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Properties of medium-density particleboard from saline Athel wood

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Abstract

The Athel tree, *Tamarix aphylla* (L), can potentially be used as a biomass crop to help manage saline subsurface drainage water in arid land irrigated agriculture. In this study, Athel wood was used to manufacture medium-density particleboard with an aim of developing new applications for the saline wood. The research investigated the effects of different types of adhesives, particle sizes, bark content (BC), resin content (RC), and hot water pretreatment on the mechanical and water resistance properties of the Athel-derived, medium-density particleboards. The measured mechanical properties included tensile strength (TS), modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond strength (IB) of the finished particleboards. Water absorption and thickness swell were used to evaluate the water resistance. Polymeric methane diphenyl diisocyanate (PMDI) resin made particleboard of better mechanical properties and water resistance than urea formaldehyde (UF). The medium size (20–40 mesh) particles gave the best mechanical properties and water resistance than of the particleboard when evaluated against the smaller size (40–60 mesh) and larger size (10–20 mesh) particles. The mechanical properties of particleboard were improved as the resin content of the UF-board increased from 7 to 16%, but deteriorated as the bark content increased from 0 to 16.2%. The particleboard made from the wood particles that had undergone hot water pretreatment had poor mechanical properties and water resistance compared with the particleboard made from the untreated particles. Saline Athel wood is an appropriate material for manufacturing particleboards.

Keywords: Saline wood; Athel; Particleboard; Urea formaldehyde; Polymeric methane diphenyl diisocyanate; Mechanical properties; Water resistance

1. Introduction

The demand for composite wood products, such as plywood, oriented strandboard (OSB), hardboard, particleboard, medium-density fiberboard, and veneer board products has recently increased substantially throughout the world (Youngquist, 1999; Sellers, 2000). According to a report from Food and Agricultural Organization (FAO) of the United Nations, the worldwide demand of particleboard panels was 56.2 Mm^3 in 1998 (Youngquist and Hamilton, 2000). The demand for particleboards in the sectors of housing construction and furniture manufacturing has continued to increase (Sellers, 2000). In North America, 76 particleboard mills produced 10.952 Mm^3 in 1998, accounting for 19% of the total wood composites produced (Sellers, 2000, 2001).

The feasibility of using fast-growing trees and agricultural residues as raw materials for particleboard production has been explored by a number of researchers. Nemli et al. (2004) reported that the overall strength

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property and water resistance of the wood composites made from black locust (*Robibia pseudoacacia* L.) were comparable to those of mature wood composites and better than European Standard for Particleboard (ESC, 1996a,b,c,d). Pugel et al. (1989, 1990) reported that the overall strength property and water resistance of the wood composite made from southern pine (*Dendroctonus frontalis* Z.) juvenile trees were similar to or better than those of mature wood composites. Red pine (*Pinus resinosa*) thinning had similar properties to aspen when it was used as a raw material for laboratory waferboards bond with phenolic resin (Li et al., 1991). Oh et al. (2003) determined the effect of four different wood types (*Pinus rigida* Miller, *Pinus densiflora* Sieb. et Zucc., *Larix leptolepis* Gordon and *Quercus acutisstima* Carruthers) on the properties of particleboards and reported that all wood types can potentially be used to produce acceptable wood composites.

The Athel tree is an introduced, fast-growing, evergreen tree that grows in southwestern United States including California (Baum, 1967). It is drought resistant and tolerant of alkaline and saline soils and grows along irrigation ditches in the bottomlands (Little, 1980; Benson and Darrow, 1981). It has been found along the saline portions of the lower Colorado and Gila rivers and in the Salton Sea Basin (Turner and Brown, 1982). The Athel also grows on salt flats, springs, and other saline habitats especially along streams and rivers (Powell, 1988). The Athel trees can absorb and concentrate some salt in the wood as growth nutrients (Simpfendorfer, 1989). In the San Joaquin Valley (SJV) of California, the Athel trees have been grown and used for removing water by transporting and concentrating salts from agricultural drainage water. Usually, the Athel wood is used for fuel because it produces a fragrant odor when burned. It has been proposed for use in making furniture and fence posts (Little, 1980; Benson and Darrow, 1981; Mozingo, 1987). New applications of its wood need to be developed before Athel can become an economically viable tree species for use in soil and water remediation.

In addition, Athel has high ash (30–40%) and salt content, making it difficult to burn even when it is dry (Simpfendorfer, 1989). This indicates that the Athel-based particleboard could have superior fire retardant and other beneficial characteristics. Silica, phenol and some oxidants, including CuO, CrO_3, and As_2O_5 have been reported to have significant effects on improving the mechanical properties, water resistance properties, and decay resistance of particleboard (Huang and Cooper, 2000; Clausen et al., 2001; Zhou and Kamden, 2002; Nemli et al., 2004). However, no literature has been found on the feasibility of using saline Athel as a raw material for particleboard.

