Physical and Mechanical Properties of Loblolly and Slash Pine Wood from Uruguayan Plantations

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Abstract

The available wood supply in Uruguay comprises trees that grow so fast in intensively managed plantations that they reach saw timber size in 25 years or fewer. Trees harvested at this age contain high proportions of juvenile wood that may lead to lumber low in stiffness and strength. A project was conducted to characterize fast-growing wood, determine engineering properties, and assign visual structural grades of lumber. The present study evaluated properties of 15- and 25-year-old loblolly (*Pinus taeda* L.) and slash (*Pinus elliottii* Eng.) pine to better understand the current available locally produced wood material. A total of 175 stump bolts from trees from two commercial plantations provided inner and outer small clear specimens for property evaluation. Specific gravity, bending, compression parallel to grain and perpendicular to grain, and shear tests were conducted. Most properties significantly increased radially away from the pith. The outer wood appears to be denser, stiffer, and stronger than the inner wood in both plantations. Wood from 15-year-old San José trees showed significantly lower properties than 25-year-old Paysandú trees, and had considerably inferior properties compared with values listed in the *Wood Handbook* (US Department of Agriculture 1999). Our results on 25-year-old Paysandú small clear specimens showed properties similar to those of previous studies on small clear and structural size pieces. Therefore, it can be expected that lumber from 25-year-old Paysandú trees will eventually comply with required properties for structural use. A second on-going phase of this study addressing structural size specimens will help to establish more definite conclusions.

The forest sector in Uruguay had a significant increase in the last 30 years as a consequence of a governmental policy to promote forest plantations. In the 1980s, estimates of Uruguay's native forest ranged from 400,000 to 600,000 ha of mostly small and curved trees with diameter at breast height (DBH) of 15 to 20 cm of limited or no industrial use; planted forest estimates ranged from 120,000 to 137,000 ha of *Pinus* and *Eucalyptus*. There were an additional 70,000 ha of *Liriodendron tulipifera, Populus deletoides, Salix humboldtiana,* and other exotic species (Ministerio de Ganadería Agricultura y Pesca [MGAP] 2005). At present, forest plantations cover almost 1 million ha. One quarter of the total planted area corresponds to *Pinus* sp. and within it, loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*) meant for sawn timber and engineered wood products comprise 39 and 45 percent, respectively (MGAP 2010). Due to their similar physical properties (Clark and Saucier 1989), these two species are usually planted indistinctly mixed in the stand, and are available for customers in a similar mixed manner. With average growth rates of 19 to 24 m^3 ha^{-1} y^{-1} (Ramos and Cabrera 2001, Morales 2007) and cutting cycles of 25 years for lumber, Uruguay provides excellent growing conditions for pine species. According to EN 1310 (European Committee for Standardization [CEN] 1997) and to the commonly accepted range of 20 to 30 m^3 ha^{-1} y^{-1} that define a fast-growing species, Uruguayan pines fall into this category.

As a result of the accelerated expansion of plantations, wood from these plantations showed high percentages of juvenile wood, making it different from that of pines harvested from older, slow-growing natural stands. The softwood lumber and plywood industries in Uruguay use relatively young trees under short rotation conditions, and they will use even more in the future with promotion of agro forestry. Trees harvested at the age of 20 to 25 years may

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contain 75 percent juvenile wood (Bendtsen 1978). The end-product concern with juvenile wood is that its physical and mechanical properties are inferior to those of mature wood (Kretschmann and Bendtsen 1992, Ying et al. 1994, Kretschmann 1997, McAlister et al. 1997, Ballarin and Palma 2003). Low specific gravity, short fibers, and high microfibril angles in juvenile wood are the main factors leading to lower strength and stiffness and higher longitudinal shrinkage compared with mature wood (Bendtsen 1978). Juvenile wood is produced by the young cambium and forms a cylinder of wood around the pith that extends the length of the tree. The faster a tree grows during the first few years of rotation, the larger the diameter of the juvenile core in the lower bole (Clark et al. 2006). Most softwood species show a radial gradient in physical properties. The transition between juvenile and mature wood is difficult to determine because it occurs gradually (Clark et al. 2006), differs between species, and varies based on the feature being measured (Mackes et al. 2005). For example, a study on plantation-grown loblolly pine conducted by Bendtsen and Senft (1986) reported 13 years as the age of maturity for specific gravity and mechanical properties, and 18 years for maturity based on fiber length. A similar pattern of change of specific gravity with age was observed in slash pine by Zobel et al. (1971). Pérez Favaro et al. (2000) reported that transition from juvenile to mature wood in loblolly pine occurred between the 8th and 12th ring based on density and tracheid length. This radial variation in wood properties within the tree has practical implications because it can directly affect strength, stiffness, and shrinkage (Sotelo Montes et al. 2007). Pearson and Gilmore (1980) claimed that the fact that lumber from fast-growing trees contains high percentages of juvenile wood, and thus low mechanical properties, does not mean that it is unsuitable for structural applications, yet it does mean that special grades and allowable values may have to be provided.

Building construction in Uruguay relies on masonry, steel, and concrete. Use of timber as a structural material represents less than 0.5 percent of the total residential construction industry. Cultural prejudices, end-users' lack of knowledge on timber technology, and mostly lack of graded material in the market are the main reasons that prevent the adoption of timber as a structural material. The very few building contractors that currently use wood complain about the quality of locally produced lumber. High moisture content, warp, and lack of standardized and ''specified'' material are the major sources of complaints and, consequently, market shares are lost to other materials. Structural use of timber relies on material characterization (stress-graded), design specifications, and building code. Design properties for the major commercial species can be established by combining small clear specimens and structural size methods. In the United States, design properties of softwoods have been derived from full-size members, and design properties for hardwoods are determined using small clear samples (Kretschmann and Hernández 2006). While the world tendency is toward in-grade testing with structural size specimens, both methods are complementary. Testing procedures for small clear specimens allows determining some properties that are difficult to obtain in structural sizes, such as shear and compression perpendicular strength. Additionally, the small clear test method focuses on the study of the inherent characteristics of wood rather than timber (Madsen 1992). In the early 2000s, some pioneer works performed at Laboratorio Tecnológico del Uruguay (LATU) on small clear specimens and structural size lumber evaluated selected properties of fast-grown pines planted in Uruguay (Pérez Favaro et al. 2000; O'Neill et al. 2002, 2003). Those studies partially characterized the national production and were the initial steps to determine the feasibility of pine wood for structural applications. The present study supplements and broadens that database.

