EFFECTS OF RADIAL GROWTH RATE ON WOOD AND LUMBER PROPERTIES OF 67-YEAR-OLD JAPANESE LARCH (*LARIX KAEMPFERI*) TREES PLANTED IN TOCHIGI, JAPAN

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Abstract. The wood and lumber properties were examined for 67-yr-old Japanese larch (*Larix kaempferi*) trees with different radial growth rates planted in Tochigi Prefecture, Japan. The trees were categorized into slow-, medium-, and fast-growing groups based on the stem diameter. No significant difference in stress-wave velocity of stems, which is closely related with Young's modulus of wood, was found among three radial growth categories (stem diameter classes). The boundary between juvenile wood (JW) and mature wood (MW) determined by latewood tracheid length (TL) existed about the 20th annual ring from the pith in all sample trees. Significant differences between JW and MW were found in most of examined wood and lumber properties. It was found that trees with fast growth do not always cause lower grade lumber properties.

Keywords: Juvenile wood, mature wood, radial growth rate, stress-wave velocity, bending property.

INTRODUCTION

The wood of larch (*Larix* spp.) species has been used for many purposes, especially for structural lumber in construction, because of its high mechanical strength properties and decay resistance (Gierlinger et al 2004; Venäläinen et al 2006; Cáceres et al 2018; Ishiguri et al 2008; Luostarinen 2011). Japanese larch (*Larix kaempferi*) is one of the major plantation tree species in Japan (Kurinobu 2005), and the wood is also used as construction lumber.

Numerous investigations have been conducted to assess juvenile wood (JW) in plantation softwood species (Zobel and van Buijtenen 1989; Kretschmann and Bendtsen 1992; Alteyrac et al 2006). Issues associated with using JW for structural lumber are derived from inferior mechanical properties and dimensional stability, lower density, shorter tracheid length (TL), and larger microfibril angle (MFA) compared with mature wood (MW) (Shiokura and Watanabe 1971; Senft et al 1985; Shivnaraine and Smith 1990; Zhou and Smith 1991; Zhu et al 2000; Nawrot et al 2014; Tanabe et al 2016). Shivnaraine and Smith (1990) pointed out that the bending properties of two by four lumber were affected by the percentage of JW within a lumber for a 50- to 60-yr-old white spruce (*Picea glauca*) tree grown in eastern Canada. Matsumura et al (2012) also examined the influence of the lumber positions (center, inner, and outer) in Japanese cedar (*Cryptomeria japonica*) logs. They found the lowest values of dynamic Young's modulus (DMOE) of the lumber in both center and inner positions. Thus, it is considered that JW largely affects lumber quality.

The effects of radial growth have been reported on wood and lumber properties in many softwood species (Donaldson 1992; Takata et al 1992; Koga et al 1996; Zhu et al 1998; Koizumi et al 2003, 2005; Yin et al 2011; McLean et al 2016; Filipescu et al 2018; Tanabe et al 2018). Takata et al (1992) reported that in both core wood and outer wood in Japanese larch, the mean annual ring width (ARW) had the same negative correlation with basic density (BD). Zhu et al (1998) studied the relationship between growth and the wood properties of Japanese larch trees with various ages and radial growth. They also pointed out that in core wood, the ring density decreased with increase in ring width for all sample trees, whereas in outer wood, this trend was not found.

Nondestructive vibration techniques are important tools for evaluating the strength properties of lumber (Ikeda and Arima 2000; Wang et al 2001; Ishiguri et al 2008). Ikeda and Arima (2000) pointed out that the MOE of lumber in Japanese cedar can be predicted by stress-wave velocity of standing trees. Thus, the stress-wave velocity of standing trees is one of the powerful tools for evaluating the MOE of lumber produced therefrom.

The objective of this study was to clarify the effects of radial growth rate on wood and lumber properties of 67-yr-old Japanese larch trees planted in Japan. In addition, effects of JW and MW on lumber properties were also discussed.

MATERIALS AND METHODS

Sample Trees

Sixty-seven-year-old Japanese larch (*L. kaempferi*) trees planted in Funyu Experimental Forest, Utsunomiya University, Japan (36°46′ N, 139°49′ E, ca. 290 m above sea level), were used in this study. Forty-two trees were selected from the stand.

Stem Diameter and Stress-Wave Velocity

Stem diameter at 1.3 m above ground was measured for the 42 trees in the stand. To evaluate the relationship between stress-wave velocity and growth rate of trees, stress-wave propagation time was determined by using a commercial handled stress-wave timer (Fakopp Microsecond Timer, Fakopp Enterprise, Agfalva, Hungary) according to a method described previously (Ishiguri et al 2008). These 42 trees were categorized into three groups according to mean (d) and standard deviation (SD) of stem diameter: slow-growth trees (small diameter class) $< d -$ one SD, $d -$ one SD $<$ medium-growth trees (middle diameter class) $< d +$ one SD, and fast-growth trees (large diameter class) $> d +$ one SD.