The objectives of this research were to (1) characterize the mechanical properties and water resistance of medium-density particleboards made from Athel as affected by adhesive type, wood particle size, bark content (BC), resin content (RC) and hot water pretreatment, (2) study the effect of moisture content (MC) and BC on the pH value of wood particles, and (3) determine the relationship between relative humidity (RH) and equilibrium moisture content (EMC) of the finished particleboards.

2. Materials and methods

2.1. Materials

Urea formaldehyde (UF) resin (C-TH39, 65.6% solid content) and polymeric methane diphenyl diisocyanate (PMDI) (100% solid content) were used as the adhesives for making the particleboards. UF was obtained from Borden Chemical Company (Hope, AR) and PMDI from Bayer Polymers LLC. (Pittsburgh, PA). Ammonium sulfate was purchased from Fisher Scientific Chemical Co. (Fair Lawn, New Jersey) and was used as the curing agent for the UF resin.

The Athel wood from 8 years old trees was collected from the Red Rock Ranch farm, CA. It was cut into approximately 40 cm long logs using a chainsaw. The logs used in this study were from three trees with diameters ranging from 5.1 to 25.4 cm and had harvest MC of 68.6%, which was measured according to the ASTM standard method (D4442-92, American Society for Testing and Materials, 1997a). The average density and bark fraction of the logs were 0.76 kg/cm^3 and 15.9%, respectively. All reported MC values are wet based (wb) unless specified otherwise. The Athel logs were further reduced into 5–10 cm long chips with a Dosko Brush Chipper (Model 1400-12) before the chips were air-dried to about 7% MC in the Biomass Laboratory at the University of California at Davis, CA.

2.2. Experiment design

2.2.1. Particleboards with different particle sizes, bark content, adhesive content, and thermal treatment

High quality particleboards of high strength, smooth surface, and equal swelling can be obtained by using a homogeneous material with a high degree of slenderness (long, thin particles), but without oversized particles, splinters, and dust. To determine the appropriate particle size for producing such high quality particleboard, the Athel wood chips were separated into heartwood and bark portions by hand using a chisel. The heartwood portion was then milled with a hammer mill (Model C269OYB, Franklin Co. Inc., Buffton, IN). The resulting particles with three different sizes of 10–20, 20–40, and 40–60 mesh were used to make particleboards using 7% UF resin for determining the effect of particle size on the quality of particleboards. The tests showed that the particleboard made with the 20–40 mesh particles had the highest quality. Therefore, the 20–40 mesh particles were used for making the rest of particleboards for study.

To determine the appropriate mill screen size for obtaining high yield of 20–40 mesh particles from milling heartwood, the heartwood chips were milled with three different screen opening sizes (1.27, 0.64, and 0.32 cm). The particle size distributions were analyzed using a modified ASTM standard method (E828-81, American Society for Testing and Materials, 1997b) with a sieve shaker (ROTAP, The W. S. Tyler Company, Cleveland, OH) and sieves (Newark Wire Cloth Co.). Because the 0.32 cm opening screen produced the highest yield of 20–40 mesh particles, it was used for producing particles for all the experiments. The wood particles were stored in a chamber to maintain a constant 7% MC at 52% RH and 21 ± 1 °C until they were used.

To determine the effect of bark content (BC) in the particles on the mechanical and dimensional stability properties of particleboard, three BC levels (0, 8, and 16.2%, total wet weight based) were prepared by using debarked heartwood particles, mixing debarked particles and bark particles, and using particles from chips without debarking, respectively. The equilibrium moisture contents of the particleboards were also determined.

The qualities of particleboards made from particles with and without thermal pretreatment were compared to determine the effectiveness of thermal treatment. Yasin and Qureshi (1990) improved eucalyptus particleboard properties by pre-treating the wood particles with hot water. Their method was modified and used in this study. The 20–40 mesh particles without bark were soaked in water contained in a beaker and heated in a water bath at 100 °C for 1 h. The suspension was then filtered using a Büchner funnel and washed three times with hot distilled water to remove the soluble extractives. The wet particles were dried in an oven at 60 °C for about 2 days until the moisture content of particles reached 7%. These particles were used to make particleboards with 7% UF resin.

To study the effect of RC of UF and BC on the quality of particleboards, a 4 × 3 full factorial design was used (Neter et al., 1996). The tested levels of RC were 7, 10, 13, and 16%, and the levels of BC were 0, 8, and 16.2%. The quality of the particleboards was fully evaluated with the methods specified in the following section.

Because PMDI has been used for making particleboard, it was also used as an adhesive in this study. The qualities of particleboards with either 4% PMDI or 7% UF resins were compared.

