	7661.5^{A}	16.21^{C}	0.638^{C}	0.385^{A}
Requirement	Min 9.00	min 3000	min 0.45	-	-	-	max 8.0	-

Each value is an average of 18 specimens; Coarse (-10/+20 mesh), fine (-20/+40 mesh), medium (-40/+60 mesh) and mixed (-10/+60 mesh); Mean values sharing the same letter in the column are not significantly different according to LSD test; BD is board density based on oven-dry weight and volume at test; MC: moisture content, MOR: modulus of rupture, MOE: modulus of elasticity, IB: internal bond, SHP: screw holding power, JHN: Janka hardness number, WA: water absorption, TS: thickness swelling, LE: linear expansion

the fiber saturation point of wood. However, in the current work, we found that this quantity of water did not give a good result; the optimum water content was found to be 0.55 ml per gram of wood, which was determined from a primary experiment carried out before manufacturing of the CBP panels. The optimum water of each gram of cement to complete its hydration was determined by hydration test and calculated by uniform mixing index, which approximately represents the area under temperature-time curve corresponding to time to reach maximum temperature, given in °C·hr (Hachmi *et al*., 1990). The optimal water to cement ratio was found to be 0.28 ml g^{-1}.

Manufacturing process of the CBP panels : Using optimal treatments, as determined by hydration test (Table 2), including a pretreatment in cold or hot water and addition of chemical additives ($CaCl_2$ or $MgCl_2$), CBP panels were manufactured according to the method outlined by other researchers (Okino et al., 2004 and Papadopoulos, 2008). The panels were made at a constant board density of 1200 kg·m^{-3} and a wood/cement ratio of 1/3 by weight. Four different wood particle sizes were selected for this experiment: -10/+20 mesh, -20/+40 mesh, -40/+60 mesh and -10/+60 mesh.

A predetermined amount of oven-dried wood particles (278 g) and aqueous solution (24.3 g of chemical additives dissolved in 383.4 ml distilled water) were hand mixed, then 810 g of Portland cement (Type I) was added, and the constituents were thoroughly mixed until the cement paste was completely hydrated (~15 min). The quantity of distilled water was calculated according to the relationship developed by Simatupang (1979), with some modification. This modification included increasing water per one gram of oven-dried wood from 0.30 ml to 0.55 ml. The moisture content was 34.47%. After 15 min of manual mixing, an open-top box of composite wood coated with a phenolic layer, with dimensions of 30 x 30 cm for the base on the inside and 3.1 cm in height, was designated to form the panel. The mixture of particles and cement was screened through a wire net with 2 mm holes to regulate the particle distribution to provide as uniform a density as possible. A square piece of wood of the same material, as the box with a thickness of 1.8 cm was placed on the top of the mixture and used to press to ensure the desired thickness of the manufactured panel. The mat was then cold pressed using a hydraulic press (Carver Monarch), at 4.0 MPa for at least 4 hr to 10 mm thickness, and the panel was kept under a constant pressure for 24 hr by using the press clamp. At the end of this time, the press was gradually opened and the panel was carefully extracted from the mold. To minimize cement capillary desiccation and enhance hydration, the panels were misted with water and then wrapped in cellophane before storing, where they

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aligned vertically at room temperature and conditioned at 20±2 °C and 65±2% relative humidity for 1 month. Three panels (replicates) from each combination were manufactured for a total of 72 panels.

Preparation of test specimens : After conditioning and before cutting, the panels were dried at approximately 70 °C for 8 hr, and the moisture content of the panels was approximately 5-12% at the time of cutting. After drying, all the CBP panels were trimmed to the dimensions of 28 by 28 cm, by cutting approximately 1 cm from each side. The panels were cut into test specimens to quantify the mechanical and physical properties, as well as the dimensional stability properties (ASTM D-1037, 1989). From each panel, two specimens for bending test, three specimens for IB test and three specimens for dimensional stability were used.

Mechanical properties : Four mechanical tests were conducted on the CBP panels, including three-point static bending, tensile perpendicular to board surfaces, screw withdrawal and Janka hardness tests. The tests were carried out using an Instron Testing Machine (Model 3382) in accordance with ASTM D-1037 (1989) with some modifications due to limited size of the panels. The modulus of rupture (MOR), modulus of elasticity (MOE), internal bond strength (IBS), screw holding power (SHP) and Janka hardness number (JHN) were recorded. After the static bending test, the specimens were cut near the failure zone and prepared according to ASTM D-1037 (1989) to determine the density and moisture content.

