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Effects of Growth Ring Parameters on Mechanical Properties of Japanese larch (*Larix kaempferi*) from Various Provenances

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Abstract

Growth ring parameters obtained by X-ray densitometry, modulus of elasticity, bending strength, compressive strength, and shear strength of 138 Japanese larch trees belonging to 23 provenances were studied to examine the effects of growth ring parameters on mechanical properties. The considered growth ring parameters were ring width, average wood density within a ring, earlywood density, latewood density, and latewood percentage. The strength properties of the small clear specimens, particularly in the outerwood, were strongly affected by wood density. Among the growth ring parameters studied, earlywood density had a major effect on average wood density in the corewood, whereas the effect of latewood percentage on average wood density was greatest in the outerwood. Compared with the other growth ring parameters, average wood density was more stable from the juvenile to mature stage, and is considered to be a reliable index of wood quality in early selection.

Key words: cambial age, juvenile wood, *Larix kaempferi*, mechanical properties, X-ray densitometry

Introduction

Japanese larch (Larix kaempferi) is planted over large areas in northern Japan, particularly in the Hokkaido and Nagano prefectures, because it has a high growth rate at the young stage. Although the juvenile wood of Japanese larch has a large spiral grain angle, which causes twists in the lumber during the drying process, and is rather weak with regard to its strength properties, mature wood has excellent mechanical properties and is used as a structural material, for example, glued laminated timber (Shigematsu 1990, Hashizume 1998).

The mechanical properties are controlled by anatomical characteristics such as wood density, grain angle, tracheid length, and microfibril angle of the S_2 layer in the cell wall. Of these characteristics, wood density is considered to have major effects on the mechanical properties of larch wood (Tokumoto *et al.* 1997). Chiba *et al.* (1980) reported that latewood percentage, which was measured by visual inspection with a magnifier, contributed a great deal to wood density. Using samples collected from a provenance trial, Nakagawa (1963) also reported a high correlation between latewood percentage and wood density. Although within-growth-ring characteristics obtained by X-ray densitometry have been studied recently (Zhu *et al.* 1998), the sample size was too small to generalize the density variation in Japanese larch. The objective of this study is to ascertain the growth ring parameters that majorly contribute to the mechanical properties of Japanese larch and hence, can be used for early selection in tree breeding.

Materials and Methods

Test specimens were sampled from 138 trees from 23 provenances (6 trees per provenance); these trees were felled at a provenance trial stand in Esashi, Hokkaido. The provenance trial was a part of the international research project initiated by Langner (1961) and the tentative results of the project were summarized by Toda and Mikami (1976). The provenances were selected from natural forests in Honshu in order to encompass the wide range of genetic diversity of Japanese larch. The experimental design of the Esashi stand was a triple lattice design with three replications (Hokkaido Forest Tree Breeding Association 1972). The stand age at the time of felling was 31 years. Before and after the felling, tree bending tests were used to study modulus of elasticity (MOE) of tree trunks (Koizumi *et al.* 1992) and the MOE of logs that were cut from the sample trees (Takata *et al.* 1992) was studied, respectively.

The sample trees were felled and cross cut at approximately 90 and 120 cm above ground level to obtain 30-cm-long logs. Each log was then quarter sawn to obtain approximately 30-mm-thick unedged plank including pith. Bark-to-bark radial strips of 5-mm thickness were cut from the air-dried planks for X-ray densitometry (Fig. 1). Finally, the small clear specimens, 20 × 20 mm^2 in cross section and 300 mm in length, were cut consecutively from both the outer sides of the air-dried planks. The specimens were divided into two groups, outerwood and corewood. Outerwood and corewood consisted of the section located on the outside and the inside of the 15th ring from the pith and were considered as mature wood and juvenile wood, respectively (Koga *et al.* 1995). There were 294 and 180 specimens of outerwood and corewood, respectively. In keeping with Japan Industrial Standards (JIS-Z2101), the MOE, bending

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strength (MOR), wood density (WD), compressive strength parallel to the grain (CS), and shear strength (SS) of the 474 specimens were tested. The average moisture content of the specimens at the time of the tests was 13.1%.