2.2.2. Effect of MC on pH values of particles

Because the MC of the particles is directly related to pH value that affects the performance of adhesive and quality of particleboards, the relationships between the MC and pH were determined for the particles with the three different BC levels (0, 8, and 16.2%). The 40–60 mesh particles were oven-dried to obtain four different MC levels (2, 4, 6, and 7%). One gram particle sample at each MC was soaked in 20 ml distilled water. The solution was kept at 20 ± 1 °C, shaken for 30 min, and then left still for 10 min in a water bath (Model R76, Reciprocal Cal Water Bath Shaker, New Brunswick Sci. Co., Inc., NJ) before the pH was measured. The pH of wood particles was determined according to the method described by Lebow and Winandy (1999) using a pH meter (AR20, Fisher Scientific Inc.). The relationship between MC and pH of the wood particles was analyzed.

2.3. Particleboard manufacture

The particleboards were made following the procedures outlined by Youngquist (1999). Adhesive resin, UF or PMDI, at a desired level specified in the experiment design section, was mixed with wood particles for 8 min at room temperature (20–22 °C) with a mixer (Model KP267XBK; KitchenAid, Greenville, OH). When UF was used, 1% (w/w) ammonium sulfate was added as a curing catalyst, based on the solid content of the UF. The resinated particles were then prepressed into a 2 cm single layer mat in a 22.8 cm × 22.8 cm wood mold.

In order to minimize the effects of density on the properties of particleboards, the bulk densities of all experimental particleboards were controlled at a constant level of about 0.72 g/cm^3, which corresponded to 0.55 cm thickness of the finished particleboard. Stops were used in the press to allow the same particleboard thickness to be achieved for all the test runs. To control the density, the theory proposed by Yossifov (1988) was used to calculate the amount of resin and wood particles required for a given resin content. For UF, the prepressed mat was pressed for 5 min in a hot press (Model 3891 Auto "M", Carver, Inc., Wabash, IN) with the temperature and pressure controlled at 152 °C and 3 MPa, respectively. For PMDI, the pressure time, temperature and pressure were 8 min, 140 °C, and 3 MP, respectively. The MC of finished particleboards was adjusted to 3.9% by conditioning the particleboards for 72 h in a Fisherbrand® Desiccator Cabinet in which the RH was maintained at 65% by using a saturated $CoCl_2$ solution and the temperature was controlled to about 20 °C. The conditioned particleboards were trimmed off about 2 cm around the edges to avoid edge effects and then cut into various sizes for the property evaluations.

2.4. Particleboard property evaluation

Mechanical properties, including tensile strength (TS), modulus of rupture (MOR), modulus of elasticity (MOE), internal bond strength (IB), and water resistance are very important specifications for particleboards. They were measured for each finished particleboard. Data analysis was performed using an SAS software package (SAS Institute, Raleigh, NC, 1992). The significance of different treatments were determined with analysis of variance (ANOVA) and least significant difference (LSD) ($\alpha = 0.05$). The specific methods used for evaluation of various properties are described as follows.

2.4.1. Mechanical properties

Finished particleboards were cut into various specimens according to ASTM standard method (D1037-99, American Society for Testing and Materials, 1999). The rectangular 3.8 cm × 15.2 cm and 5.1 cm × 17.8 cm pieces were used for TS determination and three-point-flex measurement of MOR and MOE, respectively. The 5.1 cm × 5.1 cm square pieces were used for IB measurement. The mechanical properties were determined using an Instron testing machine (Model 1122; Instron Corporation, Canton, MA) with the speed of movable crosshead set at 4 mm/min for TS test and 5 mm/min for three-point-flex and IB tests. Each reported value is the average of three measurements.

2.4.2. Water absorption and thickness swell

Water absorption and thickness swell of the particleboard samples were determined according to the ASTM standard method (ASTM D1037-99, American Society for Testing and Materials, 1999). The samples were soaked in water at room temperature (20–22 °C) for 2 and 24 h to determine the short- and long-term properties. The weight and thickness of the sample were measured before and immediately after soaking and used to calculate water absorption and thickness swell and reported as percentages of the values before soaking.

2.4.3. EMC measurement of finished particleboard

The equilibrium moisture contents (EMC) of heartwood particleboards with 7% UF resin at three different RH levels were determined using the method of Rowell et al. (1995). The particleboard specimens were stored in the chambers (Fisherbrand® Desiccator Cabinet) with constant RH levels of 50, 65, or 85% and temperature 21 ± 1 °C for about 7 days. The weight changes of all specimens were measured every 24 h until no change was observed. The EMC (dry basis) was calculated as

$$\mathrm{EMC} = \frac{\mathrm{CPW} - \mathrm{DPW}}{\mathrm{DWP}} \times 100\% \qquad (1)$$

where CPW is conditioned particleboard weight and DWP is the dry weight of particleboard.