Dimensional stability properties : The water absorption (WA), thickness swelling (TS) and linear expansion (LE) of the CBP panels were determined, going from equilibrium conditions to water immersion in water for 2 and 24 h (ASTM D-1037, 1989). The test specimens were immersed in a water bath at room temperature for 2 hr, and then taken out and weighed. The samples were then re-immersed to complete the 24 hr immersion time. The WA, TS and LE after 24 hr were expressed as a percentage of the original state.

Fractography : Scanning electron microscope (SEM) was carried out, using JSM 6360A JEOL, to study the fracture surface of the bending test specimens. The samples were soaked in liquid nitrogen as well as the surfaces of the samples were coated with gold under vacuum, prior to the SEM observation, in order to avoid electrostatic changing and heat built-up during examination.

Experimental design and statistical analysis : The analysis of variance (ANOVA) was applied, using two factorial experiments in randomized complete design, to determine the significant differences in the physical, mechanical and dimensional properties of the CBP panels. A Duncan multiple range test, at a 5% level of probability, was conducted to study the significance of the differences among species and particle size, using Statistical Analysis System, SAS (1986).

Results and Discussion

Table 2 shows that when six wood species were pre-treated with either cold or hot water and addition of 3% chemical additive, maximum hydration temperature (T_{max}) exceeded 60 °C and ranged from 72.66 °C (*F. altissima*) to 80.2 °C (*T. aphylla*); hence they were all suitable for CBP production according to Sandermann and Kohler (1964). The same trend was observed with the compatibility factor (C_A), which exceeded 68% (from 80.99% for *F. altissima* to 89.81% for *T. aphylla*) and they were thus compatible for cement mixing according to Hachmi *et al*. (1990). The time to reach maximum temperature (t_{max}) ranged from 2.5 hr for *T. aphylla* to 4.0 hr for *F. altissima*. Based on these results, the panel was pressed in an automatic hydraulic press for at least 4 hr and was then clamped for 20 hr before removal from the mold. The inhibitory index (I) of the wood-cement mixtures very low, ranging from -1.99 for *L. glauca* to -0.45 for *F. altissima* (Table 2). These resulting values were smaller than those obtained when using untreated wood particles, indicating an enhancement in the compatibility of the wood-cement, resulting from pre-treatment. These results are in agreement with previously published reports (Olorunnisola, 2007). Finally, the hydration data revealed that six wood species used could not be used directly as raw materials for CBP and they must first be pre-treated by either cold or hot water with addition of 3 wt% $CaCl_2$ or $MgCl_2$. From T_{max} and C_A, the most effective common treatments for each species of wood were determined and used to manufacture the CBP panels. The best treatment differed depending on the species of wood (Table 2).

The results of the analysis of variance revealed that the various parameters that define the physical and mechanical properties of the CBP panels differed from one species to another. This means that the species of wood had a significant effect on the properties of the produced CBP panels. The average values and significant differences of the properties of the CBP panels are given in Table 3. It is clear that the differences in the modulus of rupture (MOR) between the six wood species were statistically significant, with *C. erectus* showing the highest value (11.78 N mm^{-2}) and *F. altissima* the lowest (9.68 N mm^{-2}). The modulus of elasticity (MOE) values ranged from 3952 to 5678 N mm^{-2}. No significant differences in MOE were found between *C. erectus* and *T. aphylla* (5680 and 5470 N mm^{-2}, respectively). As shown in Table 3, MOR and MOE for all of the CBP panels met the minimum requirements set by the International Organization for Standardization (ISO 8335-1987), and these values compare favorably to CBP data published in past studies. Badejo (1988) reported MOR values from 5.22 to 11.15 N mm^{-2} and MOE values ranging from 2420 to 4820 N mm^{-2} for CBP made from mixed tropical hardwoods with varying flake geometry. Almeida *et al*. (2002) obtained MOR values in the range of 1.56 to 3.77 N mm^{-2}

and MOE values in the range of 821 to 2650 N/mm^2 for CBP panels made from the coconut shell of babaçu.