Wood Properties

Three trees were selected in three categories with small, medium, and large diameter classes. After harvesting the three trees, disks with 3 cm thickness were obtained at 1.3 m above ground for measuring wood properties. In addition, logs with 0.4 m in length were also collected from the 0.9- to 1.3-m position for measuring mechanical and physical properties. A total of 12 logs with 2 m length were obtained from the harvested trees at four different height positions of stem (four logs in each tree at the positions at 1.3-3.3, 3.3-5.3, 5.3-7.3, and 7.3-9.3 m) for evaluation of lumber quality.

To measure the ARW and latewood width, bark-to-bark strips (2 cm in thickness and 5 cm width) were also collected from the disk. The image data (1200 dpi) of the transverse section of the strips from the pith to the bark in one direction were captured by a personal computer with a scanner (GT-9300UF, EPSON, Nagano, Japan). The ARW was measured using the image analysis software (ImageJ, National Institute of Health, Bethesda, MD).

To determine BD, wedge-shaped specimens were obtained from the disks. Small blocks were cut at 1 cm intervals from the pith to the bark. BD was calculated by dividing oven-dry weight at 105°C by green volume determined by water displacement.

Bark-to-bark strips including the pith were obtained from the disks used for measuring latewood TL to determine the boundary between JW and MW. Small blocks of latewood were prepared from one side of each strip at every fifth annual ring. Then, the small blocks for measuring TL were macerated with Schulze's solution. A total of 30 tracheids in each radial position were measured using a microprojector (V-12B, Nikon, Tokyo, Japan) with a digital caliper (CD-30C, Mitutoyo, Kanagawa, Japan). The boundary was determined by the percentage of annual increment of TL calculated by using logarithmic formulas. The boundary between JW and MW was regarded as the point of one percent annual growth of the latewood TL (Shiokura 1982).

The small blocks were also used for measuring MFA in the S_2 layer of latewood tracheid. The MFA was measured by the iodine method (Senft and Bendtsen 1985). Radial sections in 20 μm thickness were obtained from the other small blocks collected from the strip using a sliding microtome (REM-710, Yamato Kohki Industrial Co., Saitama, Japan). These sections were soaked in Schulze's solution for 15 min and then rinsed with distilled water. After dehydration by graded ethanol, the sections were treated with drops of 2% iodine–potassium iodide solution and 60% nitric acid. The sections were mounted with cover slips. Photomicrographs were taken using a digital camera (E-330, Olympus, Tokyo, Japan), and MFA was determined for 30 latewood tracheids in each fifth annual ring by using ImageJ.

Bark-to-bark radial boards containing the pith with width 30 mm in thickness were obtained from the logs from 0.9 to 1.3 m above ground to

Table 1. Mean and SD of stem diameter and stress-wave velocity of the stem.

Property	Total/mean (n = 42)		Slow (n = 7)		Medium (n = 28)		Fast (n = 7)		Significance among radial growth category
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
D (cm)	23.2	4.4	17.1	0.9	22.9	2.3	30.4	1.8	a
SWV (km/s)	3.68	0.26	3.86	0.25	3.64	0.27	3.64	0.13	ns

D, stem diameter; SWV, stress-wave velocity of the stem; SD, standard deviation; n, number of trees; ns, no significance.
[a] Significance at 1% level.

prepare small specimens for bending and compressive tests. After air-drying, the boards were planed into 20 mm thickness. Then, boards were cut to 20 mm interval from the pith to the bark for the static bending test specimens (20 [R] × 20 [T] × 320 [L] mm) to analyze the radial variations of bending properties. A total of 29 specimens were collected from the boards. The static bending tests were conducted using a universal testing machine (MSC 5/500-2, Tokyo Testing Machine, Tokyo, Japan) with a 280-mm span. A load was applied to the center of the tangential surface of the specimen at 5 mm/min load rate. The load and deflection were recorded with a personal computer to calculate the MOE and MOR. After the bending test, the specimens for compressive strength (CS) parallel to grain (20 [R] × 20 [T] × 40 [L] mm) were prepared from each static bending specimen without any visual defects. The compressive tests were conducted by

