PARTICLEBOARDS MADE FROM AUSTRALIAN RED CEDAR: PROCESSING VARIABLES AND EVALUATION OF MIXED-SPECIES

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BUFALINO L, ALBINO VCS, DE SÁ VA, CORRÊA AAR, MENDES LM & ALMEIDA NA. 2012. Particleboards made from Australian red cedar: processing variables and evaluation of mixed-species. This work was developed in two stages with the following aims: (1) to evaluate physical and mechanical properties of particleboards made from wood residues of *Toona ciliata* with target densities of 0.65 and 0.70 g cm^{-3} and 6 and 9% adhesive contents, and (2) to compare particleboards made from 100% *T. ciliata* particles (TC) with particleboards made from 50% *T. ciliata* particles mixed with 50% *Pinus oocarpa* particles (TC/P) or 50% *Eucalyptus* hybrid clone particles (TC/E). In the first stage, best results were obtained with 9% urea-formaldehyde and target density of 0.70 g cm^{-3}. These processing variables were chosen for the production of mixed-species particleboards in the second stage of the work. TC particleboards had higher mechanical properties than mixed-species particleboards. For physical properties, TC particleboards were similar to TC/P particleboards. TC/E particleboards showed lowest results of mechanical properties and highest values of physical properties, and they are also suitable for interior applications. The results showed great potential in using wood residues of *T. ciliata* alone or mixed with *Eucalyptus* or *Pinus* species in particleboard production.

Keywords: *Pinus oocarpa*, *Eucalyptus* clones, *Toona ciliata*, Meliaceae

BUFALINO L, ALBINO VCS, DE SÁ VA, CORRÊA AAR, MENDES LM & ALMEIDA NA. 2012. Papan serpai yang diperbuat daripada sedar merah Australia: pembolehubah pemprosesan dan penilaian spesies campuran. Kajian ini dibangunkan dalam dua peringkat dengan tujuan berikut: (1) untuk menilai ciri-ciri fizikal dan mekanik papan serpai daripada sisa kayu *Toona ciliata* dengan ketumpatan sasaran 0.65 g cm^{-3} dan 0.70 g cm^{-3} serta kandungan perekat sebanyak 6% dan 9%, dan (2) untuk membandingkan papan serpai daripada 100% *T. ciliata* (TC) dengan papan serpai yang dibuat daripada 50% zarah *T. ciliata* yang dicampur dengan 50% zarah *Pinus oocarpa* (TC/P) atau 50% zarah hibrid klon *Eucalyptus* (TC/E). Pada peringkat pertama, keputusan terbaik diperoleh dengan 9% urea formaldehid and ketumpatan sasaran 0.70 g cm^{-3}. Pembolehubah pemprosesan ini kemudiannya dipilih bagi peringkat kedua kajian iaitu penghasilan papan serpai spesies campuran. Papan serpai TC mempunyai ciri mekanik yang lebih tinggi berbanding papan serpai spesies campuran. Bagi ciri fizikal, papan serpai TC adalah sama dengan papan serpai TC/P. Papan serpai TC/E menunjukkan ciri mekanik yang paling rendah tetapi ciri fizikal yang paling tinggi. Papan ini juga sesuai untuk kegunaan dalaman. Keputusan kajian menunjukkan bahawa sisa kayu *T. ciliata* sama ada 100% atau dicampur dengan spesies *Eucalyptus* atau *Pinus* mempunyai potensi besar dalam penghasilan papan serpai.

INTRODUCTION

Before 1900, forestry plantation activities in the tropics included the introduction and testing of exotic species. After some time, an apparent superior growth of exotic species in comparison with native species was observed in many cases (Evans 2009). In the 1960s and 1970s, several countries including Brazil, New Zealand, Australia, South Africa, Argentina and Chile developed methods and procedures to establish forestry plantations. The aim was to increase and accelerate wood production as alternative to natural resources. Currently the wood supply from *Eucalyptus* and *Pinus* species plays an undoubtedly important role in many tropical and subtropical countries around the world. Exploring new alternative forestry species is of great importance since it may diversify the product offerings of some countries and enhance their competitiveness in the global market.

Australian red cedar (*Toona ciliata* var. *australis*) has stood out as a planted forestry species in several tropical and subtropical

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countries such as Brazil, Argentina, Hawaii, Puerto Rico and Honduras. About 200 years ago, red cedar trees grew in great abundance along the east coast of Australia northwards from the vicinity of the Clyde River, but due to exploitation of the species, a large part of its natural habitat has been destroyed (Bygrave & Bygrave 2005).