Bark-to bark radial strips were X-rayed on films using 280 seconds of irradiation time after conditioning at 20°C and 65% RH. The current intensity and voltage were 14 mA and 17 kV, respectively. The developed films were scanned using a densitometer (3CS, Joice Loeble) to measure the density distribution across the growth rings. The slit size for scanning was 50 and 500 micron meter in the radial and tangential direction, respectively. The following growth ring parameters were assessed: annual ring width (RW), earlywood density (EWD), latewood density (LWD), ring density (RD: average wood density within a ring), and latewood percentage (LWP) (Fig. 2). A threshold density of 550 kg/m^3 was used to differentiate earlywood density from latewood density. These parameters were determined for each ring in two pith-to-bark directions and were averaged for each tree. The border between sapwood and heartwood was determined by visual inspection, based on a difference in color.

Results and Discussions

Mechanical properties

The mean and standard deviation of the mechanical properties of the small clear specimens for each

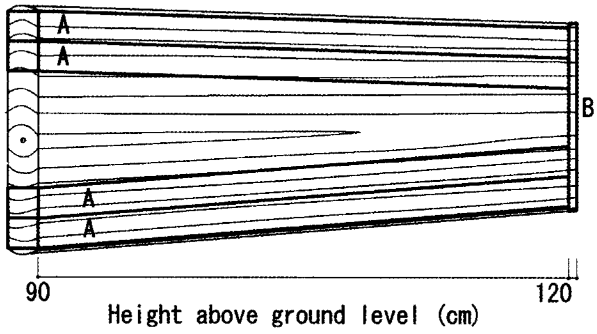

Fig. 1. Cutting diagram for specimens
A: Small clear specimens for mechanical tests, B: Radial strip for X-ray densitometry (bark to bark, 5 mm thick).

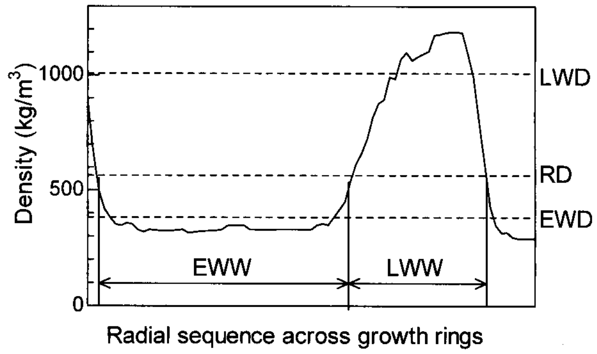

Fig. 2. Definition of growth ring parameters obtained by X-ray densitometry
LWD: Latewood density, RD: Average wood density within a ring, EWD: Earlywood density, RW: Ring width (EWW+LWW), LWP: Latewood percentage (LWW/RW × 100) Threshold density (boundary between earlywood and latewood): 550kg/m^3.

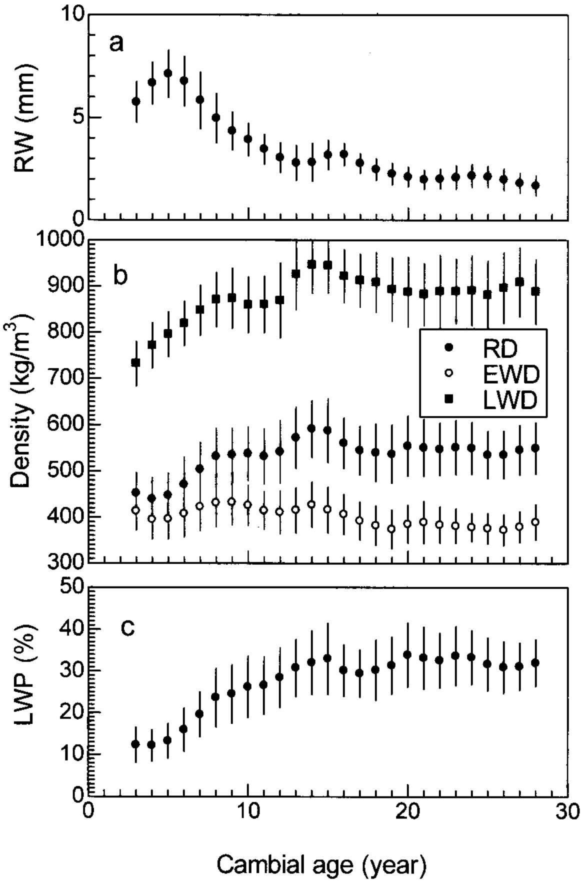

Fig. 3. Growth ring parameter trends associated with cambial age Vertical bars denote standard deviation. RW, RD, EWD, LWD, LWP are defined in Fig. 2.

provenance is listed in Table 1. Using one-way analysis of variance (ANOVA), significant differences among the provenances were found for WD, CS, and SS of the outerwood region (Table 2). The differences among the provenances with regard to the MOE and MOR were rather small, similar to that reported for the MOE of the sample logs (Takata *et al.* 1992).