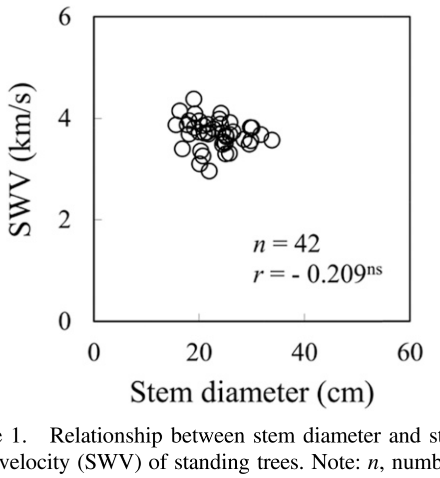

Figure 1. Relationship between stem diameter and stress-wave velocity (SWV) of standing trees. Note: n, number of trees; r, correlation coefficient; ns, no significance.

using a universal testing machine (RTF-2350, A&D, Tokyo, Japan) with a load rate of 0.5 mm/min. CS parallel to grain was calculated from maximum load (N) by dividing it by cross-sectional area (mm^2). In addition, moisture contents were measured for bending and compressive specimens. As a result, the mean MC of these specimens was 12.7%.

Lumber Properties

A total of 45 pieces of lumber measuring 100 × 50 mm in cross section were obtained from 12 logs from three trees with three different radial growth rates (diameter classes). The lumber was air-dried under conditions of 65% RH and 21°C until the mean MC of the lumber stabilized around 10%. After air-drying, the lumber was planed into 89 × 38 mm of the cross section. Bow, crook, twist, number and size of knots, wane, and slope grain were measured on the surface in each lumber according to the Japanese Agricultural Standard (JAS) for structural lumber for wood frame construction. Bow and crook were determined by measuring the maximum deflection of lumber. To determine twist, lumber was set on a flat surface of a steel beam. After fixing three edges of a lumber, the distance between remaining one edge and the flat surface was measured. In addition, the DMOE of the lumber was determined by the tapping method described in the previous article (Ishiguri et al 2008). After measuring the DMOE, the four-point static bending test was conducted using a material testing machine (IPA-100R, Maekawa Testing Machine, Tokyo, Japan). Load rate, support span, and distance between load points were 12 mm/min, 1602 mm, and 534 mm, respectively. The

MOE and MOR of the lumber were determined, respectively, by using Eqs 1 and 2:

$$\mathrm{MOE} = \frac{\Delta P(l - l')\left\{3l^2 - (l - l')^2\right\}}{8\Delta y b h^3}, \quad (1)$$

$$\mathrm{MOR} = \frac{3P_{\max}(l - l')}{2bh^2}, \quad (2)$$

where ΔP is the difference of load between 10% and 40% values of maximum load ($P_{\max}$), N; Δy is the difference of deflection corresponding to ΔP (mm); l is the span (mm); l' is the difference between load point (mm); b is the width of the specimen (mm); and h is the height of the specimen (mm).

After static bending testing, MC was determined by the oven-dry method. The ARW of the lumber was also measured. Mean and SD values of MC were 10.0 ± 0.4%. Based on the measurements, the lumber was visually graded according to JAS for structural lumber for wood frame construction.

Statistical Analysis

An analysis of variance was used to evaluate differences among growth categories for growth characteristics and wood properties. In addition, *t*-tests were also applied to evaluate the differences between JW and MW among trees and the lumber.

RESULTS AND DISCUSSION

Stem Diameter and Stress-Wave Velocity of Standing Trees

Table 1 shows the mean and SD values of stem diameter and stress-wave velocity of the stem. Mean values of stem diameter and stress-wave velocity of 42 trees were 23.2 cm and 3.68 km/s, respectively. The 42 trees were classified based on stem diameter to categorize them into three groups (slow, medium, and fast growth) (Table 1). Mean values of stem diameter and stress-wave velocity of these slow-, medium-, and fast-growth trees were 17.1 cm and 3.86 km/s, 22.9 cm and 3.64 km/s, and 30.4 cm and 3.64 km/s, respectively. The mean value of stress-wave velocity was slightly higher than that of 36-yr-old Japanese larch trees studied previously (Ishiguri et al 2008). No significant difference in stress-wave velocity of the stem was found among growth categories (Table 1). In addition, no significant correlation was also found between the stem diameter and stress-wave velocity of standing trees (Fig 1). Ikeda and Arima (2000) reported that a relatively high correlation was obtained between the stress-wave velocity of stems in 40- and 70-yr-old trees and MOE of square-sawn lumber produced from the trees of Japanese cedar. Ishiguri et al (2008) also found a significant correlation between the stress-wave velocity of trees and MOE of lumber in Japanese larch. The results obtained in the present study suggested that the radial growth rate does not always affect the Young's modulus of wood in Japanese larch trees.