Damage by the *Hypsipyla robusta* shoot borer is the main factor hindering the regeneration of the Australian red cedar in its place of origin. However, this plague does not naturally occur in America (Cunningham et al. 2005). In addition, Australian red cedar seems to be resistant to *Hypsipyla grandella* (Grijpma 1974), which is native to South America where it causes severe damage to other Meliaceae species such as *Cedrela fissilis*, *Cedrela odorata* and *Swietenia macrophylla*.

Australian red cedar wood has several uses such as furniture, decorative veneer, civil construction, boats and floorings. However, it is important to consider that any wood processing such as veneering and sawing always results in the production of a great amount of residue. Renewable and sustainable composite materials can be produced using small diameter trees and other lignocellulosic biomass such as residues of sawmilling and veneer production that can be processed into particles. The growth of particleboard industry around the world is proof for this (Rowel 2007). The world production of particleboard increased from 79,366,400 m^3 in 1999 to 93,949,802 m^3 in 2009 (FAO 2010).

Due to their relatively higher density, hardwood residues have typically not been used for the production of particleboard by the industry compared with softwood residues. This has limited the potential market for such residues (Gamage et al. 2009). However, particleboards from hardwood have been reported to have good physical and mechanical properties (Ashori & Nourbakhsh 2008, Gamage et al. 2009, Setunge et al. 2009, Suffian et al. 2010).

Wood basic density is the most important factor to be considered in particleboard production; it should range from 0.3 to 0.5 g cm^{-3} in order to result in panels with high compression ratio (Maloney 1993). Compression ratio is closely related to the physical and mechanical properties of particleboards. High-density wood may be mixed with low-density wood in order to achieve the required compression ratio for particleboards (Moslemi 1974).

The aims of this work were (1) to evaluate physical and mechanical properties of particleboards made from wood residues of *T. ciliata* with target densities of 0.65 and 0.70 g cm^{-3} and 6 and 9% adhesive contents, and (2) to compare particleboards made from 100% *T. ciliata* particles with particleboards made from 50% *T. ciliata* particles mixed with either 50% *Pinus oocarpa* particles or 50% *Eucalyptus* hybrid clone particles.

MATERIALS AND METHODS

Raw materials used to manufacture particleboards in this study were: (1) 18-year-old *P. oocarpa* wood obtained from an experimental plantation located at Lavras, Minas Gerais, Brazil, (2) 7-year-old *Eucalyptus grandis/E. urophylla* hybrid clone wood obtained from the Companhia Mineira de Metais located at Vazantes, Minas Gerais, Brazil, and (3) residual slabs from the primary processing of 18-year-old *T. ciliata* var. *australis* obtained from a commercial plantation located at Marechal Floriano, Espírito Santo, Brazil. The basic density of the wood was determined according to the NBR 11942 (ABNT 2003) standards. Total extractives and lignin contents were determined in accordance with M3/69 (ABTCP 1974a) and M70/71 (ABTCP 1974b) standards respectively using two replicates. For total extractives analyses, a Soxhlet apparatus was used and samples were extracted using a sequence of toluene–ethanol (7 hours), ethanol (6 hours) and water (3 hours). Lignin content was determined by treating the samples in cooled H_2SO_4 solution at 72%.

Logs and slabs were reduced to 90 × 200 × 25 mm pieces, transformed into strand particles (25 × 90 × 0.70 mm) and milled to produce sliver particles using a 6.14 mm sieve fastened to a hammer mill. The particles were screened through a 0.6-mm sieve to exclude fine particles and dried down to 3% moisture content using a forced air oven at 103 ± 2 °C. Thirty particles of each species were sampled and measured and the sizes obtained were 14 × 2.5 mm, 13 × 2 mm and 12.5 × 2 mm for *T. ciliata*, *P. oocarpa* and *Eucalyptus* clone particles respectively. A commercial urea-formaldehyde adhesive was used, which had the following properties: viscosity = 618.94 cP, solid content = 56.78% and pH = 7.5. Two different concentrations of urea-formaldehyde were used, i.e. 6 and 9% (based on dry mass of particles).

In addition, wax emulsion at 1.5% (based on dry mass of particles) was applied to the particles.

To make boards, particles were put in a blender where the adhesive and wax emulsion were sprayed with a spray gun. The material was put in a mat forming box (48 × 48 cm) and a manual press machine was used to perform a pre-pressing procedure at 0.78448 N mm^{-2}. The mat was then put in a hydraulic press and the boards were pressed using a press time of 8 min under 3.9224 N mm^{-2} pressure and at a temperature of 160 °C. The nominal thickness of the experimental boards was 1.5 cm. Two target densities were compared, namely, 0.60 and 0.75 g cm^{-3}.