As observed in Table 3, the values of internal bond strength (IB) were varied between 1.49 N mm^{-2} (*F. altissima*) and 1.73 N mm^{-2} (*C. erectus*). The differences in IB values between *C. erectus*, *T. aphylla* and *P. dulce* were not significant. The IB values exceeded by at least three fold the requirement set forth by the ISO standard (0.45 N mm^{-2}). These results may be attributed to the use of pre-treated wood particles in manufacturing the CBP panels, which resulted in improving the compatibility between the wood particles and cement. Many researchers have concluded that water-soluble extractives of wood retard and sometimes inhibit the normal setting and strength development of cement (Olorunnisola, 2007 and Ashori *et al*., 2011). They reported IB values from 0.4 to 1.3 N/mm^2 for a wood-wool cement board made from eucalyptus and poplar.

The ability of a panel product to hold nails is another factor to consider when evaluating its suitability as a construction material, especially when they are subjected to load. Janka hardness strength (JHN) of a produced panel is the most important measurement for flooring applications. However, no minimum requirements for the screw holding power (SHP) or JHN are specified in ISO standard for CBP panels. The values of at SHP ranged from 1448.2 N (*T. aphylla*) to 2252.5 N (*P. dulce*). The mean SHP values were comparable to the results reported by Okino *et al*. (2004) on CBP panels made from a mixture of eucalypt and rubberwood (1500 to 2020 N); however, they were higher than the results of Almeida *et al*. (2002) on CBP produced

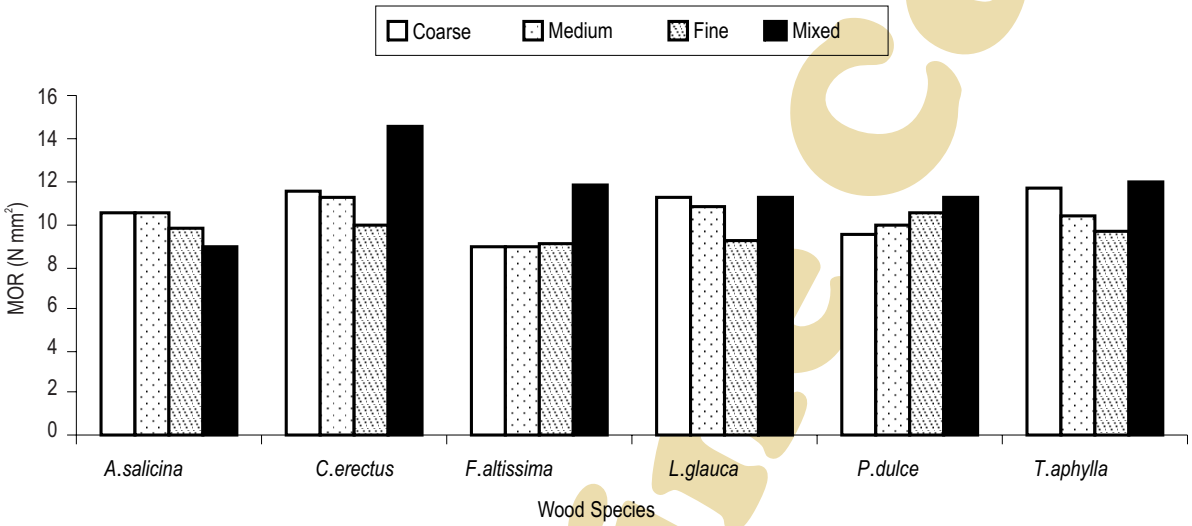

Fig. 1 : Effect of particle size on the MOR of the CBP panels made from the six wood species