The strength properties were strongly affected by WD, particularly in the outerwood section, as shown in Table 3. Large variations in the microfibril angle of the juvenile wood (Suzuki 1968) would have disturbed the correlation between WD and strength properties in the corewood section.

Growth ring parameters

The relationship between cambial age (ring number from pith) and RW showed a typical pattern for Japanese larch grown in even-aged plantations; the widest width was reached by the rings located within a few rings from the pith and then width rapidly decreased in the corewood section (Fig. 3a) (Koizumi *et al.* 1987). The average LWD increased from approximately 750 kg/m^3 in the innermost rings to approximately 900 kg/m^3 in the outerwood section (Fig. 3b). Within the corewood sections, LWP increased as RW decreased (Fig. 3c). On the other hand, EWD showed a stable value at approximately 400 kg/m^3 (Fig. 3b). Similar trends were observed in juvenile wood of *Larix sibirica* (Koizumi *et al.* 2003).

Table 1. Mechanical properties of small clear specimens for tested provenances.

Provenance (Schmalenbeck No.)		ARW (mm)		WD (kg/m^3)		MOE (GPa)		MOR (MPa)		CS (MPa)		SS (MPa)	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Akanuma (13)	Outerwood	2.5	0.4	545	22	9.8	2.2	100.3	12.3	56.5	5.3	11.4	1.0
	Corewood	3.4	0.5	551	27	8.5	2.1	91.5	16.3	56.8	7.3	11.8	2.6
Kootoku (14)	Outerwood	2.3	0.5	574	70	9.9	1.9	104.0	12.6	59.2	8.3	11.6	1.4
	Corewood	3.2	0.7	574	98	8.0	1.6	97.8	19.4	61.3	7.5	10.4	0.8
Yasubara (15)	Outerwood	2.3	0.4	533	55	10.3	1.6	99.5	16.6	54.4	8.2	11.2	2.0
	Corewood	3.7	0.6	539	44	9.2	1.4	93.1	13.4	54.3	6.0	10.9	2.0
Manza (16)	Outerwood	2.3	0.3	535	22	10.3	2.0	101.7	10.5	53.5	4.6	10.6	1.9
	Corewood	3.5	0.3	548	15	9.6	1.5	101.2	16.1	52.6	3.2	12.0	1.4
Tenjin pass (1)	Outerwood	2.3	0.5	573	39	10.2	2.8	101.9	20.9	60.8	7.7	12.3	2.2
	Corewood	3.5	0.6	588	47	8.4	1.7	95.6	21.5	58.6	5.7	11.5	1.8
Sangoome (2)	Outerwood	2.3	0.7	561	33	10.4	1.2	97.7	9.6	62.5	5.3	12.6	1.9
	Corewood	3.5	0.8	545	30	8.9	1.4	93.9	13.8	56.4	5.9	11.5	1.9
Shizuoka (-)	Outerwood	2.3	0.4	478	49	8.1	2.3	88.4	19.9	46.9	7.9	10.2	1.9
	Corewood	3.7	0.5	520	58	7.6	2.5	88.0	26.0	50.5	7.7	10.6	2.8
Lower Mizunoto (17)	Outerwood	2.3	0.4	524	44	9.4	0.8	95.5	9.2	50.5	6.8	10.6	1.1
	Corewood	3.5	0.8	525	45	7.7	0.9	88.9	15.1	47.4	6.0	11.0	2.0
