Technical Note

Properties of Juvenile and Mature Wood and Their Effects on the Bending Properties of Lumber in *Pinus taeda* Growing in Tochigi, Japan

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Abstract

Five 40-year-old *Pinus taeda* trees growing in Tochigi, Japan, were used to evaluate juvenile wood (JW) and mature wood (MW) properties and the bending properties of lumber. The boundary between JW and MW existed from the 14th to the 19th ring from pith in the sample trees. There were obvious differences in wood properties between the JW and MW: the MW had higher values in the latewood percentage and basic density and lower values in the microfibril angle. The microfibril angle and the air-dry density were closely related to the bending properties of the JW lumber and the MW lumber, respectively.

In softwoods, it is known that there is a problem with using the juvenile wood as structural lumber and pulp because it has a lower density, shorter cell length, larger microfibril angle (MFA) of the S_2 layer, and poor mechanical properties compared with mature wood (Shiokura 1982, Bendtsen and Senft 1986, Clark and Saucier 1989, Zobel and van Buijtenen 1989). It has been shown that the effects of the wood properties, such as the MFA and wood density, on the strength properties differ between juvenile and mature wood. For example, in Japanese cedar (*Cryptomeria japonica*), Ishiguri et al. (2009) pointed out that the MFA influenced mainly the bending properties of juvenile wood, whereas the air-dry density (AD) influenced mainly the bending properties of mature wood. Matsumura et al. (2012) examined the influence of the lumber positions (center [near the pith], inner, and outer [near the bark]) in large-diameter Japanese cedar logs on variations in the dynamic modulus of elasticity (DMOE) of the lumber. The results showed that the mean values of the DMOE of the lumber obtained from the center, inner, and outer positions were 4.64, 5.44, and 6.48 GPa, respectively. These differences in the DMOE of the lumber are closely related to the existence of juvenile wood. Therefore, it is important to clarify the differences in the wood and the mechanical properties between juvenile and mature wood.

Pinus taeda was introduced in Japan as a fast-growing species (Karizumi 1969), and the plantation areas of this species increased in the Kanto, Chubu, and Kinki regions of Japan from 1950 through 1960, reaching 507 hectares in 1965 (Karizumi 1969). Tsubomura et al. (2002) examined the wood properties of 30-year-old *P. taeda* grown in Miyazaki, Japan, and compared them with those of Japanese cedar. They reported that the *P. taeda* showed a larger annual ring width and higher density than the Japanese cedar; however, there are only a few reports on the wood quality and mechanical properties of the *P. taeda* grown in Japan, e.g., Tsubomura et al. (2002).

In the present study, the wood properties and bending properties of lumber were investigated in 40-year-old *P. taeda* trees planted in Tochigi, Japan. The results obtained were used to clarify the differences in the wood properties and bending properties between juvenile wood and mature wood.

Materials and Methods

Five 40-year-old *Pinus taeda* L. trees were used in the present study. These trees were planted at a pilot plantation for exotic *Pinus* species in the Funyu Experimental Forest, Utsunomiya University, Tochigi, Japan (36°46′N,

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139°49′E). The mean stem diameter at 1.2 m above the ground was 39.8 ± 7.8 cm. A disk (5 cm in thickness) from each tree was collected at a position of 2.1 m above the ground to measure the wood properties, including annual ring width (ARW), latewood percentage (LWP), basic density (BD), microfibril angle of the S_2 layer in the latewood tracheid (MFA), and latewood tracheid length (TL). In addition, a log (1.8-m length) was also collected from a section 0.2 to 2.0 m above the ground to examine the static bending properties of the lumber (95 by 45 mm in cross section).

The ARW and latewood width were measured at each annual ring, from the pith to the bark, in four different directions using a digital caliper (CD-15CP; Mitutoyo). The LWP was calculated by dividing the latewood width by the annual ring width at every annual ring. The BD, MFA, and TL were measured at every three annual rings from the pith. To avoid the effects of resin on the wood density, the specimen for the BD was extracted with an ethanol-toluene mixture (1:2, vol/vol) using a Soxhlet extractor for 6 hours. After extraction, the BD was calculated by dividing the ovendried weight by the green volume measured using the water displacement method. The radial sections (20 µm in thickness) were prepared using a sliding microtome to measure the MFA. The mean values of the MFA in 30 tracheids were measured in each radial position by the iodine method (Senft and Bendtsen 1985). Small strip specimens were macerated with Schulze's solution to measure the TL. A total of 30 latewood tracheids were measured using a microprojector (V-12; Nikon) with a digital caliper (CD-30CP; Mitutoyo).