With the current timber availability and several governmental policies that promote wood from national plantations (Ministerio de Vivienda, Ordenamiento Territorial y Medio Ambiente [MVOTMA] 2011, Gabinete Productivo 2012), the use of timber in the construction sector represents an important market opportunity for the wood industry, and thus the suitability of the resource to meet construction needs compels attention. The objective of this study was to determine the physical and mechanical properties of loblolly and slash fast-growing pines from two commercial plantations, and the degree of change of those properties radially within the stem. Subsequent articles will report on the engineering properties of pine lumber and outline grading rules and assignment to strength classes.

Materials and Methods

With the aim of obtaining representative values of the national production, the wood samples came from two commercial plantations, M1 and M2, located at two different sites within the Uruguay: M1 in Paysandú province, middle west (32°23′00″S, 57°36′00″W), and M2 in San José province, south west coast (33°51′06″S, 56°53′00″W). Both sites have a subtropical type climate characterized by hot, humid summers and generally mild to cool winters; still, San José is more humid and has narrower thermal amplitude than Paysandú. Soil types on the Paysandú site are hapludalfs and argiudolls, while at San José, hapludalfs and quartz ipsamments are predominant (Durán et al. 2006). Species composition was similar for both stands and consisted of a mixture of 90 percent slash and 10 percent loblolly pine. Seedlings were planted at 3 by 3-m and 4 by 2.50-m spacing in M1 and M2, respectively. Thinning was conducted at 5, 7, and 10 years in both stands, and also at 15 years in M1. Trees from M1 were 25 years old, had average DBH of 450 mm, and an average total height of 25 m, whereas those from M2 were 15 years old with a DBH of 300 mm and were 15 m tall.

One 1.80-m-long bolt per tree was taken at the stump, totaling 175 bolts (100 from M1 and 75 from M2). Because lumber is not sold by species, no effort was made to collect data and report results with species as a variable. Each bolt produced a 100-mm-thick center plank that contained the pith and was the width of the bolt diameter. The planks were then covered with plastic film and transported to the LATU for further processing and evaluation Each plank was divided into zones based on radial distance from the pith—inner (A) and outer (C)—to obtain small clear and straight-grained samples for mechanical and physical property determinations. For bending properties, additional specimens from an intermediate zone (B) were tested. No variation in properties along the length of individual planks was assumed. Furthermore, for bending properties, A, B, and C specimens were all cut at the same height within the plank: all three either from the top, or all three from the bottom. For each of the remaining properties, both A and C specimens were cut at the same intermediate height within the plank. Figure 1 depicts the radial location of test specimens within the plank.

Two sets of matched specimens, one from one side of the plank and the second from the opposite side, were collected for mechanical and physical property testing and were cut along the length of the plank per ASTM D143-09 (ASTM International 2011a). One set was conditioned to 20°C and 65 percent relative humidity for at least 4 weeks before testing (set H). The other set was water soaked in a tank and the moisture content (MC) kept above the fiber saturation point prior to test (set S). Specimens were labeled for identification, detailing sampling site, replicate number, location within the plank, and moisture condition. Prior to testing, cross-sectional dimensions were measured for each specimen using a hand-held caliper.

Property evaluation

Mechanical and physical tests were performed in accordance with ASTM D143-09 (ASTM International 2011a). Bending and shear tests were carried out on a Universal Minebea machine with a 50-kN load cell, in a controlled climate chamber at 20°C and 65 percent relative humidity. The rest of the tests were carried out on a Universal Minebea machine with a 250-kN load cell. Bending deflection was measured using an extensometer located at the center of the specimen. Ultimate strength for each loading case was determined. Additionally, for bending and compression tests, modulus of elasticity was computed using the slope of the linear portion of the load-deflection curve. Immediately after testing, samples were removed from near the failure zone of the test specimen for specific gravity (SG), and MC measurements using the ovendrying method. Type of test, number of replicates, and specimen location within the plank, are shown in Table 1. For compression and shear properties, an equal number of replicates from M1 and M2 planks were evaluated. The M1 subsample was randomly selected from 100 planks.

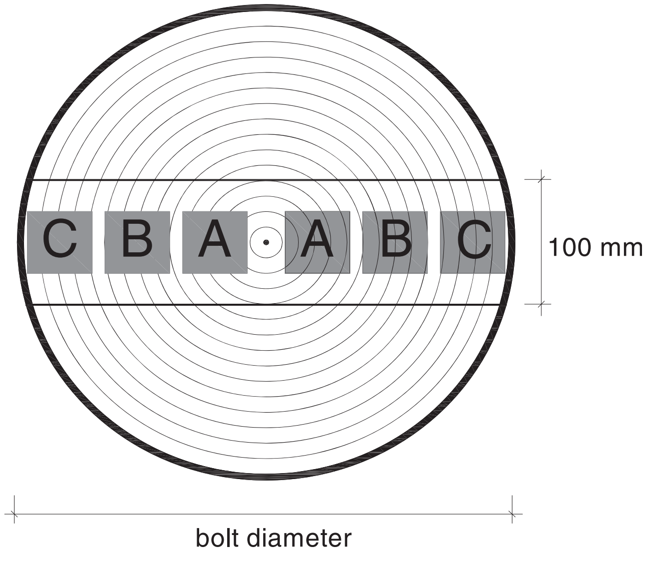

Figure 1.—Radial location of specific gravity and mechanical property test specimens from 25-year-old Paysandú (M1) and 15-year old San José (M2) trees.