The samples were stabilised in an acclimatised room (20 ± 1 °C and 65 ± 3% RH). The physical and mechanical properties evaluated were water absorption and thickness swelling after immersion for 2 and 24 hours (two 150 × 150 mm specimens), measured density (two 150 × 150 mm specimens), compression ratio (two 150 × 150 mm specimens), modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending (four 250 × 50 mm specimens), parallel compression (four 25 × 100 mm specimens) and internal bond (six 50 × 50 mm specimens). Physical properties, internal bond and parallel compression were determined in accordance with ASTM D 1037-100 (ASTM 2006) standard procedures. Static bending test was performed according to DIN 52362 (DIN 1984). Figure 1 shows the distribution of the specimens in the sample particleboards. For mechanical tests, a universal testing machine was used.

Stage 1

In this stage, 100% *T. ciliata* particleboards (TC) were studied. Two target densities (0.65 and 0.70 g cm^{-3}) and two adhesive concentrations (6 and 9%) were combined, resulting in four sample particleboards (Table 1). Three panels of each sample were produced. Data were statistically analysed by means of a completely randomised design analysis of variance. The samples were compared by Tukey's test at 5%. The best target density and adhesive content were selected based on physical and mechanical properties to be used in the second stage of the work.

Stage 2

Sample particleboards were made from 50% *T. ciliata* particles mixed with either 50% *P. oocarpa* particles (TC/P) or 50% *E. urophylla/E. grandis* hybrid clone particles (TC/E). From stage 1, the best results of physical and mechanical properties were obtained using target density of 0.70 g cm^{-3} and adhesive content 9%. These parameters were used to produce particleboards in stage 2. Mixed-species particleboards were compared with sample particleboard from stage 1 which presented best results for physical and

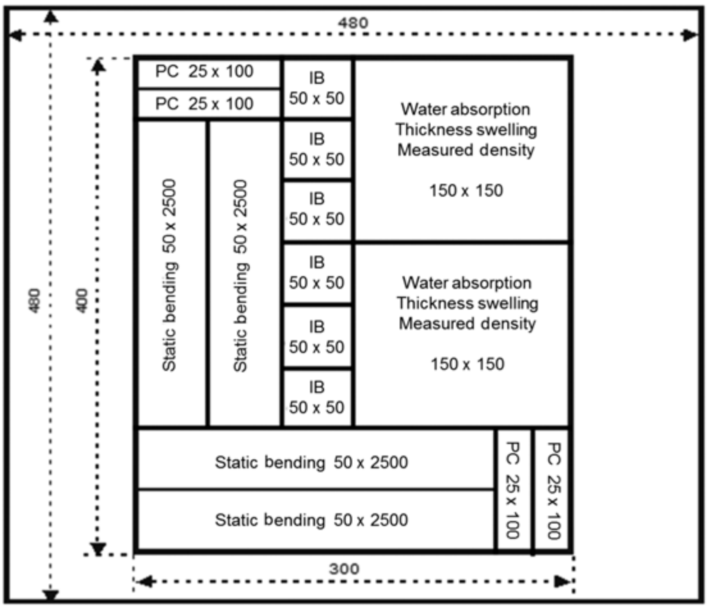

Figure 1 Distribution of the specimens in sample particleboards; PC = parallel compression, IB = internal bond; measurements are in mm

Table 1 Descriptors of sample particleboards in stage 1 (100% *Toona ciliata*)

Sample	Target density (g cm^{-3})	Urea-formaldehyde (%)
0.65/6	0.65	6
0.65/9	0.65	9
0.70/6	0.70	6
0.70/9	0.70	9

mechanical properties (Table 2). Compression ratio of particleboards made from mixed species was determined by the average density of wood species (Loh et al. 2010). Data were statistically analysed by means of a completely randomised design analysis of variance. Samples were compared by Tukey's test at 5%.

RESULTS AND DISCUSSION

Stage 1

Physical properties

Toona ciliata wood density was 0.32 g cm^{-3}, which was suitable for medium density particleboard production (Maloney 1993). Significant differences were found between treatments for measured density and compression ratio values of particleboards made with different target densities (Table 3). Average measured density values of 0.63 and 0.62 g cm^{-3} were slightly lower than the target density of 0.65 g cm^{-3}. These discrepancies might have occurred due to particle loss during the making of particleboard under laboratory conditions.