3. Results and discussion

3.1. Effect of particle size on particleboard properties

When the wood particles of three different sizes were used to make particleboards, the 20–40 mesh size resulted in the highest MOR, TS, and IB values although there were no significant differences between the 10–20 mesh and 20–40 mesh for MOE, TS, and IB (Table 1). The 20–40 mesh particles were probably covered better by the resin and may have had better bonds based on the observed structure. However, the 40–60 mesh particles had the lowest mechanical properties. This may be due to the fact that the surface areas of the 40–60 mesh particles were too large to be adequately

Table 1
Mechanical and water resistance properties of particleboards with different particle sizes

Particle size (mesh)	MOR (MPa)	MOE (MPa)	TS (MPa)	IB (MPa)	Water absorption (%)		Thickness swell (%)	
					2 h	24 h	2 h	24 h
10–20	15.3 b	2020.7 a	10.33 ab	1.41ab	51.55 a	67.03 a	23.63 b	28.42 ab
20–40	18.2 a	1991.8 a	10.80 a	1.51 a	47.66 b	57.15 b	23.13 b	26.36 b
40–60	10.7 c	1302.0 b	9.61 b	1.32 b	54.65 a	64.65 a	26.95 a	30.32 a

Values within the same column followed by different letters are significantly different at $P < 0.05$. The particleboards were made with 7% UF and without bark.

Table 2
Effect of RH on EMC of the particleboard (20 °C)

Selected aqueous salt solution	RH (%)	EMC (%)
$Mg(NO_3)_2 \cdot 6H_2O$	50	3.50 c
$CoCl_2$	65	3.88 b
KCl	85	4.29 a

Values within the same column followed by different letters are significantly different at $P < 0.05$. The particleboards were made from 20 to 40 mesh particles with 7% UF and without bark.

Table 3
Weight percentage (%) of wood particles in different sizes

Particle sizes (mesh)	Screen sizes of hammer mill (cm)		
	1.27	0.64	0.32
6	16.6	0	0.1
10	35.0	0.3	1.8
20	34.1	6.9	23.6
40	11.8	36.2	45.8
100	2.0	42.5	23.7
Pan	0.3	9.1	5.2
Total	99.8	95.0	100.2

covered by the adhesives when the same mass ratio of adhesives and particles was used (Wang and Sun, 2002). However, the 10–20 mesh particles could be too large and resulted in weak bonds formed between the particles. The pores between particles could be easily seen and not all the particles were bond well by the resin. There is a need to study if different viscosities of resin and application techniques should be used for different size particles for achieving better quality particleboard compared with the procedures used in this study.

After 24 h soaking, the particleboards with different particle sizes showed significant differences in water absorption and thickness swell. The particleboard made from the 20–40 mesh particles had the lowest water absorption and thickness swell, and is consistent with the mechanical property results.

The EMC is important quality information for determining the applications of particleboard. High EMC could limit the use of particleboards due to weakened stability at high RH levels. The EMC of particleboards made from 20 to 40 mesh particles with 7% UF resin only increased from 3.50 to 4.29% as RH increased from 50 to 85% (Table 2). This indicates that the particleboards could perform well in the environments of relatively high humidity.

Because the particleboards with the 20–40 mesh particles had the most desirable quality, it is ideal to produce high percentage of 20–40 mesh particles from milling the chips. The size distributions of the particles obtained from the hammer mill with three different screen sizes are shown in Table 3. The highest percentage of the 20–40 mesh particles was obtained by using the 0.32 cm screen. Therefore, the 0.32 cm screen was used for preparing wood particles for all the other experiments.

3.2. *Effect of thermal pretreatment on particleboard properties*

When the wood particles were pretreated with 100 °C water, the color of water after treatment was dark red. The treated wood particles were lighter in color than the untreated particles. The particleboard made from the hot water treated particles had significantly lower mechanical properties than the particleboard made from the untreated particles even though the moisture contents of the treated and untreated particles were the same (Table 4). Such results could imply that some extractives, such as salts of Cu and Cr and phenolic substance, in the wood particles were important for the strength of the particleboard and the amount of extractives was reduced by the hot water pretreatment. Another factor could be the increased pH in the treated wood particles, making the particles and UF resin become less compatible. The changes of structure (e.g., cell wall components) and/or the surface properties of particles caused by the hot water pretreatment might also contribute to the lower mechanical properties of the particleboards. The mechanism of particleboard quality change caused by the pretreatment needs to be further investigated.

The results of water resistance also discourage the use of hot-water pretreatment. The particleboards made

Table 4
Mechanical and water resistance properties of particleboards made from hot water treated particles

Sample	MOR (MPa)	MOE (MPa)	TS (MPa)	IB (MPa)	Water absorption (%)		Thickness swell (%)	
					2 h	24 h	2 h	24 h
Treated	14.7 b	1604.6 b	8.94 b	1.25 b	58.80 a	82.81 a	27.27 a	33.33 a
Untreated	18.2 a	1991.8 a	10.80 a	1.51 a	47.66 b	57.15 b	23.13 b	26.36 b

Values within the same column followed by different letters are significantly different at $P < 0.05$. The particleboards were made with 7% UF and without bark.