Table 1.—Specimen and test details.

Type of test[a]	Specimen size (mm)	No. of replicates		Specimen location within the tree[b]
		Green	~14% MC[c]	
Static bending				
M1	50 × 50 × 760	108	291	A, B, and C
M2	50 × 50 × 760	105	190	A, B, and C
Compression parallel to grain				
M1	50 × 50 × 200	74	74	A and C
M2	50 × 50 × 200	76	76	A and C
Compression perpendicular to grain				
M1	50 × 50 × 150	74	74	A and C
M2	50 × 50 × 150	74	74	A and C
Shear				
M1	50 × 50 × 63	74	74	A and C
M2	50 × 50 × 63	74	76	A and C

[a] M1 and M2 are samples from 25-year-old Paysandú and 15-year-old San José plantations, respectively.

[b] With respect to radial position from pith to bark. A = inner; B = intermediate; C = outer.

[c] MC = moisture content.

Mechanical properties were adjusted to 12 percent MC per ASTM D2915-97 (American Society for Testing and Materials [ASTM] 2000):

$$P_{\mathrm{MC2}} = P_{\mathrm{MC1}} \left[\frac{(\alpha - \beta \times \mathrm{MC}_2)}{(\alpha - \beta \times \mathrm{MC}_1)} \right] \tag{1}$$

where P_{MC1} is the property measured at MC_1 (in percent), and α and β are moisture constants.

SGs were adjusted to 12 percent MC (US Department of Agriculture [USDA] 1999):

$$\mathrm{SG}_2 = \frac{\mathrm{SG}_1}{[1 - 0.265(30 - \mathrm{MC}_2)/100 \cdot \mathrm{SG}_1]} \tag{2}$$

where SG_2 is the SG at the desired moisture content, MC_2 (in percent), and SG_1 is the basic SG (ovendry weight and green volume basis).

Data analysis

To aid future characterization of the available material, variation between M1 and M2 samples was first analyzed. For each group, specimen data were ordered from low to high and descriptive statistics were estimated. Additionally, the fifth percent exclusion limit (5th percentile) for each property was established directly from the test results; it was determined by the value associated to the ranked statistic that corresponds to 5 percent of the sample size. When this value did not match an experimental result, interpolation between two marks was performed.

Specimen properties for each combination of site and radial position within the tree were compared ($P < 0.05$) using a 2-way analysis of variance (ANOVA). Subsequently, Fisher least significant difference (LSD) was used to compute the mean values and perform pairwise comparisons to determine significant differences with respect to radial position within trees. All tests were conducted at the 95 percent confidence level ($\alpha = 0.05$).

Results and Discussion

Results of the 2-way ANOVA are shown in Table 2. Both site and radial position within the tree had a significant

Table 2.—Analysis of variance results of mechanical properties of loblolly and slash pine wood.[a]

MC	Source of variation[b]	Bending			Compression strength		
		MOE	MOR	SG	Parallel	Perpendicular	Shear strength
~14%	Site	***	***	***	***	***	***
	Position	***	***	***	***	NS	*
	Site × position	NS	NS	NS	NS	NS	NS
Green	Site	***	***	***	***	***	***
	Position	***	***	***	***	NS	NS
	Site × position	**	**	NS	NS	NS	NS

[a] MC = moisture content; MOE = modulus of elasticity; MOR = modulus of rupture; SG = specific gravity; *, **, and *** = significant at the 0.05, 0.01, and 0.001 levels, respectively; NS = not significant.

[b] Site = M1 and M2; position = position within the tree, i.e., A, B, and C.

effect on SG, bending properties, compression parallel to grain, and shear strength of dry specimens, while for compression perpendicular to grain, only the site effect was significant. The two main factors are independent from each other because no interactions were significant for any property of dry specimens listed in Table 2. Results of green specimens were similar to those of dry ones, with the exception of shear strength where only site effect was significant. Additionally, interaction between the main factors was observed only on bending properties.

Specific gravity

The mean SGs of all testing specimens adjusted to 12 percent MC were 0.49 and 0.40 for 25-year-old Paysandú (M1) and 15-year-old San José (M2) samples, respectively (Table 3). These means were lower than the 0.59 value given in the *Wood Handbook* (USDA 1999) for mature slash pine at 12 percent MC. However, the mean SG from M1 samples was close to the listed 0.51 for mature loblolly pine at 12 percent MC. On the other hand, the mean relative SG of Paysandú specimens (0.47) was fairly comparable to the mean relative SG of 24-year-old loblolly pine from Río Negro (0.45) reported by O'Neill et al. (2003). Furthermore, studies on slash pine from a 24-year-old plantation located in Río Negro found relative SGs of 0.42 (O'Neill et al. 2002).

As a preliminary step to aid in identifying variation in mechanical properties, SGs from the two plantations were compared. ANOVA showed that the SG from 25-year-old Paysandú trees is significantly greater than the SG from 15-year-old San José trees ($P < 0.001$). The fact that age at harvest differed between plantations could explain, to some extent, the decrease in SG and mechanical properties (discussed in a later section) found in the wood from San José trees. However, in a forest stand not only silvicultural practices, but also soil type and climate regimes within others, affect many important factors (e.g., density, fiber length, straightness of grain, juvenile wood) that impact the suitability of wood for structural purposes (Bowyer et al. 2003). Since the growing conditions in the two forest stands were not identical, no definite conclusion on the influence of tree age on wood properties from this research can be made.