Table 2. Mean and SD of wood properties in each sample tree.

Property	Slow (tree no. 1)			Medium (tree no. 2)			Fast (tree no. 3)			Significance among three growth categories
	n	Mean	SD	*n*	Mean	SD	*n*	Mean	SD	
Annual ring width (mm)	66	1.1	1.2	66	1.6	1.2	66	2.1	1.8	a
Tracheid length (mm)	13	4.06	0.61	13	4.24	0.61	13	4.56	0.65	ns
MFA (degree)	13	12.1	4.1	13	13.7	4.4	13	14.3	4.3	ns
Basic density (g/cm^3)	7	0.48	0.04	9	0.48	0.06	15	0.49	0.07	ns
MOE (GPa)	7	10.07	2.68	9	9.12	3.73	13	7.82	2.78	ns
MOR (MPa)	7	82.6	16.2	9	78.4	20.8	13	71.7	15.0	ns
CS (MPa)	7	38.5	5.3	9	34.8	9.0	13	32.8	6.5	ns

n, number of radial positions in a tree; SD, standard deviation; MFA, microfibril angle in the S_2 layer of latewood tracheid; CS, compressive strength parallel to grain; ns, no significance.
[a] Significance at 1% level.

Wood Properties

Three trees with different radial growth rates (stem diameter class) were harvested for examining wood properties. The stem diameter and tree height of the harvested trees were 17.2 cm and 21.7 m (slow-growth tree, small diameter class, tree no. 1), 22.7 cm and 22.7 m (medium-growth tree, middle diameter class, tree no. 2), and 33.8 cm and 24.1 m (fast-growth tree, large diameter class, tree no. 3), respectively.

Mean ARWs of trees with slow, medium, and fast radial growth were 1.1, 1.6, and 2.1 mm, respectively (Table 2). A significant difference among three growth categories was found only in the ARW. The ARW first increased for several years, showed peak values, and then decreased until around the 40th annual ring from the pith (Fig 2). After that two patterns were found in the variation. In the slow-growth tree (tree no. 1), the ARW showed an almost constant value toward the bark. On the other hand, in medium- (tree no. 2) and fast-growth trees (tree no. 3), the ARW slightly increased toward the bark (Fig 2). The mean values of the ARW of Japanese larch in the present study were lower than those of 31-yr-old Japanese larch trees planted in Hokkaido, Japan (Koizumi et al 2005), 35-yr-old Japanese larch grown in Sweden (Karlman et al 2005), and fast-growing 85-yr-old Siberian larch (*Larix sibirica*) trees grown in Finland (Luostarinen 2011).

As shown in Fig 2, latewood TL in all trees gradually increased up to about the 20th annual ring from the pith and then showed an almost constant value. The mean latewood TL of trees ranged from 4.06 to 4.56 mm (Table 2). The obtained values were longer than those (2.8-3.1 mm) in 40- to 80-yr-old Siberian larch trees naturally grown in south Siberia (Koizumi et al 2003) and those (3.5-4.0 mm) in 15- to 30-yr-old Japanese larch planted in eastern Hokkaido, Japan (Koga et al 1996).

The values for MFA of the S_2 layer in latewood tracheids were 12.1, 13.7, and 14.3° for slow- (tree no. 1), medium- (tree no. 2), and fast-growth (tree no. 3) trees, respectively (Table 2). The MFA decreased up to the 20th annual ring from the pith and then became an almost constant value (Fig 2). The mean values of MFA at the 20th annual ring from the pith in the present study (13.3-15.9°) were considerably smaller than those of Siberian larch trees as determined by X-ray diffractometry (22.0-29.4°) (Koizumi et al 2003).