Table 5
Mechanical and water resistance properties of particleboards with different UF resin contents (RC) and bark contents (BC)

BC (%)	UF RC (%)	MOR (MPa)	MOE (MPa)	TS (MPa)	IB (MPa)	Water absorption (%)		Thickness swell (%)	
						2 h	24 h	2 h	24 h
0	7	18.2 d	1991.8 f	10.80 bc	1.51 cbd	47.66 abc	57.15 bcd	23.13 ab	26.36 abc
0	10	21.4 b	2105.3 cd	13.39 abc	1.62 ab	35.84 cde	52.94 cde	15.11 de	16.90 efg
0	13	21.5 b	2134.0 c	15.27 ab	1.68 a	21.43 ef	44.48 e	9.55 fg	14.44 g
0	16	23.7 a	2384.9 a	17.62 a	1.73 a	19.79 f	42.96 e	8.32 g	12.87 g
8	7	16.1 f	1883.5 hi	8.69 c	1.24 fg	52.63 ab	63.25 abc	25.14 ab	29.56 ab
8	10	17.1 e	1928.2 g	9.68 bc	1.39 def	45.35 abc	58.61 bcd	17.23 dc	20.76 cdef
8	13	18.6 d	2050.6 e	10.54 bc	1.46 cde	30.21 def	50.12 de	12.78 defg	16.89 efg
8	16	19.6 c	2198.2 b	12.72 abc	1.65 ab	28.68 def	48.23 de	10.45 efg	14.71 fg
16.2	7	15.5 f	1844.8 i	9.47 c	1.21 g	57.64 a	70.26 a	27.89 a	32.67 a
16.2	10	16.1 f	1898.3 gh	9.99 bc	1.31 efg	48.27 abc	65.57 ab	21.98 bc	24.59 bcd
16.2	13	18.0 d	1934.6 g	10.24 bc	1.40 de	39.32 bcd	58.19 bcd	16.38 d	21.37 cde
16.2	16	18.5 d	2089.7 de	11.98 abc	1.59 abc	37.54 dc	55.68 bcd	13.57 def	18.34 defg

Values within the same column followed by different letters are significantly different at $P < 0.05$.

with treated particles had significantly higher short-term and long-term water absorption and thickness swell. The long-term water absorption and thickness swell increased by about 31 and 21%, respectively. Therefore, hot water pretreatment is not recommended for making such particleboards.

3.3. *Effect of bark and resin on particleboard properties*

Both the bark content (BC) and resin content (RC) had significant effects on the mechanical properties of particleboard (Table 5). However, no significant interactions were observed between the main variables based on the ANOVA analysis. At a constant level of BC, higher RC values resulted in higher values of MOR, MOE, TS, and IB, which were expected. However, higher RC also means higher production cost. Proper levels of RC depend on cost and quality requirements for a specific application.

The particleboard with bark had lower MOE, MOR, TS, and IB values than the particleboard without bark. This could be due to the presence of bark resulted in lower overall quality of fibers (Moslemi, 1935; Semple et al., 2002) and higher pH of wood particles, which might have inhibited the curing of UF (William, 1980; Sauter, 1996; Mo et al., 2003; Zhang et al., 2003). At constant MC, the presence of bark in the particles caused slight increase in pH, which could be due to less acidic chemicals contained in the bark than in the heartwood (Fig. 1). Such results indicate that the bond between UF and heartwood particles could be stronger than the bond between UF and bark particles, because the lower pH is more favorable to improving the bond quality of UF, which is a pH sensitive resin (Sauter, 1996). The pH of wood particles was significantly affected by the MC of particles. The pH increased from 4.82 to 5.44, from 4.91 to 5.56, and from 4.98 to 5.58 for 0, 8, and 16.2% BC,

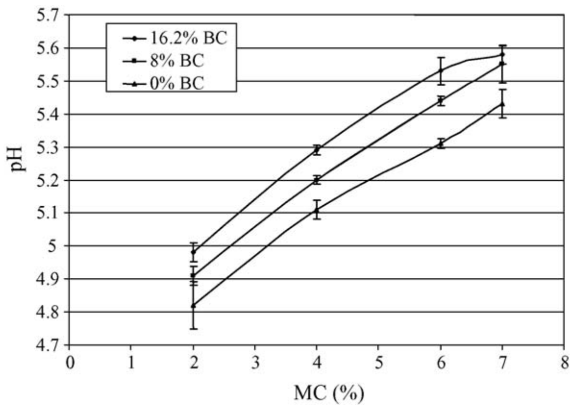

Fig. 1. Effect of moisture content (MC) and bark content (BC) on pH value of Athel wood particles.

Table 6
IB, MOE, MOR, and thickness swell values required to meet ANSI A208.1

Grade[a]	MOR (MPa)	MOE (MPa)	IB (MPa)	Thickness swell[b] (%)
M-1	11.0	1725	0.4	8
M-S	12.5	1900	0.4	8
M-2	14.5	2225	0.45	8
M-3	16.5	2750	0.55	8

[a] M-1 and M-S are for commercial usage and M-2 and M-3 are for industrial use.