It was found that radial location within the tree significantly affected the SG of samples from both plantations. Pairwise comparisons on SG from bending specimens confirmed that SG significantly decreased from C to B, and from B to A positions (Table 4). As an example, SG decreased 7 and 11 percent closer to the pith (C vs. B, and C vs. A) for Paysandú samples, and 9 and 13 percent for San José samples (Table 4). A box plot of SG variation through tree radial zone in Figure 2 illustrates this trend. Coefficients of variation (COVs) of M1 A, B, and C specimens were identical to the 10 percent listed in the *Wood Handbook*. For M2 samples, a similar COV was observed in A specimens, whereas COVs of 13 and 12 percent were found in B and C specimens, respectively. The variation in SG with radial distance from the pith in the present study seems reasonably consistent with previous findings on loblolly and slash pines planted in Uruguay (O'Neill et al. 2002, 2003; O'Neill and Tarigo 2008). These studies noted that within the tree, radial variation of SG is related among other factors, to the presence of juvenile or

Table 3.—Summary of mechanical properties of loblolly and slash pine wood.[a]

		SG			MOE (MPa)			MOR (MPa)			C-parallel strength (MPa)			C-perpendicular strength (MPa)			Shear strength (MPa)[c]		
Sample source[b]	MC	Mean	SD	5th percentile	Mean	SD	5th percentile	Mean	SD	5th percentile	Mean	SD	5th percentile	Mean	SD	5th percentile	Mean	SD	5th percentile
M1	12%	0.488	0.065	0.376	7,444	2,511	3,925	65.6	14.9	42.2	37.2	9.4	25.0	9.7	2.6	6.3	9.3	1.4	7.8
	~14%	0.477	0.065	0.369	7,196	2,427	3,794	62.4	14.2	40.1	33.7	8.5	22.6	9.7	2.6	6.3	9.0	1.4	6.7
	Green	0.412	0.057	0.318	5,498	2,204	2,411	38.6	8.8	25.8	17.5	4.0	12.4	3.6	0.91	2.4	5.5	0.94	4.3
M2	12%	0.401	0.058	0.314	5,124	1,680	2,857	46.8	11.5	28.9	27.2	5.3	20.6	7.1	1.6	4.8	8.1	1.2	6.1
	~14%	0.393	0.058	0.309	4,953	1,624	2,762	44.5	10.9	27.5	24.6	4.8	18.6	7.1	1.6	4.8	7.6	1.2	5.9
	Green	0.352	0.045	0.277	3,894	1,314	2,121	30.4	6.0	21.3	13.8	3.1	9.9	3.2	0.75	2.2	4.9	1.08	3.19

[a] MC = moisture content; SG = specific gravity; MOE = modulus of elasticity; MOR = modulus of rupture; C-parallel = compression parallel to the grain; C-perpendicular = compression perpendicular to the grain.

[b] M1 and M2 are samples from 25-year-old Paysandú and 15-year-old San José plantations, respectively.

[c] Mean of tangential and radial shear strength.

Table 4.—Bending property variation within the tree with respect to radial position.[a]

MC	Radial position[b]	Sample size	SG Mean	SG SD	SG LSD[c]	MOE (MPa) Mean	MOE (MPa) SD	MOE (MPa) LSD	MOR (MPa) Mean	MOR (MPa) SD	MOR (MPa) LSD
~14%	M1										
	A	97	0.473	0.049	BC	5,955	2,282	BC	55.2	13.6	BC
	B	97	0.510	0.052	AC	7,092	2,211	AC	63.1	13.1	AC
	C	97	0.534	0.057	AB	8,505	2,179	AB	68.5	12.7	AB
	M2										
	A	74	0.390	0.038	BC	4,067	1,036	BC	38.7	7.5	BC
	B	42	0.428	0.054	AC	4,717	1,540	AC	43.1	12.1	A
	C	74	0.446	0.055	AB	5,936	1,654	AB	50.7	9.9	A
Green	M1										
	A	36	0.378	0.035	BC	3,821	1,131	BC	31.6	4.6	BC
	B	36	0.415	0.047	AC	5,412	1,932	AC	37.4	6.1	AC
	C	36	0.446	0.053	AB	7,185	2,020	AB	46.6	7.7	AB
	M2										
	A	35	0.329	0.029	BC	3,083	839	C	26.9	3.5	C
	B	35	0.347	0.030	AC	3,735	1,184	C	29.1	5.4	C
	C	35	0.383	0.041	AB	4,863	1,227	AB	35.1	5.6	AB

[a] MC = moisture content; SG = specific gravity; MOE = modulus of elasticity; MOR = modulus of rupture.

[b] M1 and M2 are samples from 25-year-old Paysandú and 15-year-old San José plantations, respectively.

[c] LSD = least significant difference pairwise comparisons at the 0.05 level. Letters represent tree sections that have mean values that are significantly different from the tree section listed in the column ''Radial position.''

mature wood. Based on an analysis of density and tracheid length, Ballarin and Palma (2003) established that transition from juvenile to mature wood in loblolly pine occurred between the ages of 14 and 18 years, while Tasissa and Burkhart (1998) lowered the threshold to 11 and 13 years for the same species. For slash pine, Clark and Saucier (1989) found a similar period of juvenility to loblolly pine. In line with those findings and the SG trends depicted in Figure 2, it is apparent that the trees (and thus test samples) from the San José plantation are composed of nearly all juvenile wood. Concerning the Paysandú trees, it could be assumed that inner specimens (A) consist of juvenile wood, outer specimens (C) of mature wood, and intermediate specimens (B) of transition wood. SG data indicate that it may be reasonable to expect variations in mechanical properties based on these three zones.

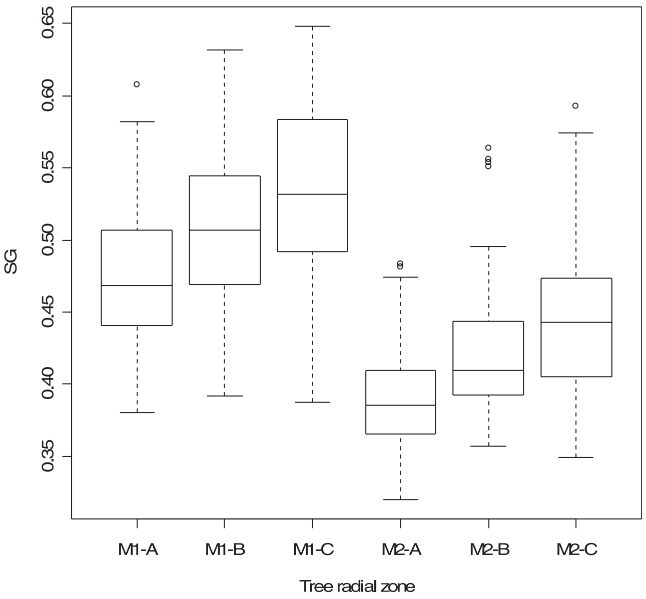

Figure 2.—Box plots of specific gravity (SG) for inner (A), intermediate (B), and outer (C) specimens from 25-year-old Paysandú (M1) and 15-year old San José (M2) samples.