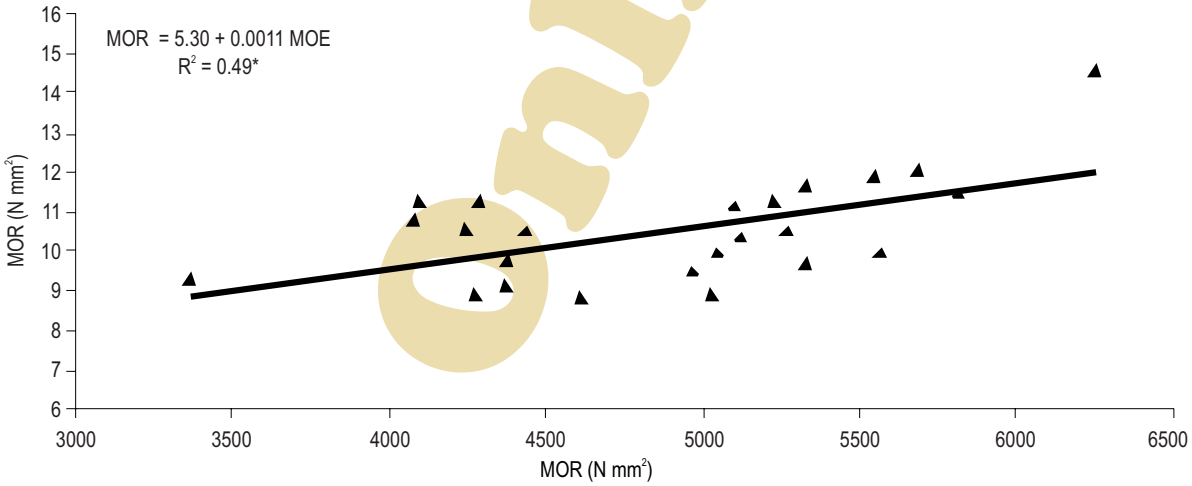

Fig. 2 : Relationship between the MOR and MOE of the CBP panels

from the coconut shell of babaçu (474 to 1146 N). The values of JHN were between 5532.9 N (*T. aphylla*) and 8477.7 N (*P. dulce*). No JHN values were available in the literature for comparison.

Regarding the dimensional stability of the produced CBP panels, the results indicate that the lowest water absorption, judging by 24 hr water immersion (WA) values, was observed in the panels made from *F. altissima* (12.93%) and *P. dulce* (17.08%) with addition of 3% Mg Cl_2. The boards made from *T. aphylla* and *L. glauca* with addition of 3% $CaCl_2$, had highest WA values (21.41 and 23.40%, respectively). The values of thickness swelling (TS) after the 24 hr water immersion ranged from 0.62% (F. altissima) to 1.53% (P. dulce) and were well below the maximum limit set by ISO standard (8.0%). The values of linear expansion (LE) were very consistent, ranging from 0.32% (C. erectus) to 0.63% (P. dulce). Although WA and LE requirements were not specified in ISO standard for CBP panels, the CBP panels made from six wood species had higher dimensional stability in comparison to previously reported examples, indicated by lower values of WA and LE. These variations in WA between six wood species were also observed by Sudin and Ibrahim (2001). They found that boards made from *Acacia mangium* with addition of 2 wt% $Al_2(SO_4)_3$ had the highest dimensional stability (7.79% WA and 0.78% TS), followed by the samples treated with $MgCl_2$ (10.12% WA and 0.93% TS) and $CaCl_2$ (27.47% WA and 3.33% TS). Almeida *et al.* (2002) reported that the use of an additive generally