Figure 2 depicts the water absorption and thickness swelling of TC particleboards. Water absorption after 2 and 24 hours were influenced by target density and urea-formaldehyde content. Particleboards made with 9% urea-formaldehyde and target density of 0.70 g cm^{-3} had significantly lower values of water absorption after 24 hours than other TC particleboards. Particleboards made with 6% urea-formaldehyde and target density of 0.65 g cm^{-3} showed the highest results of water absorption after 2 and 24 hours. Increases in particleboard density normally result in decreases in water absorption. This is mainly attributed to a physical barrier to the water intake caused by a decrease in void between particles in higher density particleboards which also have higher compression ratio.

Water absorption values of 95.8 and 104.6% after 24 hours have been reported for particleboards with target density of 0.70 g cm^{-3} and wax emulsion at 1% from 7- and 12-year-old *E. urophylla* respectively (Mendes et al. 2009). The values were much higher than those obtained in the current study for TC particleboards with target density of 0.70 g cm^{-3}. This result may be partially attributed to the higher wax content (1.5%) used in the current study.

A significant difference among different particleboards was observed for thickness swelling of TC particleboards after 2 and 24 hours. Lower values were obtained for particleboards with 9% urea-formaldehyde. This was mainly attributed to the higher adhesive amount per particle which might have improved glue bonding and reduced swelling. Particleboards with 6% urea-formaldehyde showed lower thickness swelling at target density 0.70 g cm^{-3}. An increase in particleboard density can result in higher contact between particles and improvement of their glue bonds which may reduce thickness swelling (Gatchell et al. 1966, Clad 1967).

The EN 312-3 (EN 2003) standard for thickness swelling after 24 hours requires values below 14% for non-load-bearing boards for use in humid conditions (type P3). Thus, none of TC particleboards had thickness swelling below the maximum stipulated by the standard.

Mechanical properties

Particleboards with 9% urea-formaldehyde and target density of 0.70 g cm^{-3} had significantly greater MOR than the rest of the TC particleboards (Figure 3). MOE and parallel compression values were higher for particleboards with target density of 0.70 g cm^{-3}. Increases in mechanical properties are expected with increases in particleboard density, which may be attributed to the greater volume of wood particles that are compacted and to the increase in interparticle contact

Table 2 Descriptors of sample particleboards in stage 2

Sample	*Toona ciliata*	*Pinus oocarpa*	*Eucalyptus* clone
TC	100%	-	-
TC/P	50%	50%	-
TC/E	50%	-	50%

Table 3 Measured density and compression ratio of the particleboards in stage 1

Sample	Measured density (g cm^{-3})	Compression ratio
0.65/6	0.63 b	2.08 b
0.65/9	0.62 b	2.06 b
0.70/6	0.70 a	1.87 a
0.70/9	0.70 a	1.87 a

Details of samples are as in Table 1; means followed by the same letter in the same column do not differ at $p < 0.05$

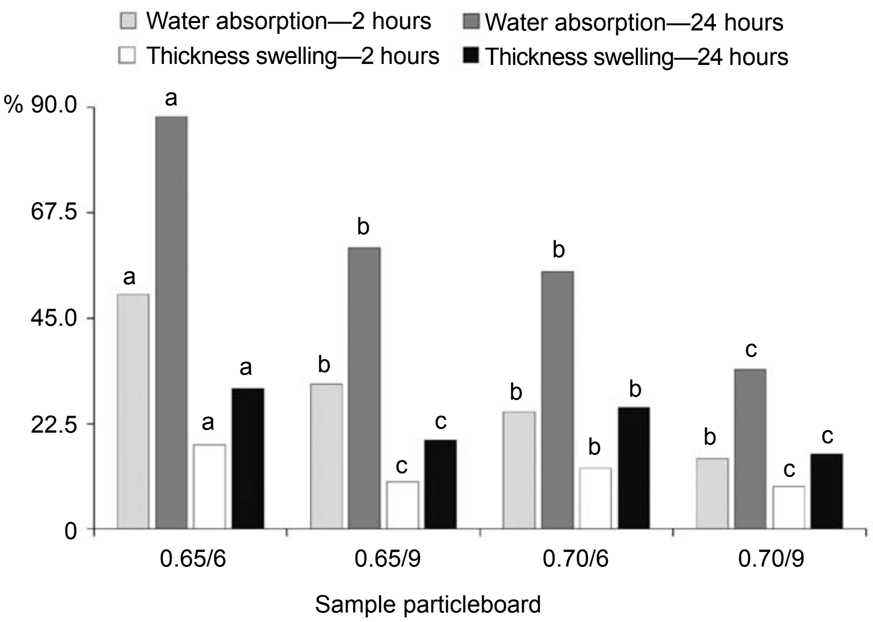

Figure 2 Physical properties of the particleboards in stage 1 (100% *Toona ciliata*); details of samples are as in Table 1; means followed by the same letter do not differ at $p < 0.05$

(Kelly 1977). Several works reported increases in mechanical property values with increases in densities for particleboards (Barboutis & Philippou 2005, Zheng et al. 2006).