The lumber was prepared to create as many boards as possible from each log, with a total of 82 boards obtained. After air-drying for 6 months, the lumber was planed to 1,800 by 89 by 38 mm to measure the bending properties. The DMOE was measured using an FFT analyzer (AD-3527; A&D) and a piezoelectric acceleration sensor (PV-85; RION) by the tapping method (Arima et al. 1993). After measuring the DMOE, a static bending test was conducted using a universal testing machine (DCS-5000; Shimadzu) with a center load of lumber. The span and crosshead speed were 1,500 mm and 10 mm/min, respectively. The modulus of elasticity (MOE) and modulus of rupture (MOR) were calculated using a data analyzer (Dataledy 401; Shimadzu).

Results and Discussion

Wood properties

Figure 1 shows the radial variations of the ARW, LWP, BD, TL, and MFA in the five sample trees. It can be seen that the ARW decreased up to approximately the 15th annual ring from the pith. After that, two patterns were found in the variation: (1) the ARW in one pattern (Trees 1 and 2) increased up to the 21st annual ring from the pith, and then it showed an almost constant value, and (2) the ARW in the other pattern (Trees 3 to 5) showed an almost constant value from the 15th annual ring toward the bark. The mean value and standard deviation of the ARW in the five trees were 5.4 and 1.2 mm, respectively (Table 1). The LWP rapidly increased up to the 15th annual ring from the pith (Fig. 1); then, it was around 30 percent in all of the sample trees. Based on these results, the mean value and standard deviation of the LWP were 26.8 and 2.9 percent, respectively (Table 1). Clark and Saucier (1989) examined

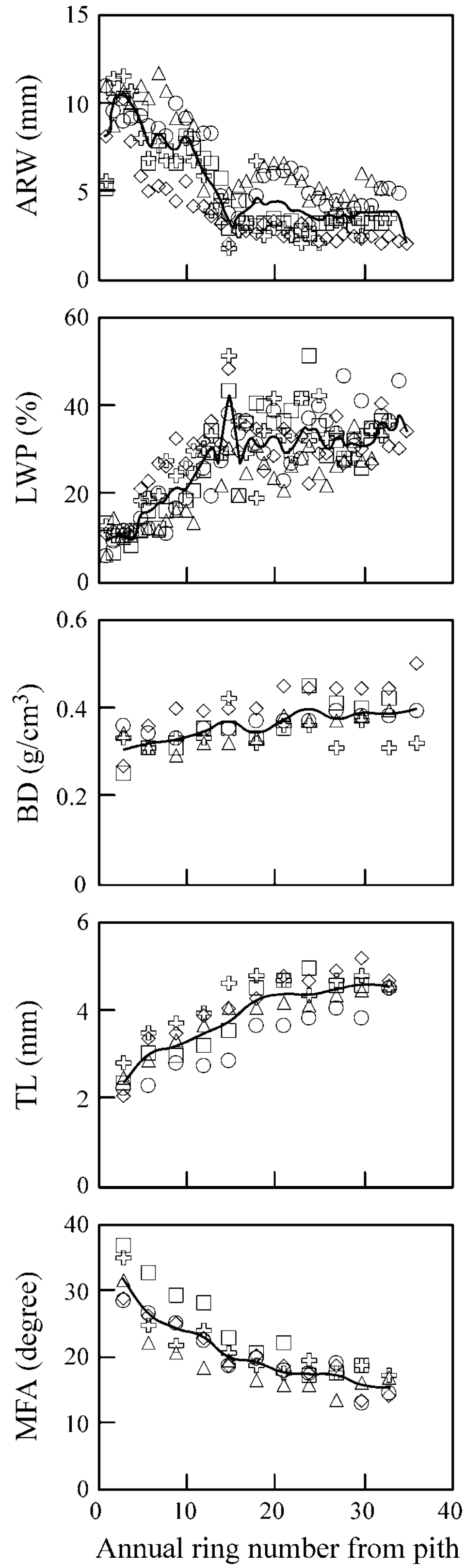

Figure 1.—Radial variations in the wood properties in the five sample trees. ARW = annual ring width; LWP = latewood percentage; BD = basic density extracted with organic solvent; TL = latewood tracheid length; MFA = microfibril angle of S_2 layer in latewood tracheid. Circles, triangles, squares, diamonds, and crosses indicate sample Trees 1 to 5, respectively. Solid lines indicate mean value of five sample trees.