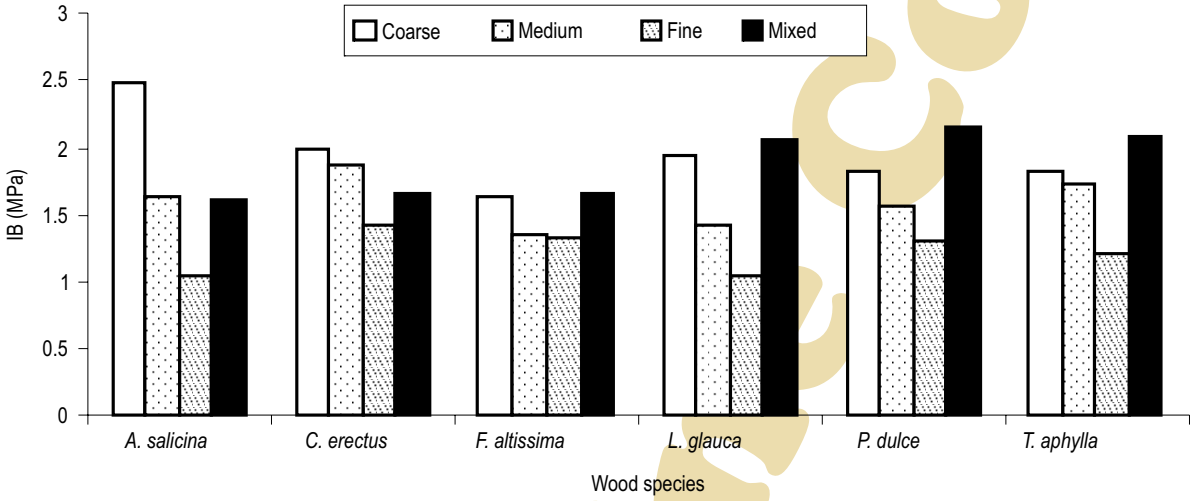

Fig. 3 : Internal bond of CBP as affected by the interaction between wood species and particle size

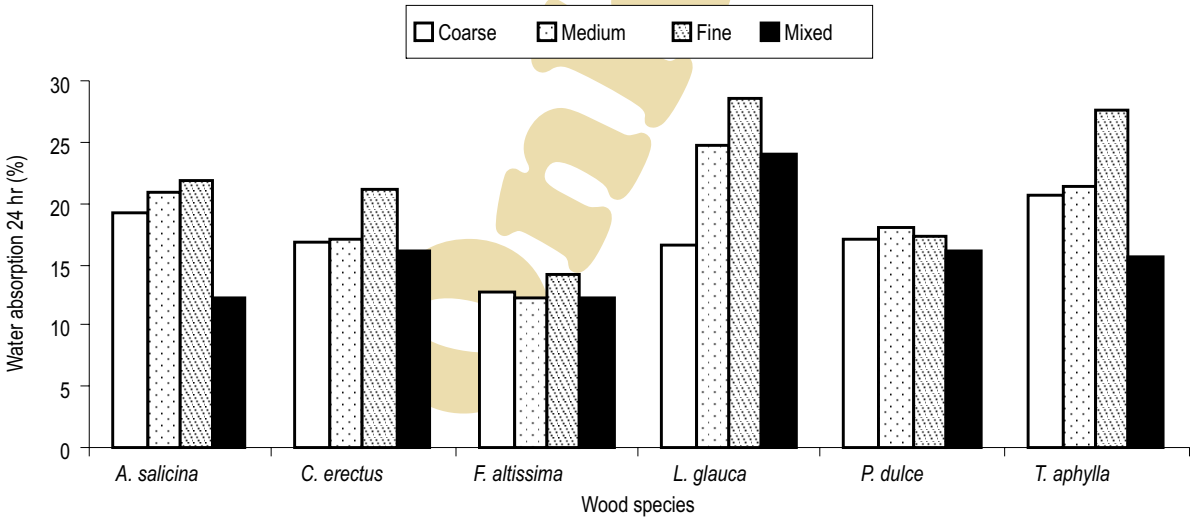

Fig. 4 : Water absorption of CBP panels made from six wood species as affected by wood particle size

improved the properties of boards in the same density range. The authors also found that the presence of $CaCl_2$ caused an increase of 21% in TS and 19% decrease in WA. They attributed this result to the affinity of $CaCl_2$ for water. The presence of bark has also been shown to increase the WA capacity and swelling of the boards. This effect was likely due to increased water absorption capacity of bark compared with other wood material. These findings suggest that the use of CBPs made from residues containing bark may be best suited to interior applications (Semple *et al.*, 2002).

Generally, the mechanical properties of CBP panels made in this study were superior to those of other cement-bonded composites using different lignocellulosic materials under different manufacturing variables, such as epicarp of babassu fiber (Almedia *et al*., 2002), particles of *Acacia mangium* (Sudin and Ibrahim, 2001), particles from the Australian mallee species (Semple *et al*., 2002), and mixed particles of eucalypt and poplar (Ashori *et al*., 2011). The properties of CBP panels were comparable to the results gathered on cypress or mixed particles of eucalypt and rubberwood (Okino *et al*., 2004), rattan (Olorunnisola, 2007), mixed flakes of tropical hardwood (Badejo, 1988), and arhar stalks (Aggarwal *et al*., 2008). All the physical and mechanical properties of the CBP panels made from the six 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 those reported by other researchers around the world (Moslemi and Pfister, 1984, and Papadopoulos, 2008). According to these results, CBP panels can be made from tree prunings of six wood species studied after pre-treating the particles with either cold water immersion or hot water extraction and adding 3% by cement weight of either calcium chloride or magnesium chloride as an accelerator.