An increase in adhesive content from 6 to 9% significantly increased MOR value for particleboards with target density of 0.70 g cm^{-3} (Figure 3). Mechanical properties of several alternative wood species (*Eucalyptus camaldulensis*, *Prosopis juliflora*, *Tamarix stricta* and *Phoenix dactylifera*) improved as adhesive content increased from 9 to 11% (Ashori & Nourbakhsh 2008). Particleboards made from athel (*Tamarix aphylla*) wood also showed a similar trend when adhesive content was increased from 7 to 16% (Zheng et al. 2006).

TC particleboards made with both target densities and adhesive contents met EN 312-3 (EN 2003) requirements for MOE and MOR which specified 1950 and 14 MPa respectively for non-load-bearing boards for use in humid conditions (type P3).

TC particleboards made with 6% urea-formaldehyde and target density of 0.65 g cm^{-3} had the lowest internal bond value (Figure 4). When adhesive content was held constant, higher internal bond values were found for particleboards made with 0.70 g cm^{-3}. According to Vital et al. (1974), increases in particleboard density may cause increases in internal bond due to increase in adhesive efficiency by additional and improved glue bonds. Besides, increases in adhesive content result in higher amount of adhesive available per particle.

TC particleboards made with both target densities and adhesive contents also met EN 312-3 (EN 2003) requirements for internal bond, which specified 0.45 MPa for non load-bearing boards for use in humid conditions (type P3).

Overall analyses showed that better results were obtained for particleboards produced with 9% urea-formaldehyde and 0.70 g cm^{-3} target density. For this reason, these processing variables were chosen for the production of mixed particleboards in the second stage of the work,

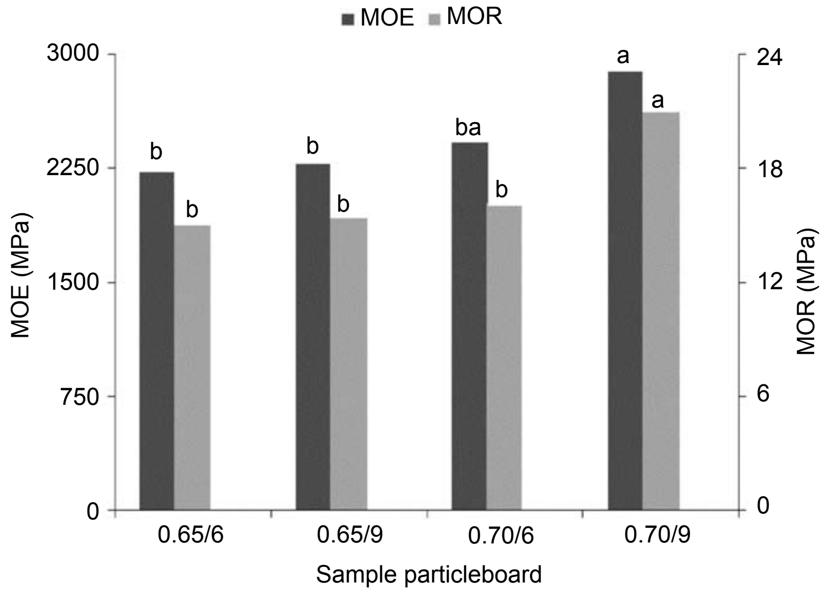

Figure 3 MOE and MOR of the particleboards in stage 1 (100% *Toona ciliata*); details of samples are as in Table 1; means followed by the same letter do not differ at $p < 0.05$