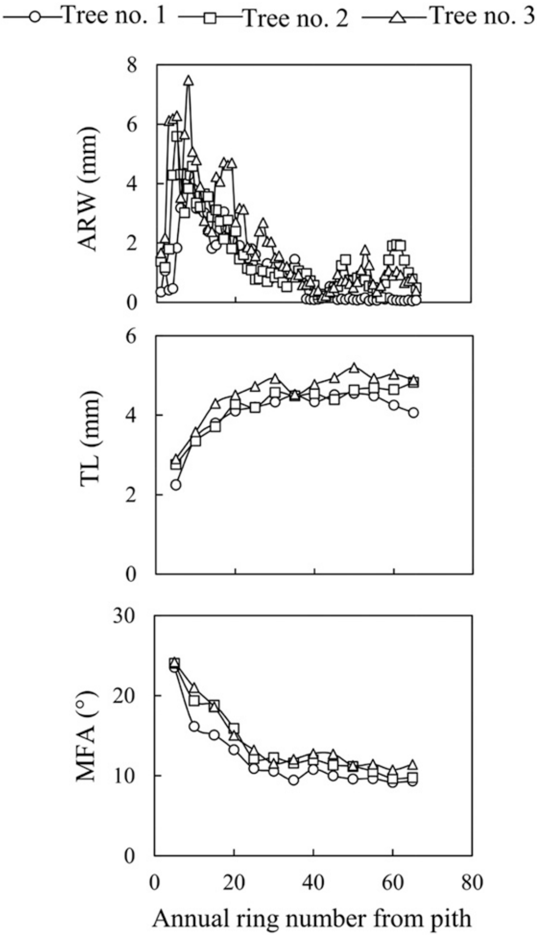

Figure 2. Radial variations of annual ring width (ARW), latewood tracheid length (TL), and microfibril angle (MFA) in the S_2 layer of latewood tracheid (MFA) in relation to the annual ring number from the pith.

Although three trees with different diameters were selected, mean values of BD were similar among three trees, being 0.48-0.49 g/cm^3 (Table 2). As shown in Fig 3, radial variations of BD were also similar among three trees: BD gradually decreased near the bark side. Similar

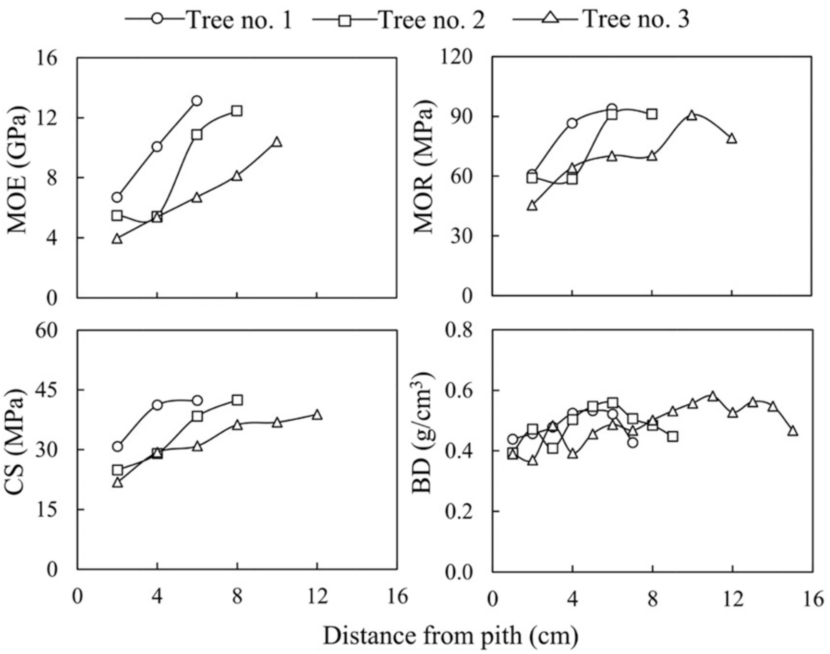

Figure 3. Radial variations of mechanical and physical properties in relation to distance from the pith. Note: CS, compressive strength parallel to grain; BD, basic density.

radial variations of wood density were also observed by other researchers in Japanese larch (Zhu et al 1998; Koizumi et al 2005) and Siberian larch (Koizumi et al 2003). However, mean values in the present study were relatively lower than those obtained by other researchers for Japanese larch and Siberian larch (Zhu et al 1998; Koizumi et al 2003, 2005).

The mean values of MOE, MOR, and CS in selected trees ranged from 7.82 to 10.07 GPa, 71.7 to 82.6 MPa, and 32.8 to 38.5MPa, respectively (Table 2). As shown in Fig 3, MOE, MOR, and CS showed lowest values near the pith and increased toward the bark. The highest mean values of MOE, MOR, and CS were found in the slow-growth tree (tree no. 1) (Table 2). Koizumi et al (2005) reported that the mean values of MOE, MOR, and CS for 31-yr-old Japanese larch trees planted in Hokkaido were 8.2 to 9.5 GPa, 93.3 to 97.2 MPa, and 54.0 to 55.1 MPa, respectively. The mean values of Japanese larch used in the present study were similar or relatively smaller than those obtained in Japanese larch planted in Japan (Koizumi et al 2005) and Siberian larch naturally grown in Russia and Mongolia (Koizumi et al 2003; Ishiguri et al 2018).

JW and MW

Zhu et al (2000) reported that JW of Japanese larch existed from 15th to 20th annual rings from the pith. The obtained results in the present study were almost same as those obtained in Japanese larch by other researchers (Shiokura 1982; Zhu et al 2000). In the present study, as shown in Table 3, the boundary was about the 20th annual ring from the pith in all sample trees.