Mechanical property evaluation

Bending.—Modulus of elasticity (MOE) and modulus of rupture (MOR) values for loblolly and slash pine from the two plantations are presented in Table 3. Overall mean values from Paysandú samples (M1) are in close agreement with previous studies on the same species and similar age (O'Neill et al. 2002, 2003). Average values of 6,699 and 63 MPa for MOE and MOR, respectively, were reported for slash pine clear wood samples from a 24-year-old plantation (O'Neill et al. 2002). Another study on a 24-year-old loblolly pine plantation found average values of 8,190 and 73 MPa for bending stiffness and strength, respectively (O'Neill et al. 2003). Bending tests results of San José specimens (M2) showed significantly lower values than those from Paysandú. For further comparison, M1 properties were adjusted to 12 percent MC and then compared with reference values listed in the *Wood Handbook* (USDA 1999). According to the *Wood Handbook,* expected MOE and MOR for 12 percent MC loblolly pine are 12,300 MPa (65% increase) and 88 MPa (33% increase). For slash pine, MOE and MOR reference values are greater at 13,700 MPa (84%) and 112 MPa (69%), respectively. Increased differences were observed when reference values were compared with M2 specimens. Note that the mechanical and physical properties values listed in the *Wood Handbook* are based on mature wood, whereas in the present study, the results came from samples that comprise high proportions of juvenile wood. Furthermore, in previous studies on 24-year-old pines, O'Neill et al. (2002, 2003) tested both small clear and structural size specimens and claimed that 27 percent of slash and 87 percent of loblolly pine lumber complied with the requirements of JAS 143 (Japanese Agricultural Standard Association 1994) for structural softwood lumber. Because our results on small clear specimens are close to those reported by O'Neill et al. (2002, 2003), it could be expected that lumber from 25-year-old Paysandú trees have the strength and stiffness to meet the requirements for structural use, the results of which will be addressed in a future article.

Box plots of MOE and MOR data for each plantation presented in Figures 3 and 4 depict an increasing trend in properties throughout pith to bark. Statistical analysis indicated in Table 2 found that variation in location within the tree was significant for bending properties in both plantations. Pairwise comparisons of M1 specimens confirmed that bending properties significantly decreased from C to B, and from B to A positions (Table 4). For M1 samples, proximity to the pith had a highly significant effect on MOE with a decrease of 16 and 30 percent in stiffness closer to the pith (inner zone). MOR followed a similar trend with a reduction of 13 and 19 percent nearer to the pith. Analogous behavior was observed within M2 samples. Statistical analysis revealed a continuous decrease of MOE from bark to pith, although the trend was less pronounced between the outer and intermediate zones ($P < 0.01$). This tendency was evident in MOR behavior where no significant difference between outer and intermediate zones was observed.

Additionally, box plots of bending properties (Figs. 3 and 4) depict the variability found in data for both M1 and M2. For M1 samples, the COVs of MOE and MOR were 34 and 24 percent, 31 and 21 percent, and 26 and 18 percent, for A, B, and C specimens, respectively, resulting in higher percentages compared with the 22 and 16 percent for MOE and MOR listed in the *Wood Handbook*. Similar COVs for both stiffness and strength were found in M2. The large variability observed in MOE and MOR could be explained by the fact that although A, B, and C bending specimens were cut at the same height of individual planks, the sets of these three specimens were taken either from the top or bottom of the planks. Therefore, it could be a difference in age of the tested specimens that contributed to the increase in variation of bending properties. In addition, this difference could be less evident in mechanical test specimens other than bending specimens, because they were cut at approximately mid-height rather than at the extremes of individual planks.

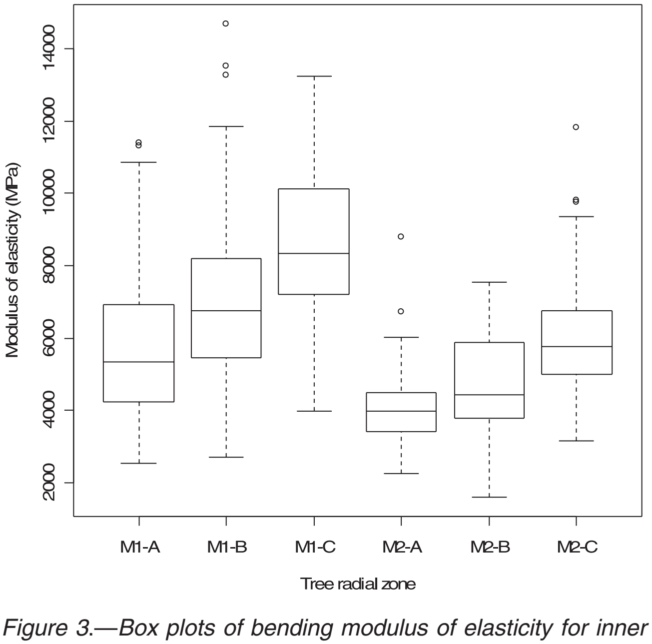

Figure 3.—Box plots of bending modulus of elasticity for inner (A), intermediate (B), and outer (C) specimens from 25-year-old Paysandú (M1) and 15-year old San José (M2) samples.