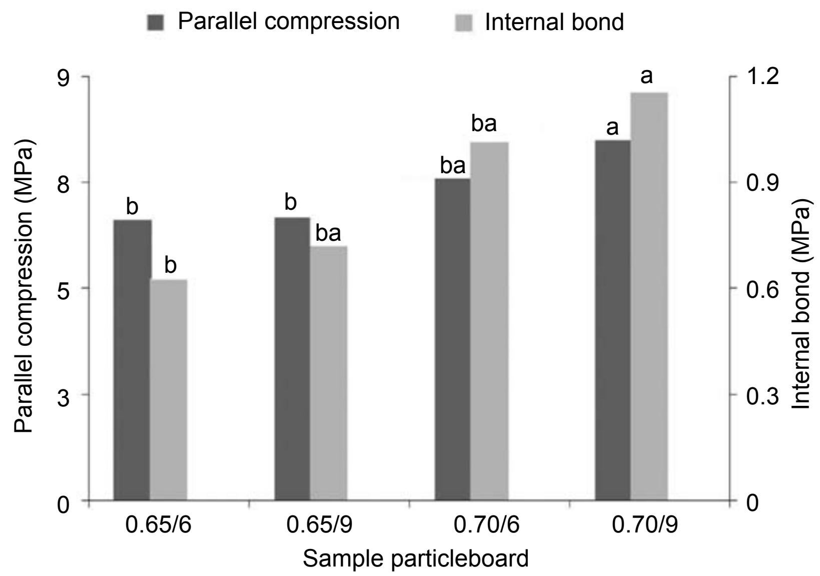

Figure 4 Parallel compression and internal bond of particleboards in stage 1 (100% *Toona ciliata*); details of samples are as in Table 1; means followed by the same letter do not differ at $p < 0.05$

which were compared with TC particleboards from sample 4 of the first stage.

TC particleboards made with both target densities and adhesive contents were in accordance with EN 312-3 (EN 2003) requirements for all mechanical properties. Although they did not have adequate thickness swelling for exterior use, all sample particleboards studied in this stage were suitable for use in dry conditions and they could be commercialised as particleboards type P2 for interior fitments.

Stage 2

Physical properties

Table 4 shows chemical analysis and basic density of the wood species used in this stage. The highest extractive and lignin contents were found in *T. ciliata* and *P. oocarpa* wood respectively.

There was no significant difference for determined densities between particleboards (Table 5). TC/E particleboards had the lowest compression ratio. Compression ratios of TC and TC/P particleboards were statistically equal, but value of the former was higher (Table 5).

TC/E particleboards had greater water absorption after two hours immersion compared with TC/P particleboards (Figure 5). However, water absorption after 24 hours was statistical equal between all particleboards although TC/E showed the highest value. The low compression ratio in TC/E was probably the main cause for the high value of water absorption since they had more voids which might allow water entrance.

Thickness swelling after two hours of immersion showed significant difference between samples. The best result was found for TC/P particleboards with swelling of 5%. After 24 hours, TC and TC/P particleboards demonstrated similar results of thickness swelling which might be related to their high compression ratios. TC/E particleboards had the highest value for this property. Increase in swelling is related to increase in the compression ratio due to higher release of compression stresses during water immersion. Compression stresses are induced into particleboard during pressing of mat in the hot press. However, a higher amount of wood per unit volume may also result in an increase in resin efficiency through additional and improved glue bonds, which may decrease thickness swelling (Gatchell et al. 1966).

Besides compression ratio, chemical composition of wood from different species may also influence water resistance of particleboards. *Toona ciliata* wood had the highest extractive content (Table 4). The positive effect of high contents of extractives on water resistance of particleboards has been reported (Nemli et al.

Table 4 Measured density and chemical composition of the wood species

Wood	Basic density (g cm^{-3})	Extractive content (%)	Lignin content (%)
Toona ciliata	0.32	12.95	24.41
Pinus oocarpa	0.36	6.35	26.67
Eucalyptus hybrid	0.53	6.83	22.76

Table 5 Measured density and compression ratio of the particleboards in stage 2

Sample	Actual density (g cm^{-3})	Compression ratio
TC	0.71 a	2.21 a
TC/P	0.69 a	2.02 a
TC/E	0.68 a	1.60 b

TC = 100% *T. ciliata*, TC/P = 50% *T. ciliata* + 50% *P. oocarpa*, TC/E = 50% *T. ciliata* + 50% *E. grandis* × *urophylla*; means followed by the same letter in the same column do not differ at $p < 0.05$