Table 1.—Values of the wood properties in the five sample trees.[a]

Tree no.	Mean (SD)				
	ARW (mm)	LWP (%)	BD (g/cm^3)	TL (mm)	MFA (degrees)
1	6.4 (2.2)	27.4 (11.2)	0.37 (0.02)	3.29 (0.76)	20.2 (4.9)
2	6.9 (2.5)	21.8 (8.0)	0.34 (0.04)	3.80 (0.67)	18.6 (4.9)
3	5.2 (2.5)	27.3 (11.8)	0.36 (0.06)	3.81 (0.92)	24.4 (6.8)
4	3.9 (2.2)	28.7 (8.2)	0.41 (0.06)	4.10 (0.65)	20.3 (4.9)
5	4.9 (2.8)	28.7 (9.6)	0.34 (0.03)	4.19 (0.74)	21.2 (5.2)
Mean/total	5.4 (1.2)	26.8 (2.9)	0.36 (0.03)	3.84 (0.74)	20.9 (5.1)

[a] ARW = annual ring width; LWP = percentage of latewood; BD = basic density extracted with organic solvent; TL = latewood tracheid length; MFA = microfibril angle of S_2 layer in latewood tracheid.

radial variations in the LWP in *P. taeda* and reported that the LWP increased up to the 18th annual ring, recording over 50 percent at the 18th annual ring from the pith. Although our results showed a similar radial pattern of the LWP to that of Clark and Saucier (1989), the mean value of the LWP was smaller than that reported by them.

The mean value and standard deviation of the BD were 0.36 and 0.03 g/cm^3 (Table 1). The mean value was smaller than the BD measured by the US Department of Agriculture (USDA 1987) in *P. taeda* (0.48 g/cm^3). The mean value of BD in four of the five trees (except Tree 5) gradually increased from the pith to the bark (Fig. 1). Bendtsen and Senft (1986) reported that the wood density in *P. taeda* increased up to the 13th annual ring from the pith and then showed an almost constant value. Our results were similar to those obtained by several researchers (Kollmann and Côté 1984, Bendtsen and Senft 1986).

The mean value of the TL gradually increased up to the 18th annual ring from the pith, and then it showed an almost constant value (Fig. 1). In contrast, the MFA decreased up to the 18th annual ring from the pith and then showed an almost constant value (Fig. 1). The radial variations of the TL and MFA were similar to those obtained in other coniferous species (Zobel and van Buijtenen 1989). Furthermore, the mean values and standard deviations for the TL and MFA were 3.84 and 0.74 mm and 20.9 and 5.1 degrees, respectively (Table 1).

Comparison of wood properties between juvenile and mature wood

The boundary between the juvenile and mature wood was determined according to the method described by Shiokura (1982), in which a logarithmical formula was obtained as a function of the annual ring number from the pith. The ring number in which the increased ratio of the TL becomes less than 1 percent was regarded as the boundary between juvenile and mature wood (Shiokura 1982). Based on these results, the boundary between juvenile and mature wood in five sample trees existed from the 14th to the 19th annual ring from the pith (Fig. 2).

There are some previous reports dealing with the boundary between juvenile and mature wood in *P. taeda*. For example, Bendtsen and Senft (1986) reported that the xylem after the 13th ring from the pith was determined to be mature wood by using the radial variations in the MOE, MOR, compressive strength, and ovendry density. In addition, Clark et al. (2006) determined the boundary between the juvenile and mature wood of *P. taeda* using two different methods—the threshold method and the segmented modeling approach—using the wood density determined via X-ray densitometry and the LWP as indicators. They reported that the boundaries between juvenile and mature wood were 7.3 and 9.3 years when using the wood density determined via X-ray densitometry as an indicator and 10.5 and 8.1 years when using the LWP as an indicator, respectively. The boundary between the juvenile and mature wood obtained in the present study was similar to those reported previously (Bendtsen and Senft 1986, Clark et al. 2006).

When the boundary between juvenile wood and mature wood was regarded as the 14th annual ring from pith, significant differences at the 1 percent level were recognized in all of the wood properties investigated in the present study between juvenile and mature wood (Table 2). The LWP in the juvenile wood was almost half of that in the mature wood, while the MFA in the juvenile wood was 1.5 times higher than that in the mature wood. In general, the juvenile wood showed a lower density, shorter TL, larger MFA, and inferior mechanical properties (Zobel and van Buijtenen 1989). These trends were also true for the *P. taeda* examined in the present study.