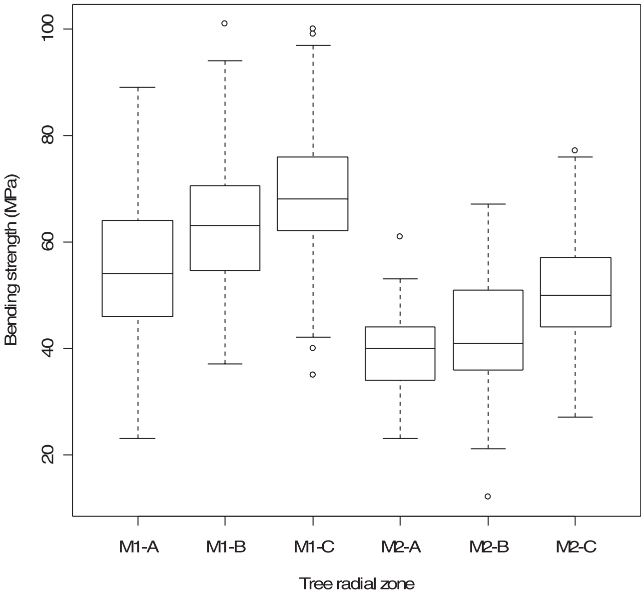

Figure 4.—Box plots of bending modulus of rupture for inner (A), intermediate (B), and outer (C) specimens from 25-year-old Paysandú (M1) and 15-year old San José (M2) samples.

Compression.—Mean values of compression parallel and perpendicular to grain tests from the two plantations specimens are shown in Table 3. Compression parallel strength of Paysandú samples was similar to previous findings on 24-year-old loblolly and slash pines reported by Pérez del Castillo and Venturino (2003). Test results were lower than those given in the *Wood Handbook*. The reference values at 12 percent MC for mature loblolly and slash pine found in the *Wood Handbook* (49.2 and 59.1 MPa) indicate a reduction in compression parallel strength of specimens tested in this study by 24 and 34 percent for loblolly and slash pine, respectively. For compression perpendicular strength, results from 25-year-old Paysandú specimens are 80 and 40 percent greater than the 5.4 and 7.0 MPa listed in the *Wood Handbook* for loblolly and slash pines, respectively. Compression perpendicular strength specimens from the 15-year-old San José plantation showed identical values to those reported in the *Wood Handbook* for mature slash pine.

Figures 5 and 6 illustrate the within-tree variation in compression strengths by radial zones for both plantations. Statistical analysis verified that variation in location within the tree had a significant effect on compression parallel strength for specimens from both plantations (Table 5). For M1, specimens located close to the pith (inner zone) showed a 23 percent decrease in compression parallel strength compared with outer specimens. Similar behavior was found in M2 samples with 16 percent reduction for compression parallel strength from bark to pith. Alternatively, compression perpendicular strength of M1 specimens was not significantly affected by radial position within the tree, but M2 inner specimens showed significantly lower values compared with those close to bark ($P < 0.01$) (Table 5).

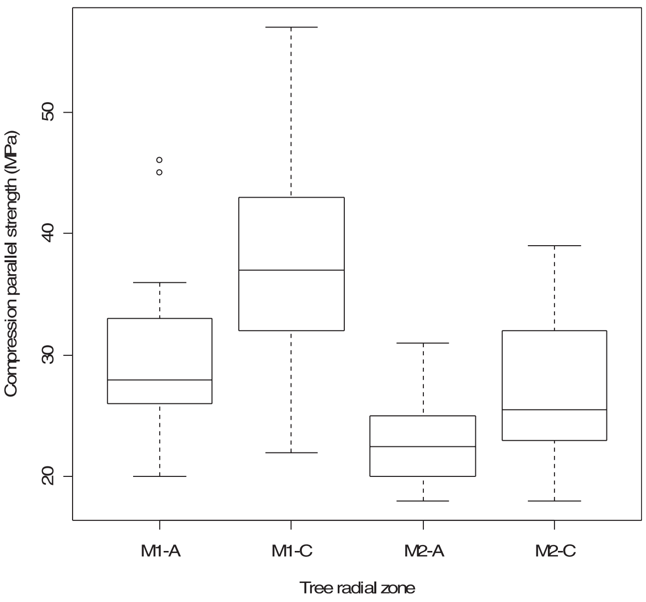

Figure 5.—Box plots of compression parallel strength for inner (A) and outer (C) specimens from 25-year-old Paysandú (M1) and 15-year old San José (M2) samples.

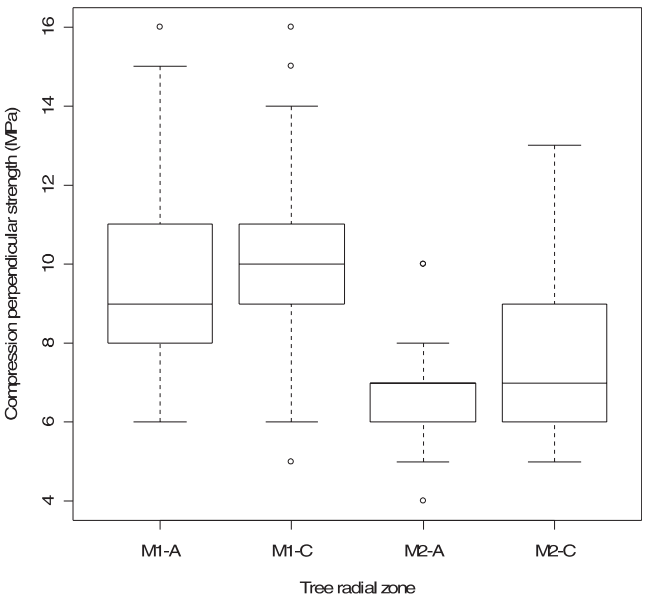

Figure 6.—Box plots of compression perpendicular strength for inner (A) and outer (C) specimens from 25-year-old Paysandú (M1) and 15-year old San José (M2) samples.