A sieving unit with sieves of 10, 20, 40 and 60 mesh was used to separate the wood meal into three different particle sizes. Coarse wood particles refer to the particles passing through 10

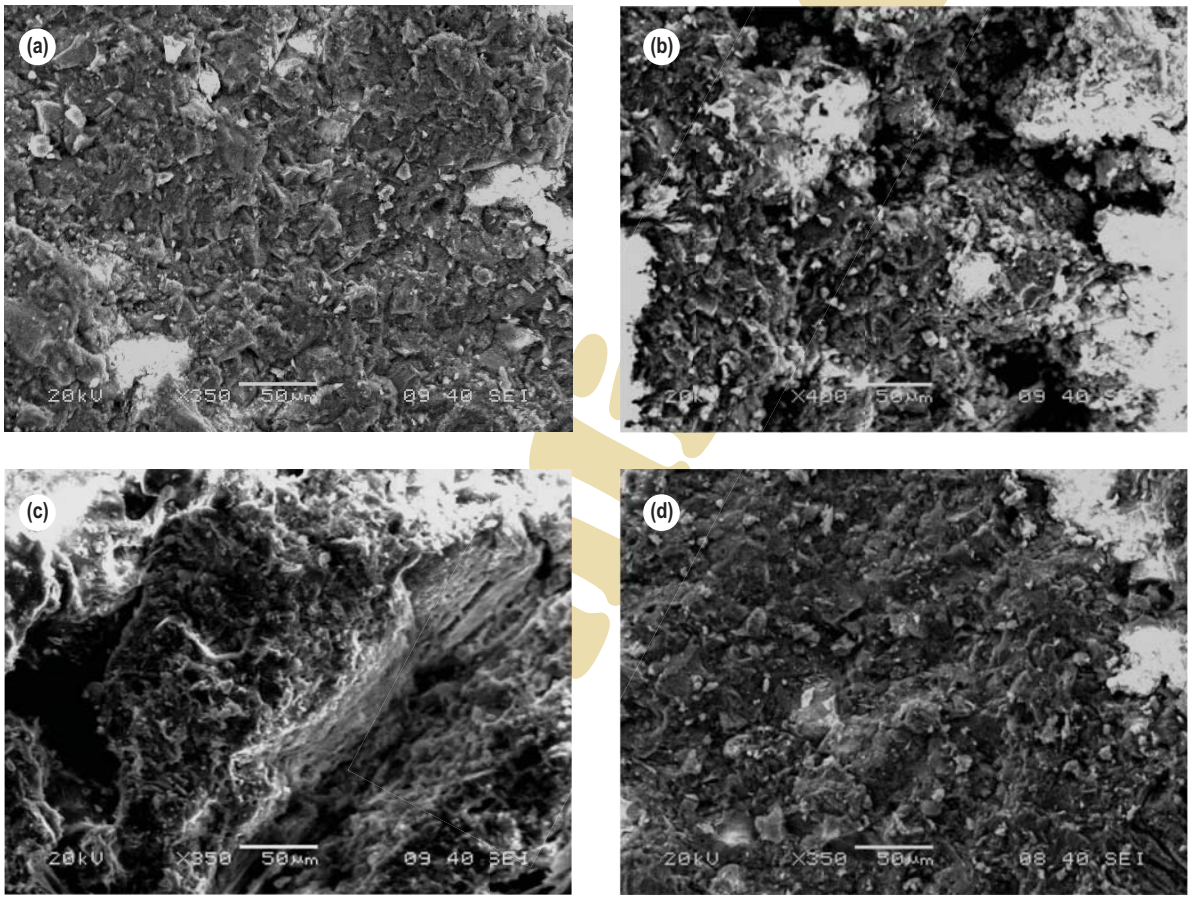

Fig. 5 : SEM micrographs of the bending fractures samples of the CBP panels: (a) coarse particles, (b) medium particles, (c) fine particles and (d) mixed particles

mesh and retained on 20 mesh, (-10/+20), medium particles refer to the particles between 20 mesh and 40 mesh (-20/+40), and fine particles refer to those caught between 40 mesh and 60 mesh screens (-40/+60). In addition, -10/+60 was made as a mixture of 25, 50, and 25% of the coarse, medium and fine particles, respectively.