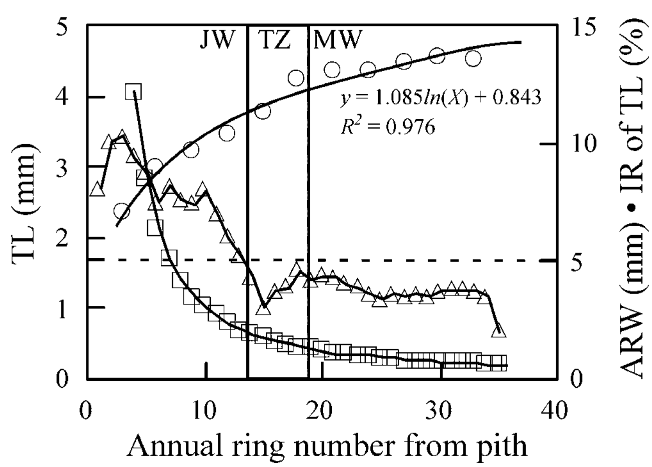

Figure 2.—Radial variations in mean values of five sample trees in latewood tracheid length (TL), annual ring width (ARW), and increase ratio (IR) of TL. Circles, triangles, and squares indicate TL, ARW, and IR of TL, respectively. IR of TL was determined according to the method described by Shiokura (1982). Gray color area is transition zone (TZ) from juvenile wood (JW) to mature wood (MW) determined by IR of TL. Dotted line indicates threshold value of annual ring width to classify the JW and MW in lumber.

Table 2.—Comparison of the wood properties between the juvenile wood and mature wood.[a]

Property	Mean (SD)		Significance
	Juvenile wood	Mature wood	
ARW (mm)	7.9 (1.2)	3.8 (1.2)	**
LWP (%)	18.1 (3.7)	32.4 (3.4)	**
BD (g/cm^3)	0.33 (0.02)	0.38 (0.03)	**
TL (mm)	3.02 (0.36)	4.33 (0.36)	**
MFA (degree)	26.4 (3.1)	17.7 (1.4)	**

[a] The boundary between juvenile and mature wood is the 14th annual ring from the pith. ARW = annual ring width; LWP = percentage of latewood; BD = basic density extracted with organic solvent; TL = latewood tracheid length; MFA = microfibril angle of S_2 layer in latewood tracheid; ** = significant difference at the 1 percent level.

Bending properties of lumber

Table 3 shows the bending properties of the lumber in this study. The mean values of the MOE and MOR among the five trees were 5.09 GPa and 43.5 MPa, respectively. Biblis et al. (1995) reported that the MOE and MOR of 2 by 4 lumber from 35-year-old *P. taeda* trees were 10 to 13 GPa and 30 to 60 MPa, respectively. In addition, in 40-year-old *P. taeda*, the MOE and MOR of 2 by 4 lumber were 13 GPa and 40 MPa, respectively (McAlister et al. 1997). The value of the MOE obtained here was smaller than those reported by other researchers; however, the MOR in our study showed similar values to those of other reports (Biblis et al. 1995, McAlister et al. 1997). In general, it has been shown that the BD correlates with the mechanical properties (Pearson and Gilmore 1980, Green and Kretschmann 1997). In the present study, the BD and MOE showed relatively lower values compared with those reported by the USDA (1987) in *P. taeda*, suggesting that a lower density in the sample trees used here resulted in a lower MOE value in the lumber.

Effects of juvenile wood on strength properties of lumber

In the present study, the boundary between juvenile and mature wood was the 14th to 19th annual ring from the pith. The mean values of the ARW in the 13th ring and after the 14th annual ring from the pith were 5.2 and about 4.0 mm, respectively; thus, the lumber was classified into juvenile and mature wood by using an ARW of 5.0 mm as the threshold value (Fig. 2). The results of this study show significant differences between the juvenile and mature woods in the bending properties of the lumber (Table 3): the mature wood showed higher values in its bending properties than those in the juvenile wood. Our results were similar to those reported for *P. taeda* by several previous researchers (Pearson and Gilmore 1980, Kretschmann and Bendtsen 1992).