In addition, box plots of compression parallel strength (Fig. 5) graphically show the data of M1 and M2 samples. For A specimens, COVs for M1 and M2 samples equaled or were less than (13 percent) the 18 percent listed in the *Wood Handbook*. For C specimens, COVs were 22 and 19 percent for M1 and M2, respectively, percentages that slightly surpassed the reference value. Also, the variability of compression perpendicular strength shown in box plots (Fig. 6), and COVs ranging from 28 to 17 percent for M1 and M2 A and C specimens, indicated identical or reduced percentages compared with the 28 percent listed in the *Wood Handbook*.

Shear.—Mean values of shear parallel tests from the two plantations specimens are shown in Table 3. Because there were no significant differences between specimens with 0° (tangential) and 90° (radial) growth ring orientations, shear strength values in Table 3 are averages from both orientations. Note that this lack of influence of ring orientation on shear strength has been earlier reported for loblolly pine wood (Kretschmann 2008). The adjusted result of 9.3 MPa for M1 samples agreed well with the 9.6 MPa listed in the *Wood Handbook* for mature loblolly pine at 12 percent MC. However, the reference value (*Wood Handbook*) of 11.6 MPa at 12 percent MC for mature slash pine indicates a reduction in compression strength of specimens tested in this study by 20 percent. For M2 samples, adjusted shear strength did not agree (8.1 MPa) with reference values for either loblolly or slash pines.

Figure 7 shows the within-tree variation in shear strength by radial zones for both plantations. Statistical analysis found that variation in location within the tree had a significant effect on the shear parallel strength for specimens from both plantations (Table 6). For M1, specimens located close to the pith showed a 14 percent decrease in shear parallel strength, compared with those

Table 5.—Compressive property variation within the tree with respect to radial position.[a]

MC	Radial position[b]	Sample size	C-parallel strength (MPa)			Sample size	C-perpendicular strength (MPa)		
			Mean	SD	Sig.[c]		Mean	SD	Sig.
~14%	M1								
	A	37	29.3	5.2		37	9.6	2.7	
	C	37	38.2	8.9	***	37	9.8	2.4	
	M2								
	A	38	22.5	2.9		37	6.7	1.7	
	C	38	26.7	5.4	***	37	7.6	1.9	**
Green	M1								
	A	37	15.2	2.3		37	3.5	0.7	
	C	37	19.8	4.0	***	37	3.7	1.1	
	M2								
	A	38	12.0	1.7		37	3.1	1.7	
	C	38	15.7	3.2	***	37	3.3	3.2	

[a] MC = moisture content; C-parallel = compression parallel to the grain; C-perpendicular = compression perpendicular to the grain.

[b] M1 and M2 are samples from 25-year-old Paysandú and 15-year-old San José plantations, respectively.

[c] Sig. = asterisks denote significant differences compared with A: *$\alpha = 0.05$; **$\alpha = 0.01$; ***$\alpha = 0.001$.

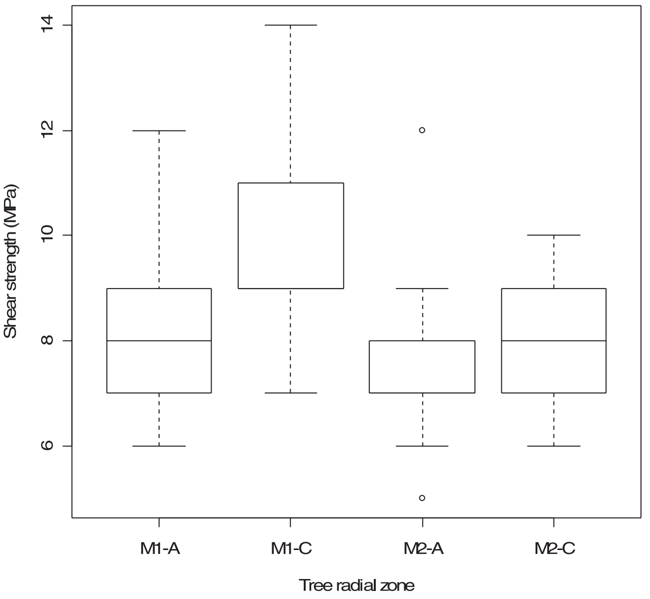

Figure 7.—Box plots of shear strength for inner (A) and outer (C) specimens from 25-year-old Paysandú (M1) and 15-year old San José (M2) samples.

located near the bark zone. For M2, a 12 percent reduction in shear strength was observed.

Variability of shear strength shown in box plots (Fig. 7) and COVs ranging from 13 to 15 percent for A and C specimens from both M1 and M2, closely agreed with the 14 percent listed in the *Wood Handbook*.

MC effects

Strength and elastic properties increased when MC decreased as shown in Tables 3 to 6. Ratios of dry (≈14% MC) to green MOE, MOR, compression parallel, compression perpendicular, and shear strength for M1 were 1.31, 1.62, 1.93, 2.69, 1.64, respectively. These values were similar to those listed in ASTM D2555-06 (ASTM 2011b) for loblolly pine. Ratios for M2 were slightly lower compared with M1; however, the trend was well defined.

Table 6.—Shear property variation within the tree with respect to radial position.

MC[a]	Radial position[b]	Sample size	Shear strength (MPa) Mean	SD	Sig.[c]
~14%	M1				
	A	37	8.4	1.3	
	C	37	9.6	1.3	*
	M2				
	A	38	7.1	0.9	
	C	38	8.1	1.3	*
Green	M1				
	A	37	5.5	0.9	
	C	37	5.6	0.9	
	M2				
	A	37	4.8	1.0	
	C	37	5.0	1.2	

[a] MC = moisture content.

[b] M1 and M2 are samples from 25-year-old Paysandú and 15-year-old San José plantations, respectively.

[c] Sig. = asterisks denote significant differences compared with A: *α = 0.05; **α = 0.01; ***α = 0.001.

Table 7.—Regression equations of mechanical properties.