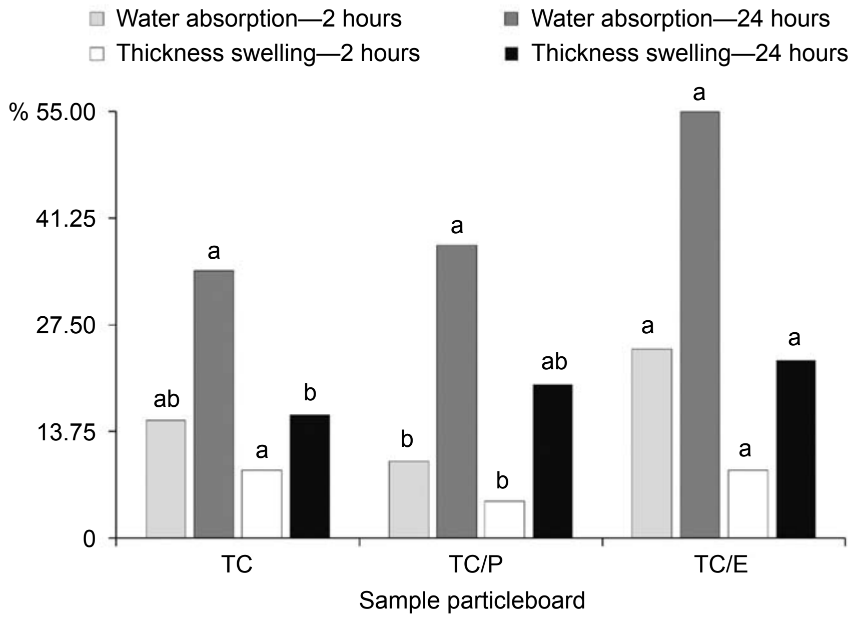

Figure 5 Physical properties of the particleboards in stage 2; TC = 100% *T. ciliata*, TC/P = 50% *T. ciliata* + 50% *P. oocarpa*, TC/E = 50% *T. ciliata* + 50% *E. grandis* × *urophylla*; means followed by the same letter do not differ at $p < 0.05$

2004, Buyuksari et al. 2010) and the resistance of TC/P particleboards to water may also be attributed to the highest lignin content of *P. oocarpa* wood, which imparts hydrophobicity to wood cells (Joseleau et al. 2004). Since lignin is a natural wood binder, thickness swelling and water absorption values of particleboards made from high lignin content materials are lower because of the improved bond formation between particles during mat forming process (Sellers et al. 1988, Khedari et al. 2004).

The highest thickness swelling of TC/E particleboards may also be attributed to the sorption behaviour of *Eucalyptus* clone, which had the highest basic density (Table 4). Wood of high density swells to a greater extent than wood of low density in response to changes in moisture content (Sellers et al. 1988).

The EN 312-3 (EN 2003) standard for thickness swelling after 24 hours requires values below 14% for non-load-bearing boards for use in humid conditions (type P3). Unfortunately, results of the current study showed that particleboards in stage 2 did not present values below the maximum required value.

Mechanical properties

MOR and MOE of TC/P and TC/E particleboards were similar but inferior to TC particleboards (Figure 6). This may be mainly attributed to the highest compression ratio presented by TC particleboards. The higher lignin content in *T. ciliata* and *P. oocarpa* species compared with *Eucalyptus* clone might have also contributed to increases in MOE and MOR. Lignin improves bond formation between particles resulting in increase in mechanical properties.

All particleboards produced in the second stage of the work met EN 312-3 (EN 2003) requirements for MOE and MOR. The standard specified 1950 and 14 MPa for MOE and MOR respectively for non-load-bearing boards for use in humid conditions (type 3).

The highest parallel compression was observed in TC/P particleboard (Figure 7). This result may have been influenced by the highest lignin content found for *P. oocarpa* wood. Lignin acts as a stiffener of cellulose microfibrils and appears to prevent or limit movement perpendicular to the grain (Sweet & Winandy 1999). A positive relationship was reported between increase in lignin content and increase in compression strength of the cell wall in Norway spruce (Gindl & Teischinger 2002).

Internal bond was similar between different particleboard compositions in this study (Figure 7). If other processing variables are held constant, lower compression ratio particleboards should present higher internal bond due to the greater