Table 4 shows the correlation coefficients between the wood properties and the bending properties of the lumber. In all of the lumber ($n = 82$), there were significant correlations (1% level) between the ARW or AD and the bending properties of the lumber (Table 4). However, significant correlations between the ARW and bending properties were found in the juvenile wood, not in the mature wood. In contrast, significant correlations between the AD and DMOE or MOE were recognized in the mature wood but not in the juvenile wood. However, there were significant correlations between the AD and MOR in both the juvenile and the mature wood. In general, the MFA was strongly related to the MOE: the higher the MFA, the lower the MOE (Hirakawa and Fujisawa 1995, Lachenbruch et al. 2010). In the present study, the MFA in the juvenile wood was greater than that in the mature wood (Table 2). One could consider, therefore, that the ARW was not directly related to the bending properties of the lumber but that the MOE may correlate with the MFA. Hirakawa and Fujisawa (1995) reported that the MFA in the juvenile wood of the Japanese cedar varied greatly compared with that of the mature wood. They also reported that, because of the large variation in the MFA, no significant correlation between the density and MOE was found in the juvenile wood. In the mature wood, on the other hand, the MFA did not vary as much compared with the juvenile wood (Table 2). Thus, the smaller variation in the MFA, with a smaller deviation, might lead to a significant correlation between the AD and MOE in the mature wood. Based on these results, it can be concluded that, in *P. taeda*, the MFA and AD can predict the bending properties of lumber produced from juvenile wood and mature wood, respectively.

Conclusions

In the present study, the wood properties and bending properties of lumber were examined in five 40-year-old *P. taeda* trees planted in Tochigi, Japan. The results obtained are as follows.

1. All of the wood properties showed similar radial patterns compared with previous reports on *P. taeda*. The ARW, LWP, and BD showed different radial patterns among the five sample trees.
2. The boundary between juvenile and mature wood in five sample trees grown in Tochigi, Japan, existed from the 14th to the 19th annual ring from the pith via the radial

Table 3.—Values of the bending properties of the lumber.[a]

Position	Mean (SD)				
	ARW (mm)	AD (g/cm^3)	DMOE (GPa)	MOE (GPa)	MOR (MPa)
Total (n = 82)	6.8 (2.4)	0.47 (0.04)	6.64 (2.28)	5.09 (1.66)	43.5 (10.3)
JW (n = 60)	7.7 (2.0)	0.47 (0.03)	5.91 (1.90)	4.56 (1.42)	40.7 (8.9)
MW (n = 22)	4.1 (0.6)	0.49 (0.05)	8.58 (2.08)	6.53 (1.42)	51.3 (9.8)
Sig. between JW and MW	*	**	*	*	*

[a] The boundary between juvenile and mature wood is determined by the threshold value of the annual ring width (5.0 mm). ARW = annual ring width; AD = air-dry density; DMOE = dynamic modulus of elasticity; MOE = modulus of elasticity; MOR = modulus of rupture; JW = juvenile wood; MW = mature wood; Sig. = significance; * = significant difference at the 5 percent level; ** = significant difference at the 1 percent level.

Table 4.—Correlation coefficients (r) between the wood properties (Factor 1) and bending properties (Factor 2) of the lumber.[a]

Factor 1	Factor 2	Total ($n = 82$)		JW ($n = 60$)		MW ($n = 22$)	
		r	Sig.	*r*	Sig.	*r*	Sig.
ARW	DMOE	−0.586	**	−0.413	**	−0.295	NS
	MOE	−0.583	**	−0.395	**	−0.291	NS
	MOR	−0.492	**	−0.286	*	−0.385	NS
AD	DMOE	0.414	**	0.141	NS	0.662	**
	MOE	0.394	**	0.140	NS	0.649	**
	MOR	0.544	**	0.304	*	0.832	**

[a] The boundary between juvenile and mature wood is the 14th annual ring from the pith. n = number of boards; Sig. = significance; ARW = annual ring width; AD = air-dried density; DMOE = dynamic modulus of elasticity; MOE = modulus of elasticity; MOR = modulus of rupture; JW = juvenile wood; MW = mature wood; * = significant at 5 percent level; ** = significant at 1 percent level; NS = not significant.

variations of the TL, which was similar to those reported by several researchers.

3. The mature wood had significantly good wood and mechanical properties compared with the juvenile wood. The LWP of the mature wood showed almost twice the value of that of the juvenile wood.
4. The effects of the wood properties on the bending properties of the lumber differed between the juvenile and mature wood. The MFA and AD affected the bending properties of the lumber in the juvenile and mature wood, respectively.

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