[b] Thickness swell standard is specific for manufactured home decking particleboard.

Table 7
Mechanical and water resistance properties of particleboards bond with 7% UF and 4% PMDI

Adhesive	MOR (MPa)	MOE (MPa)	TS (MPa)	IB (MPa)	Water absorption (%)		Thickness swell (%)	
					2 h	24 h	2 h	24 h
PMDI	19.6 a	2052.4 a	11.59 a	1.68 a	20.99 b	49.02 b	10.71 b	15.72 b
UF	18.2 b	1991.8 b	10.80 a	1.51 b	47.66 a	57.15 a	23.13 a	26.36 a

Values within the same column followed by different letters are significantly different at $P < 0.05$. The particleboards were made without bark.

respectively, as the MC increased from 2 to 7%. The results were similar to that of Goto and Onishi (1967), but the reasons causing pH increase at high MC are still unknown.

The mechanical properties of all the particleboards exceeded the minimum mechanical property requirements for type M-1 particleboard according to U.S. Standard ANSI/A208.1 (CPA, 1999) (Table 6). Therefore, the debarking process may be unnecessary if the Athel wood is used for making M-1 particleboard with 7% UF resin. The IB values of the particleboards were significantly higher than the values specified in the standard. The particleboard made from particles without bark and 16% UF had the best mechanical properties in the test ranges. Its mechanical properties even exceeded the minimum mechanical property requirements for type M-2 particleboard.

The 2 and 24 h water absorption and thickness swell results are also presented in Table 5. In general, water absorption and thickness swell decreased with the increase of UF content. The presence of bark in the particleboards resulted in higher water absorption and thickness swell. Little interaction effects between RC and BC occurred for the water resistance of particleboard, and is consistent with the results related to the mechanical properties.

It has been suggested that furniture particleboards require less than 60% long term water absorption and less than 25% long term thickness swell obtained with ASTM D1037-99 (Yossifov, 1975; Maloney, 1977). The water resistance properties of the particleboards made in this study are better than those suggested values. However, they did not meet the U.S. Standard ANSI/A208.1 requirement. To improve the water resistance and thickness swell, three different methods could be considered based on current practices in the particleboard manufacturing industry. The first method is to add wax (0.5–1%) to the mixture of adhesive and particles during the manufacturing process. The second method is to decrease "springback" effect by reducing the density of the particleboards (Okino et al., 2004). If reducing particleboard density is not desirable for certain applications, adding wax should be used even though the mechanical properties may be lowered to some degree (Grigoriou, 2003; Okino et al., 2004; Papadopoulos et al., 2002, 2004). The third method is to acetylate the particles (Wisherd and Wilson, 1979; Hofstrand et al., 1984).

3.4. Effect of UF and PMDI adhesives on particleboard properties

The 4% PMDI particleboard had significantly higher MOR, MOE, and IB than the 7% UF board even though the difference in TS of the particleboards was not significant (Table 7). The test results of water absorption after 2 and 24 h soaking also showed that the PMDI particleboards had significantly better quality than the UF particleboard. The PMDI particleboard maintained relatively stable dimensions and had low water absorption. It is well known that PMDI has a significantly superior water resistance than UF (Vick, 1999).

The PMDI particleboard had about 50% less thickness swell than the UF particleboard. The thickness swell is affected by bond quality (Sauter, 1996) and adhesive properties (Boquillon et al., 2004). Since the particle bond resulting from 7% UF was not as strong as the bond from 4% PMDI, more water was able to penetrate into the particleboard, resulting in significantly greater swell. The thickness swell of 4% PMDI particleboard is still larger than that allowed by the U.S. Standard ANSI/A208.1. This may be reduced by adding wax or other hydrophobic substances during particleboard manufacture (Nemli et al., 2004), but the procedure has not yet been tested.

4. Conclusions

The results of this study indicate that saline Athel wood is a suitable raw material for making particleboards. High quality particleboards were obtained by using wood particles of 20–40 mesh. The particleboards made with PMDI at 4% RC had better product quality than the particleboards made with UF at 7% RC. If water resistance is important for the applications of the particleboards, PMDI appears to be the preferred adhesive even though its cost could be higher than UF. When UF was used, the quality of particleboards was improved with the increase of RC of UF from 7 to 16%. The presence of bark in the particles resulted in increased pH and reduced quality of finished products because UF was very sensitive to the pH of particles. Almost all the particleboards made in this study exceeded the minimum mechanical property requirements for MOR, MOE, and IB for type M-1 particleboard based on U.S. Standard ANSI/A208.1. The Athel particleboards may perform well in the relatively high humidity environment due to their low EMC.

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References

American Society of Testing and Materials, 1997a. Standard Test Method for Direct Moisture Content Measurement of Wood and Wood-Base Materials. Designation: ASTM D4444-92 (Reapproved 1997). ASTM, West Conshohocken, PA, pp. 517–521.