Analysis of variance indicated that the effect of wood particle size on the properties of CBP panels was significant except for board density, moisture content and linear expansion after 24 hr water immersion. Table 4 shows the mean values of the physical and mechanical properties of the CBP panels as affected by the particle size of the wood. It can be seen that the density and moisture content of the CBP panels were generally similar among different sizes, and the differences were not significant. The results showed that the MOR, MOE, IB and thickness swelling (TS) of the CBP panels appeared to decrease with decreasing wood particle size from -10/+20 mesh to -40/+60 mesh. However, the inverse trend was observed for the screw-holding power (SHP), Janka hardness number (JHN), water absorption (WA) and linear expansion (LE) of the CBP panels; these values increased with decreasing particle size (Table 4). Ma *et al*. (2000) reported that the size of raw material affected the MOR and MOE of rice straw CBP panels. They concluded that large particles (retained on an 8 mm mesh screen) imparted higher strength than small particles (passing through a 1-mm mesh screen). Semple *et al*. (2002) attributed relatively good compatibility of the mallee eucalypt wood residues with cement to the unfavorable geometry of the particles generated from in-field chipping. They concluded that the small particle size and aspect ratio of chipped residues was the primary cause of low mechanical strength of the CBP boards. Badejo (1988) reported that the longer and thinner flakes, stronger, stiffer and more dimensionally stable the cement-bonded particleboard made from mixed tropical hardwoods. Using longer flakes significantly increased the MOR and MOE and improved the dimensional stability in terms of water absorption and thickness swelling.

The decreased strength of CBP panels with decreasing wood particle size may be attributed to the fact that fine particles have a much lower aspect ratio than coarse particles. This most likely accounts for the lower strength of the CBP panels; a strong correlation between the aspect ratio of wood particles used in CBP panel manufacturing and the resulting mechanical properties was shown by Semple *et al*. (2002). Compared to the panels from a single particle size (coarse, fine or medium), the results showed that the CBP panels from mixed wood particles (-10/+60 mesh) possessed improved mechanical properties, including MOR, MOE, SHP and JHN, as well as increased dimensional stability (Table 4). These results support the findings of Badejo (1988), Huang and Cooper (2000) and Olorunnisola (2007). It was concluded that using different particle sizes (rather than a single size) tends to enhance the bending strength and dimensional stability of wood-cement composites. Using different particle sizes as opposed to a single particle size tends to enhance the bending strength of the wood-cement composites (Huang and Cooper, 2000). Olorunnisola (2007) found that "as received" particles produced CBP composites with highest MOR, and attributed this result to the random size distribution of the rattan particles used in the composites. These results are supported by the earlier observations of Ahn and Moslemi (1980) and Tonoli *et al*. (2011).

Increasing WA as a result of decreasing particle size may be due to a lesser coating of particles by cement due to the increased surface area of the fine particles. Another explanation for high penetration of water in the panels made from fine wood particles was due to increase in voids, as observed by SEM (Fig. 5). It can be said that the smaller the particles, the more voids there are to be filled, leading to a higher water absorption and thickness swelling. Erakhrumen *et al*. (2008) reported that lowering the cement proportion in composite manufacturing might lead to a large quantity of exposed particles and free internal spaces, which are possible contributing factors to the trend in the WA and the instability of the board. The increase of wood-to-wood bonds reduces the interfacial area of contact between the wood particles and the cement matrix, thus diminishing the potential of a given wood to bond with the matrix (Ashori *et al*., 2011).

In this study, for most of the properties measured, mixed particles proved to be best for the manufacture of CBP panels.

Analysis of variance showed that interaction between wood species and wood particle size was highly significant for all physical, mechanical and dimensional stability properties except the values of MOE and linear expansion after 24 hr (LE) were not significant. With few expansion, especially for *A. salicina*, the best particle size for each species was mixed particles (-10/+60 mesh). Mixed particles gave the highest mechanical values. On the other hand, manufacturing wood-cement panels by using mixed particles gave panels with high dimensional stability.