Significant differences between JW and MW were recognized in all wood properties except for BD of slow- and medium-growth trees (tree no. 1 and tree no. 2), and CS in the slow-growth tree (tree no. 1) (Table 4). The JW had a greater MFA, a lower BD, and inferior mechanical properties. Similar trends were also reported by other researchers (Shiokura and Watanabe 1971; Zobel

Table 3. Boundary between JW and MW based on radial variation of latewood tracheid length.

Tree no.	Logarithmic formula	r^2	Boundary between JW and MW (annual ring number from the pith)
Slow (tree no. 1)	$y = 1.658\log10(X) + 1.655$	0.759	20
Medium (tree no. 2)	$y = 1.766\log10(X) + 1.672$	0.932	22
Fast (tree no. 3)	$y = 1.825\log10(X) + 1.905$	0.877	20

JW, juvenile wood; MW, mature wood; r^2, coefficient of determination.

and van Buijtenen 1989; Shivnaraine and Smith1990; Zhu et al 2000). It is, therefore, considered that classification of JW and MW is important for the production of higher quality wood from plantation-grown Japanese larch. On the other hand, in Yezo spruce (*Picea jezoensis*) and Sakhalin fir (*Abies sachalinensis*), Shiokura and Watanabe (1971) pointed out that the formation of JW in the trees, of which initial radial growth was extremely suppressed, was prolonged compared with the trees with normal initial growth. Similar results were also obtained in more than 200-yr-old Siberian larch trees naturally grown in Mongolia (Ishiguri et al 2018). In the present study, however, the boundaries were almost the same for three trees (Table 3). Although a tree (tree no. 1) was selected as the slow-growth group, the radial growth rate was not extremely suppressed. Thus, it is concluded that the boundary was not affected by the radial growth rate.

Lumber Quality

A total of 8, 11, and 26 pieces of lumber were obtained by sawing of logs obtained from slow-, medium-, and fast-growth trees, respectively. Mean values of MC of the lumber were 10.0, 9.9, and 10.1% for the lumber from slow-, medium-, and fast-growth trees, respectively.

Figure 4 shows the results of visual grading for the lumber tested in this study. Each lumber was assigned to a grade (select structural [SS], No. 1,

Table 4. Comparison of wood properties between JW and MW in each tree.

Tree no.	Position		ARW (mm)	TL (mm)	MFA (degree)	BD (g/cm^3)	MOE (GPa)	MOR (MPa)	CS (MPa)
Slow (tree no. 1)	JW	*n*	20	4	4	4	4	4	4
		Mean	2.4	3.39	17.0	0.47	8.38	73.6	36.0
		SD	1.2	0.81	4.5	0.04	1.97	16.4	6.1
	MW	*n*	46	9	9	3	2	2	2
		Mean	0.5	4.36	10.0	0.49	13.14	93.8	42.3
		SD	0.6	0.17	0.7	0.06	0.84	2.8	0.5
	Significance		b	a	a	ns	b	a	ns
Medium (tree no. 2)	JW	*n*	22	4	4	6	6	6	6
		Mean	2.9	3.52	19.5	0.48	7.26	69.6	30.7
		SD	1.2	0.64	3.4	0.07	3.12	18.8	8.4
	MW	*n*	44	9	9	3	2	2	2
		Mean	0.9	4.55	11.2	0.48	12.46	91.2	42.4
		SD	0.4	0.18	1.0	0.03	0.41	12.8	1.6
	Significance		b	a	b	ns	b	b	b
Fast (tree no. 3)	JW	*n*	20	4	4	9	8	8	8
		Mean	4.3	3.82	19.7	0.45	6.06	62.6	29.6
		SD	1.4	0.74	3.9	0.06	1.96	11.0	5.9
	MW	*n*	46	9	9	6	4	4	4
		Mean	1.1	4. 88	11.9	0.54	10.59	84.9	37.9
		SD	0.7	0.19	0.8	0.04	0.54	6.8	3.3
	Significance		b	a	a	b	b	b	b

JW, juvenile wood; MW, mature wood; *n*, number of radial position in a tree; SD, standard deviation; ARW, annual ring width; BD, basic density; TL, latewood tracheid length; MFA, microfibril angle in the S_2 layer of latewood tracheid; CS, compressive strength parallel to grain; ns, no significance.
[a] Significance at 5% level.
[b] Significance at 1% level.