American Society of Testing and Materials, 1997b. Standard Test Method for Designating the Size of RDF-3 from its Sieve Analysis. Designation: ASTM E828-81 (Reapproved 1997). ASTM, West Conshohocken, PA, pp. 699–706.

American Society of Testing and Materials, 1999. Standard Test Method for Evaluating Properties of Wood-Base Fiber and Particle Panel Materials. Designation: ASTM D1037-99. ASTM, West Conshohocken, PA, pp. 142–171.

Baum, B.R., 1967. Introduced and naturalized tamarisks in the United States and Canada [Tamaricaceae]. Baileya 15, 19–25.

Benson, L., Darrow, R.A., 1981. The Trees and Shrubs of the Southwestern Deserts. The University of Arizona Press, Tucson, AZ, pp. 43–50.

Boquillon, N., Elbez, G., Schonfeld, U., 2004. Properties of wheat straw particleboards bonded with different types of resin. J. Wood Sci. 50, 230–235.

Clausen, C.A., Kartal, S.N., Muehl, J., 2001. Particleboard made from remediated CCA-treated wood: evaluation of panel properties. Forest Prod. J. 51, 61–64.

Composite Panel Association, 1999. American National Standard. Particleboard ANSI A208.1-1999. CPA, Gaithersburg, MD, 11 pp.

European Standardization Committee (ESC), 1996a. Particleboards Specifications. Part 2. Requirements for General Purpose Boards for Use in Dry Conditions. EN 312-2. ESC, Brussells, Belgium.

European Standardization Committee (ESC), 1996b. Particleboards Specifications. Part 3. Requirements for Boards for Interior Fitments (including furniture) for Use in Dry Conditions. EN 312-3. ESC, Brussells, Belgium.

European Standardization Committee (ESC), 1996c. Particleboards Specifications. Part 4. Requirements for Load-bearing Boards for Use in Dry Conditions. EN 312-4. ESC, Brussells, Belgium.

European Standardization Committee (ESC), 1996d. Particleboards Specifications. Part 6. Requirements for Heavy Duty Load-bearing Boards for Use in Dry Conditions. EN 312-6. ESC, Brussells, Belgium.

Goto, T., Onishi, H., 1967. Studies on the pH va1ue of wood. II. Inf1uence of various factors on the pH va1ue of wood. Bull. Faculty Agric., Shimane University 15, 75–79 (in Japanese).

Grigoriou, A.H., 2003. Waste paper-wood composites bonded with isocyanate. Wood Sci. Technol. 37, 79–89.

Hofstrand, A.D., Moslemi, A.A., Garcia, J.F., 1984. Curing characteristics of wood particles from nine northern Rocky Mountains species mixed with Portland cement. Forest Prod. J. 25 (3), 48–53.

Huang, C., Cooper, P.A., 2000. Cement-bonded particleboards using CCA-treated wood removed from service. Forest Prod. J. 50, 49–55.

Lebow, S.T., Winandy, J.E., 1999. Effect of fire-retardant treatment on plywood pH and the relationship of pH to strength properties. Wood Sci. Technol. 33 (4), 285–298.

Li, M., Gertjejansen, R.O., Ritter, D.C., 1991. Red pine thinnings as a raw material for waferboard. Forest Prod. J. 41 (7/8), 41–43.

Little, E.L., 1980. The Audubon Society Field Guide to North American Trees, Northern Region. Chanticleer Press, Inc., New York, pp. 56–70.

Maloney, T.M., 1977. Modern Particleboard Manufacturing. Miller Freeman Publications, Inc., San Francisco, CA, pp. 99–112.

Mo, X., Cheng, E., Wang, D., Sun, X.S., 2003. Physical properties of medium-density wheat straw particleboard using different adhesive. Ind. Crops Prod. 18, 47–53.

Moslemi, A.A., 1935. Materials: Particleboard, vol. 1., first ed. Southern Illinois University Press, London, pp. 21–33.

Mozingo, H.N., 1987. Shrubs of the Great Basin: A Natural History. University of Nevada Press, Reno, NV, 342 pp.

Nemli, G., Hiziroglu, S., Usta, M., Serin, Z., Ozdemir, T., Kalaycioglu, H., 2004. Effect of residue type and tannin content on properties of particleboard manufacture from black locust. Forest Prod. J. 54, 36–40.

Neter, J., Kutner, M.H., Nachtsheim, C.J., Wasserman, W., 1996. Applied Linear Statistical Models, third ed. McGraw-Hill. Book Co, NY, pp. 1052–1060.

Oh, Y.S., Cha, J.K., Kwak, J.H., 2003. Properties of particleboard from Korean thinning logs. Forest Prod. J. 53, 67–69.

Okino, E.Y.A., Teixeira, D.E., Souza, M.R.D., Santana, M.A.E., Sousa, M.E.D., 2004. Properties of oriented strandboard made of wood species from Brazilian planted forests: Part 1: 80 mm-long strands of *Pinus taeda* L. Holz Roh Werkst 60, 36–39.