Sample source[a]	Regression equation[b]	Coefficient of determination (R^2)
M1	Bending	
	MOR = 151 × SG − 14.2	0.39
	MOE = 21,877 × SG − 3,870	0.28
	MOR = 133 × MOE − 1,085	0.61
	C-parallel strength = 58 × SG + 8.13	0.16
	C-perpendicular strength = 17 × SG + 2.3	0.15
	Shear strength = 19 × SG + 0.7	0.45
M2	Bending	
	MOR = 109 × SG − 1.24	0.30
	MOE = 9,996 × SG + 748	0.11
	MOR = 113 × MOE − 78	0.57
	C-parallel strength = 35 × SG + 11.2	0.15
	C-perpendicular strength = 13 × SG + 2.5	0.15
	Shear strength = 18 × SG + 0.6	0.56

[a] M1 and M2 are samples from 25-year-old Paysandú and 15-year-old San José plantations, respectively.

[b] MOR = modulus of rupture; SG = specific gravity; MOE = modulus of elasticity; C-parallel = compression parallel to the grain; C-perpendicular = compression perpendicular to the grain.

Relationship between mechanical properties and SG

Plots of SG versus each mechanical property tested in this study (i.e., MOR, MOE, compression parallel, compression perpendicular, and shear strength) were generated and linear regression equations for the two plantations are shown in Table 7. Regression lines fitted to data with specimens considered as independent observations revealed that R^2 values were very low for the line fitted to the relationship between SG and each mechanical property from 25-year-old Paysandú samples (M1 specimens). A similar analysis of data from 15-year-old San José samples (M2 specimens) yielded less significant linear relationships between SG and most mechanical properties, with the exception of SG versus shear strength, which has a higher R^2 value for M2 samples compared with M1 samples. Although a strong relationship between SG and mechanical properties is well documented for mature wood (USDA 1999), the lack of significance for wood tested in this study was not unexpected. Similar results were reported by Mackes et al. (2005). They claimed that because of a high percentage of juvenile wood encountered in small-diameter ponderosa pine, the widely accepted SG–mechanical properties relationships may not be as significant as those typically found with wood from large slower growing trees. Furthermore, Langum et al. (2009) stated that mechanical properties of clear wood are governed not only by density but by microfibril angle as well. The lack of significance between SG and mechanical properties observed in this study could be explained by the fact that in early growth of pines the earlywood and the latewood are quite close in density, and properties are more influenced by microfibril angle and chemical makeup of the wood. It is expected that as the tree matures, the proportion of latewood tracheids with thicker walls and higher SG increases compared with the initial stages of growth where thin-walled earlywood cells are predominant. This fact will probably contribute more to the overall improvement in the relationship between mechanical properties and density.

Relationship between MOE and MOR

Figure 8 shows the regression results for bending MOE versus MOR for M1 samples, with coefficients of determination of 0.77 and 0.61 in the green and dry states, respectively. Similar analysis for M2 samples yielded coefficients of determination of 0.67 and 0.57 in the green and dry states, respectively. These results suggest that the bending strength of loblolly and slash pine wood can be reasonably predicted by the corresponding bending stiffness.

Conclusions

The purpose of this study was to characterize loblolly and slash pine wood from two commercial plantations in Uruguay with the goal of gaining a better understanding of this material. Small clear test specimens cut from a 25-year-old plantation sited in Paysandú (middle west), and from a 15-year-old plantation located in San José (south west), were studied. Variations of properties by radial location within trees were evaluated. Generally, most properties significantly increased radially away from the pith for specimens from both plantations. The outer wood appears denser, stiffer, and stronger than the inner wood. Changes in SG within tree amounted to an 11 to 13 percent increase from pith to bark zones, results that closely agree with previously reported trends for loblolly and slash pines. Trees from San José were composed of high proportions of juvenile wood resulting in strength and stiffness values between 45 and 62 percent lower than what is reported for mature wood of the corresponding species in the *Wood Handbook* (USDA 1999). Bending stiffness and strength increased with increasing distance from pith, for both plantations. Compression parallel strength and shear strength were lower in the inner compared with the outer zone of trees from both plantations. Compression perpendicular strength increased with increasing distance from pith for San José trees, however no variation was observed in Paysandú trees.

The relationships between SG and each mechanical property were not as significant as typically found for wood from mature trees. Nevertheless, the correlation between MOE and MOR offers an opportunity for nondestructive evaluation of this material.

Based on these findings, wood from 15-year-old San José trees has considerably lower properties compared with reference values listed in the *Wood Handbook*. Presumably, age is the primary reason for the low properties observed, and it is expected that the lumber from these trees would also have structural low properties. Wood from 25-year-old Paysandú trees showed physical and mechanical properties similar to previously reported values on small clear specimens for the same species under similar site conditions and age in Uruguay (O'Neill et al. 2002, 2003). Bearing in mind that in those studies pine lumber met the requisites of JAS 143, it can be expected that lumber from 25-year-old Paysandú trees will eventually comply with the requirements for structural applications as well. More research on structural size specimens is required to establish definite conclusions and to outline a structural grading system for loblolly and slash pine from Uruguayan plantations.

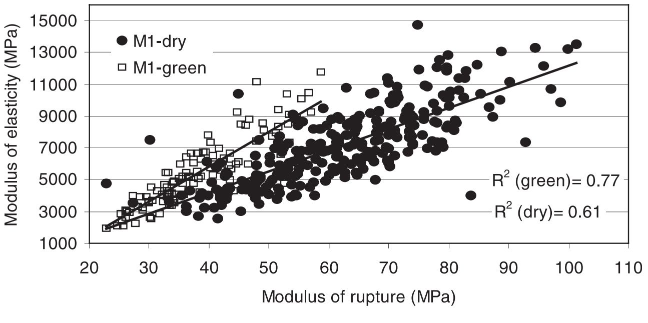

Figure 8.—Relationship between modulus of elasticity and modulus of rupture for 25-year-old Paysandú samples (M1).

Acknowledgments

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