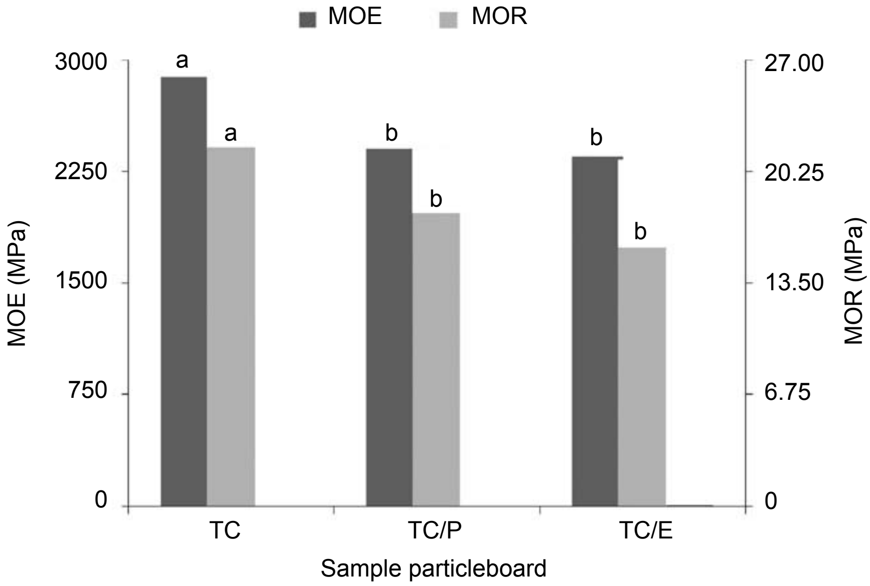

Figure 6 MOE and MOR of the particleboards in stage 2; TC = 100% *T. ciliata*, TC/P = 50% *T. ciliata* + 50% *P. oocarpa*, TC/E = 50% *T. ciliata* + 50% *E. grandis* × *urophylla*; means followed by the same letter do not differ at $p < 0.05$

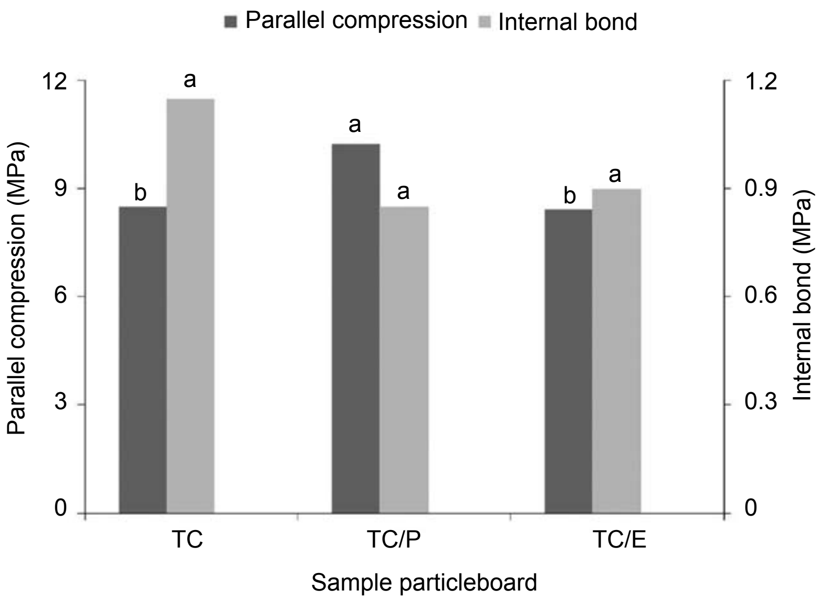

Figure 7 Parallel compression and internal bond of the particleboards in stage 2; TC = 100% *T. ciliata*, TC/P = 50% *T. ciliata* + 50% *P. oocarpa*, TC/E = 50% *T. ciliata* + 50% *E. grandis* × *urophylla*; means followed by the same letter do not differ at $p < 0.05$

amount of adhesive available per particle. However, 9% urea-formaldehyde seemed to be sufficient for internal bonding resistance.

All particleboards from the second stage of the work met the EN 312-3 (EN 2003) requirements for internal bond, which specified 0.45 MPa for non-load-bearing boards for use in humid conditions.

Overall results showed that particleboards made from 100% *T. ciliata* presented better results for mechanical properties than mixed particleboards, except for parallel compression. For physical properties, TC particleboards were similar to TC/P particleboards. TC/E particleboards presented the lowest mechanical properties, although still within the EN 312-

3 (EN 2003) standard, and highest physical properties. The particleboard compositions studied were in accordance with EN 312-3 (EN 2003) requirements for all mechanical properties. Although they did not have adequate thickness swelling for exterior use, particleboards in stage 2 were suitable for use in dry conditions and they could be commercialised as particleboards type P2 for interior fitments.

Results of the current study showed a great potential for using *T. ciliata* wood residues either alone or mixed with *Eucalyptus* or *Pinus* wood. Both of these species are widely cultivated in tropical and subtropical countries. The introduction of new species in particleboard market will be crucial in the following years since an increased demand for forest resources in various applications has led to a shortage in wood supply. The use of residues opens up new opportunities for both residue generators and potential residue users such as the particleboard industry (Gamage et al. 2009).

CONCLUSIONS

TC particleboard made with 9% urea-formaldehyde and a target density of 0.70 g cm^{-3} showed better results compared with the rest of the compositions tested. All TC particleboards could be used in dry conditions.

TC particleboards had better mechanical properties than mixed-species particleboards. For physical properties, the performances of TC particleboards were similar to TC/P particleboards. Both of these particleboards performed better than TC/E particleboards.

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