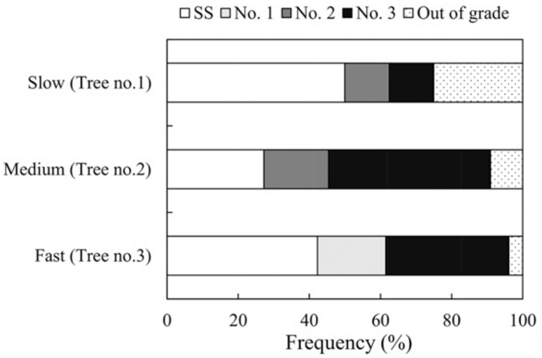

Figure 4. Percentage of each grading class for lumber. Note: The lumber was graded into five classes (select structural [SS], No. 1, No. 2, No. 3, and out of grade) by Japanese Agriculture Standard for structural lumber for wood frame construction.

No. 2 or No. 3, and out of grade) by visual grading according to JAS for structural lumber for wood frame construction. Lumber assigned in the SS and No.1 grades were 50, 27, and 62% for slow- (tree no. 1), medium- (tree no. 2), and fast-growth (tree no. 3) trees, respectively (Fig 4). In addition, 25, 9, and 4% of the lumber were out of grade for slow- (tree no. 1), medium- (tree no. 2), and fast-growth trees (tree no. 3), respectively.

As shown in Table 5, the total number of the lumber in SS, No. 1, No. 2, No. 3, and out of grade (45 pieces of lumber from three trees) was 18, 5, 3, 15, and 4 pieces of lumber, respectively. The main downgrading factors were wane and knot. Although the MOE and MOR in the out of grade lumber showed lower values than those in other grades, no significant differences in MOE and MOR were found among grades. On the other hand, the JW percentage was higher in the lumber graded for No 3 and out of grade.

Table 6 shows mean and SD of lumber quality in each tree. The mean ARW of lumber was 2.4, 2.0, and 2.8 mm, respectively. Significant differences in air-dry density were found among three trees. For crook, bow, and twist, mean values ranged from 0.4 to 1.2 mm, 1.3 to 2.3 mm, and 1.4 to 3.0 mm, respectively. The smallest mean values were found in the fast-growth tree (tree no. 3). Significant differences were found in crook and twist among trees. Mean DMOE, MOE and MOR of the lumber ranged from 14.17 to 15.00 GPa, 14.53 to 15.12 GPa, and from 63.2 to 85.6 MPa, respectively. The mean values of DMOE, MOE, and MOR of Japanese larch in this study were higher than those of the lumber produced from 36-yr-old Japanese larch trees (Ishiguri et al 2008).

No significant differences among the three trees were found in MOE and MOR (Table 6). This result corresponded to that of stress-wave velocity of the stem presented in Table 1. These results indicated that the visual grades for the lumber did not seem to be affected by the radial growth rate.

In the present study, the lumber were classified into JW and MW on the basis of boundary presented in Table 3. As the results, all the lumber from the slow-growth tree (tree no. 1) were JW,

Table 5. Mean values of bending properties of lumber in each grade.

Grade	*n*	Factors to downgrade	JW (%)	MOE (GPa)	MOR (MPa)
SS	18	—	33.3	15.77	84.4
No. 1	5	Knot (100%)	40.0	14.17	87.1
No. 2	3	Wane (100%)	33.3	16.33	93.7
No. 3	15	Knot (26.6%)	46.7	14.31	74.9
		Knot and wane (26.6%)			
		Wane (33.3%)			
		Wane and crack (13.3%)			
Out of grade	4	Wane (75%)	100.0	12.88	57.0
		Wane and crack (25%)			
Total/mean	45	—	44.4	14.89	79.4
P-values	—	—		0.069	0.216

n, number of lumber in each grade; JW, juvenile wood; SS, select structural. Values in parentheses in factors to downgrade indicate the occurrence frequency against the number of lumber in each grade. *P*-values were obtained by the analysis variance of test.

Table 6. Mean and SD of wood and bending properties of lumber in each tree.

	Slow (tree no. 1) (n = 8)				Medium (tree no. 2) (n = 11)				Fast (tree no. 3) (n = 26)				
Property	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Significance among trees
ARW (mm)	2.4	0.4	1.8	2.9	2.0	0.9	1.1	3.8	2.8	1.3	1.3	5.2	ns
MC (%)	10.0	0.3	9.7	10.4	9.9	0.5	9.2	10.6	10.1	0.3	9.2	10.6	ns
AD (g/cm^3)	0.55	0.02	0.53	0.58	0.58	0.03	0.52	0.62	0.59	0.04	0.50	0.65	[a]
Crook (mm)	1.2	0.8	0.0	2.1	0.5	0.7	0.0	2.0	0.4	0.7	0.0	2.5	[a]
Bow (mm)	2.3	1.8	0.0	4.5	1.6	1.3	0.0	3.5	1.3	1.3	0.0	4.1	ns
Twist (mm)	2.0	2.4	0.0	5.5	3.0	1.8	0.0	5.5	1.4	1.2	0.0	4.0	[a]
DMOE (GPa)	14.17	0.98	12.87	15.68	15.00	2.28	10.50	18.20	14.97	2.44	9.56	18.07	ns
MOE (GPa)	14.53	1.11	12.83	16.18	15.12	2.70	11.19	19.15	14.90	2.42	9.95	18.42	ns
MOR (MPa)	63.2	17.8	43.3	83.4	77.9	23.2	41.6	106.0	85.6	26.0	41.5	133.3	ns