In this work, two trends were obtained for MOR (Fig. 1); the first trend was obtained with four wood species namely *A. salicina, C. erectus, L. glauca* and *T. aphylla* where MOR decreased with decrease in particle size of wood from 10/20 mesh to 40/60 mesh. The second was an inverse trend obtained with *P. dulce*. No significant differences were obtained for MOR values of the CBP panels made from each of the three particle size of *F. altissima*. It can be seen that CBP panels made from each of the six wood species using mixed particles had the highest MOR values compared to the panels made of single particle size (one size), except for *A. salicina*. Interaction between wood species and particle size for MOE was not significant. However, MOR was directly related to modulus of elasticity (MOE), R^2= 0.49, of the CBP panels made from six wood species (Fig. 2). This result is in agreement with Badejo (1988) who

observed a high positive correlation between MOR and MOE of mixed tropical wood-cement composites. However, this result is in contrast with Olorunnisola (2007) who reported a weak positive correlation in rattan-cement composites.

The effects of wood species and particle size on the IBS of the CBP panels made from six wood species are presented in Fig. 3. It can be seen that decreasing the particle size of wood decreased the IB of the CBP panels. For *L. glauca*, *P. dulce* and *T. aphylla*, the CBP panels from mixed wood particles showed improved IBS compared with the panels from particles of a single size. However, for the remaining three species, the IB values of the CBP panels made from mixed wood particles fall in the range of values observed for coarse and fine particles.

For six wood species used, decreasing the wood particle size from -10/+20 mesh to -40/+60 mesh significantly increased the water absorption of the CBP panels. On the other hand, the CBP panels manufactured by using mixed wood particles (-10/+60 mesh) had the lowest values of WA. The highest WA values were obtained with the CBP panels made from fine particles of *L. glauca* and *T. aphylla* (28.51 and 27.69%, respectively). The lowest WA values were recorded with the CBP panels made from *A. salicina* and *F. altissima* using mixed wood particles (12.15 and 12.21%, respectively).

The CPB panels were also analyzed by SEM imaging of the fracture surface of the bending samples to identify the changes in the surface and the interfacial area between the wood particles and the cement matrix. Fig. 5 shows the SEM micrographs of the bending fracture surface of the CBP panels made from different particle sizes of *T. aphylla* wood. The morphological investigation of the cryo-fracture samples showed a good dispersion of the wood particles in the cement matrix for all of the samples (Fig. 5). However, voids were observed in the cement matrix and sometimes around the wood particles, which indicates a high level of porosity in the wood-cement matrix. Addition of chemical additives, *i.e.*, calcium chloride or magnesium chloride, appears to substantially change the shape of the crystals formed. This observation is consistent with reports from Ahn and Moslemi (1980). These crystals resulted from hydration of basic cement compounds. No pulling out of the fibers in the CBP panels was observed in the micrographs of the fractured surface of the bending samples. Also noticeable the number of voids increasing as the particle size of wood decreases from -10/+20 mesh (Fig. 5a) to -40/+60 mesh (Fig. 5c). In the meantime, the diameter of the voids was observed to decrease as the particle size decreased. It can be seen in Fig. 5d that using a large range of wood particle sizes, in other words, mixed particles of -10/+60 mesh, resulted in a good dispersion of the particles into the cement matrix. It is clear from Fig. 5d that both types of voids (small and large) were found, but there were fewer than in the other CBP panels shown in Fig. 5 a, b and c. These results are in agreement with those reported by Tonoli *et al*. (2011), who found that short eucalyptus fibers are better distributed than pinus fibers. The SEM investigation of the CBP panel samples showed that the composites break through fibrillation of the cement matrix. Voids found in the CBP panels might be attributed to the presence of air from the wood particles; no air was trapped in the fiber-free area.

The hydration data revealed that the tree prunings of six wood species used could not be used directly as raw materials for CBP and they must be first pre-treated by either cold or hot water and addition of 3 wt% $CaCl_2$ or $MgCl_2$. The pruning materials were suitable for manufacturing high quality of CBP panels at a target density of 1200 kg m^{-3}. The species of wood and particle size of the tree prunings had a significant effect on the properties of the produced CBP panels.

The produced panels meet the strength and dimensional stability requirements of commercial CBP panels. The CBP panels had higher dimensional stability in comparison to previously reported values, indicated by lower values of WA and LE.

Mixed-size or coarse particles should be used to produce high quality CBP panels. Production of wood-cement composites from the tree prunings may help to solve some environmental problems getting rid of these residues and could be an alternative wood source for composite industry.

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