Papadopoulos, A.N., Traboulay, E.A., Hill, C.A.S., 2002. One layer experimental particleboard from coconut chips—(*Cocos nucifera* L.). Holz als Roh- und Werksoff 60, 394–396.

Papadopoulos, A.N., Hill, C.A.S., Gkaraveli, A., Ntalos, G.A., Karastergiou, S.P., 2004. Bamboo chips (*Bambusa vulgaris*) as an alterntive lignocellulosic raw material for particleboard manufacture. Holz Roh Werkst 60, 36–39.

Powell, A.M., 1988. Trees and Shrubs of Trans-Pecos Texas Including Big Bend and Guadalupe Mountains National Parks. Big Bend Natural History Association, Big Bend National Park, TX, 536 pp.

Pugel, A.D., Price, E.W., Hsc, C.Y., 1989. Composite from southern pine juvenile wood. Part 1. Panel fabrication and initial properties. Forest Prod. J. 40 (1), 29–33.

Pugel, A.D., Price, E.W., Hsc, C.Y., 1990. Composite from southern pine juvenile wood. Part 2. Durability and dimensional stability. Forest Prod. J. 40 (3), 57–61.

Rowell, R.M., Kawai, S., Inoue, M., 1995. Dimensionally stabilized, very low density fiberboard. Wood Fiber Sci. 27, 428–436.

SAS, 1992. SAS User's Guide. SAS Institute Inc., Cary, NC.

Sauter, S.L., 1996. Developing composites from wheat straw. In: Proceedings of the 30th International Symposium of Washington State University on Particleboard/Composite Materials, pp. 197–214.

Sellers, T., 2000. Growing markets for engineered products spurs research. Wood Technol. 127 (3), 40–43.

Sellers, T., 2001. Wood adhesive innovations and applications in North American. Forest Prod. J. 51 (6), 12–22.

Semple, K.E., Cunningham, R.B., Evans, P.D., 2002. The suitability of five western Australian mallee eucalypt species for wood-cement composites. Ind. Crops Prod. 16, 89–100.

Simpfendorfer, K.J., 1989. Continuation of #17679 - Keywords. Lands and Forests Bull. Lands and Forests Division, Department of Conservation, Forests and Lands, No. 30. East Melbourne, Victoria, Australia, 55 pp.

Turner, R.M., Brown, D.E., 1982. Sonoran desert-scrub. In: Brown, D.E. (Ed.), Biotic Communities of the American Southwest—United States and Mexico. Desert Plants 4 (1–4), 181–221.

Vick, C.B., 1999. Adhesive bonding of wood materials. In: Wood Handbook: Wood as an Engineering Material. Gen. Tech. Rept. FPL-GRT-113. USDA Forest Serv., Forest Prod. Lab., Madison, WI, pp. 1–24 (Chapter 9).

Wang, D., Sun, X., 2002. Low density particleboard from wheat straw and corn pith. Ind. Crops Prod. 15, 43–50.

William, E.J., 1980. Effect of pH and buffering capacity of wood on gel time of UF resin. Wood Fiber 30, 255–263.

Wisherd, K.D., Wilson, B., 1979. Bark as a supplement to wood furnish for particleboard. Forest Prod. J. 29 (2), 35–40.

Yasin, S.M., Qureshi, T.A., 1990. Cement bonded particleboard from eucalyptus camaldulensis wood. Pakistan J. Forestry. 40, 53–60.

Yossifov, N.A., 1975. Production of wood particleboards. Gov. Dept. for publication of Agriculture Lit, Sofia, Bulgaria.

Yossifov, N.A., 1988. Mathematical modeling of parameters characterizing the gluing links between particles in particleboards. In: Mechanical Wood Technology. No. 34 in Res. Pap. Series. Higher Inst. of Forestry and Wood Tech., Sofia, Bulgaria.

Youngquist, J.A., 1999. Wood-based composites and panel products. In: Wood Handbook: Wood as an Engineering Material. Gen. Tech. Rept. FPL-GRT-113. USDA Forest Serv., Forest Prod. Lab., Madison, WI, pp. 1–31 (Chapter 10).

Youngquist, J.A., Hamilton, T.E., 2000. A look at the world's timber resources and processing facilities. In: Proceedings of the XXI IUFRO World Congress 2000, Sub-plenary sessions, vol. 1, Kuala Lumpur, Malaysia, pp. 183–190.

Zhang, Y., Lu, X., Pizzi, A., Delmotte, L., 2003. Wheat straw particleboard bonding improvements by enzyme pretreatment. Holz als Roh- und Werkstoff 61, 49–54.

Zhou, Y., Kamden, D.P., 2002. Effect of cement/wood ratio on the properties of cement-bonded particleboard using CCA-treatment wood removed from service. Forest Prod. J. 52, 77–81.