n, number of lumber; SD, standard deviation; Min., minimum; Max., maximum; ARW, annual ring width; MC, MC determined by oven-dry method; AD, air-dry density; DMOE, dynamic Young's modulus; ns, no significance.
[a] Significance at 5% level.

whereas those from medium- (tree no. 2) and fast-growth trees (tree no. 3) were classified into both wood types (Table 7). Thus, differences of lumber properties between JWand MW were compared for medium- (tree no. 2) and fast-growth rate trees (tree no. 3). Significant differences between JW and MW were found in most of measured properties except for bow, MOE, and MOR in the medium-growth tree (tree no. 2), and crook in the fast-growth tree (tree no. 3). By contrast, significant differences between trees were found for crook and twist in JW and for air-dry density, bow, and twist in MW (Table 7). Generally, bending properties of lumber are lower in JW than those in MW (McLean et al 2016; Tanabe et al 2016; Filipescu et al 2018). For example, Tanabe et al (2016) reported that in loblolly pine (*Pinus taeda*), MW had significantly good wood and mechanical properties compared with JW. Based on the results, it is considered that when the lumber is produced from Japanese larch trees, the proportion of JW in a tree is an essential problem for lumber properties rather than the radial growth rate.

CONCLUSIONS

Effects of the radial growth rate were investigated on wood and lumber properties of Japanese larch (*L. kaempferi*) trees. No significant differences in stress-wave velocity of stems were found among radial growth categories. The boundaries between JW and MW were almost the same for the all sample trees with different radial growth. Significant differences between JW and MW were

Table 7. Effects of JW on lumber properties in tree nos. 2 and 3.

	Medium (tree no. 2)					Fast (tree no. 3)						
	JW (n = 3)		MW (n = 8)			JW (n = 9)		MW (n = 17)				
Property	Mean	SD	Mean	SD	Sig. (1)	Mean	SD	Mean	SD	Sig. (1)	Sig. (2) in JW	Sig. (2) in MW
ARW (mm)	3.1	0.9	1.6	0.6	[a]	4.4	0.5	1.9	0.4	[b]	ns	ns
MC (%)	10.0	0.5	9.9	0.5	ns	10.1	0.4	10.0	0.3	ns	ns	ns
AD (g/cm^3)	0.54	0.01	0.60	0.02	[b]	0.54	0.02	0.62	0.02	[b]	ns	[b]
Crook (mm)	0.0	0.0	1.0	0.7	[a]	0.7	0.9	0.9	1.5	ns	[a]	ns
Bow (mm)	1.0	1.7	1.9	1.1	ns	1.9	0.8	0.9	1.5	[a]	ns	[a]
Twist (mm)	4.5	1.0	2.4	0.9	[a]	2.4	0.8	0.9	1.1	[b]	[a]	[a]
DMOE (GPa)	12.04	1.34	16.11	1.6	[b]	11.99	1.07	16.55	1.05	[b]	ns	ns
MOE (GPa)	12.63	1.20	16.06	2.52	ns	12.16	1.29	16.35	1.36	[b]	ns	ns
MOR (MPa)	64.8	21.1	82.8	23.3	ns	66.7	20.8	95.5	23.1	[b]	ns	ns

n, number of lumber; SD, standard deviation; JW, juvenile wood; MW, mature wood; Sig. (1); significance between JW and MW in a tree; Sig. (2), significance between trees; ARW, annual ring width; MC, MC determined by the oven-dry method; AD, air-dry density; DMOE, dynamic Young's modulus; ns, no significance.
[a] Significance at 5% level.
[b] Significance at 1% level.

found in most of examined wood properties and mechanical properties of lumber, suggesting that identification of JW and MW is important for wood utilization of this species, especially for structural lumber production. Higher grade and good lumber properties were obtained from the tree with fast growth. It is concluded that the boundary between JW and MW is not affected by the radial growth rate. In addition, the results also indicated that the fast growth rate does not negatively affect wood properties.

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