Kutsukake (18)	Outerwood	2.9	0.9	529	40	9.2	2.1	98.2	19.2	52.6	7.7	10.5	1.0
	Corewood	4.0	1.4	539	34	8.2	1.9	96.2	19.4	52.8	4.7	11.3	1.8
Oiwake (19)	Outerwood	2.7	0.6	541	47	9.6	0.4	96.0	8.4	54.1	7.1	10.7	2.0
	Corewood	3.9	1.2	554	39	8.0	1.0	91.4	8.8	51.3	7.0	13.1	2.7
Tadeshina (7)	Outerwood	2.4	0.5	489	50	8.6	1.7	86.3	11.8	49.3	7.8	9.9	2.0
	Corewood	3.7	0.5	497	60	7.3	1.1	81.3	6.2	48.8	8.7	10.5	2.6
Toyohira (8)	Outerwood	2.2	0.5	548	47	10.4	1.7	101.8	14.8	56.8	5.1	11.9	1.8
	Corewood	4.0	0.7	552	41	8.6	1.2	96.5	6.3	54.3	5.0	10.2	1.0
Upper Tatsuzawa (10)	Outerwood	2.5	0.4	543	46	7.8	2.1	89.1	14.5	54.8	7.4	13.0	1.7
	Corewood	3.7	0.5	547	37	6.9	1.6	86.4	15.0	54.2	5.4	11.7	1.8
Lower Tatsuzawa (9)	Outerwood	2.5	0.5	531	22	8.8	2.0	93.3	14.5	54.7	5.2	11.5	1.8
	Corewood	4.2	0.7	577	59	7.4	1.6	93.4	13.8	55.0	0.7	11.6	3.0
Uminokuchi (6)	Outerwood	2.5	0.4	581	30	9.7	2.1	107.3	14.3	60.3	6.3	12.6	2.6
	Corewood	4.0	0.9	567	28	7.9	1.7	95.0	12.4	56.8	6.3	11.8	1.2
Mt. Kobushidake (4)	Outerwood	2.5	0.5	542	45	9.9	1.6	101.1	13.4	56.9	7.9	11.3	1.3
	Corewood	3.8	0.8	576	34	8.5	1.2	97.6	10.7	57.3	7.2	11.9	1.5
Lower Takasegawa (22)	Outerwood	2.5	0.5	522	26	8.2	2.0	89.6	13.8	52.0	6.2	12.3	1.6
	Corewood	3.7	0.6	555	26	7.4	2.9	94.8	19.8	54.9	4.3	13.8	3.2
Kamikoochi (20)	Outerwood	2.0	0.4	575	21	11.0	1.3	106.7	12.0	62.5	5.8	12.3	2.1
	Corewood	3.9	0.6	539	24	8.4	1.3	97.8	14.0	54.6	5.6	10.7	1.4
Mt. Hachimoriyama (25)	Outerwood	2.4	0.5	553	46	10.6	1.2	108.7	9.6	55.9	4.9	11.9	2.3
	Corewood	3.6	0.5	530	66	9.0	1.1	96.3	9.2	52.1	7.1	10.7	1.8
Mt. Ontake (24)	Outerwood	2.4	0.5	501	31	8.3	1.6	85.1	13.2	53.4	6.9	10.6	2.4
	Corewood	3.5	0.4	527	22	7.2	1.2	80.4	11.7	50.7	4.0	13.0	2.2
Mt. Kiso-komagatake (23)	Outerwood	2.4	0.5	536	34	10.0	1.6	97.8	10.7	54.4	3.6	12.7	1.9
	Corewood	3.6	0.6	554	31	10.5	1.3	107.6	3.9	57.7	1.3	12.5	1.8
Mt. Kai-komagatake (11)	Outerwood	2.8	0.5	522	24	9.9	1.5	97.7	11.4	55.8	7.6	10.5	1.2
	Corewood	3.6	1.0	553	59	8.4	0.9	90.9	9.1	54.8	9.5	11.6	1.4
Mt. Akaishi-oosawadake (12)	Outerwood	2.7	0.8	494	32	8.6	1.6	87.6	9.9	50.5	7.5	9.9	1.3
	Corewood	4.1	0.9	497	40	7.9	1.2	90.2	10.3	49.3	7.7	9.8	1.6
Averages	Outerwood	2.4	0.5	536	38	9.5	1.7	97.2	13.2	55.1	6.6	11.4	1.8
	Corewood	3.7	0.7	546	42	8.2	1.5	93.3	13.6	54.0	5.8	11.5	1.9

ARW: Average ring width, WD: Wood density, MOE: Bending modulus of elasticity, MOR: Bending strength,
CS: Compressive strength parallel to grain, SS: Shear strength.

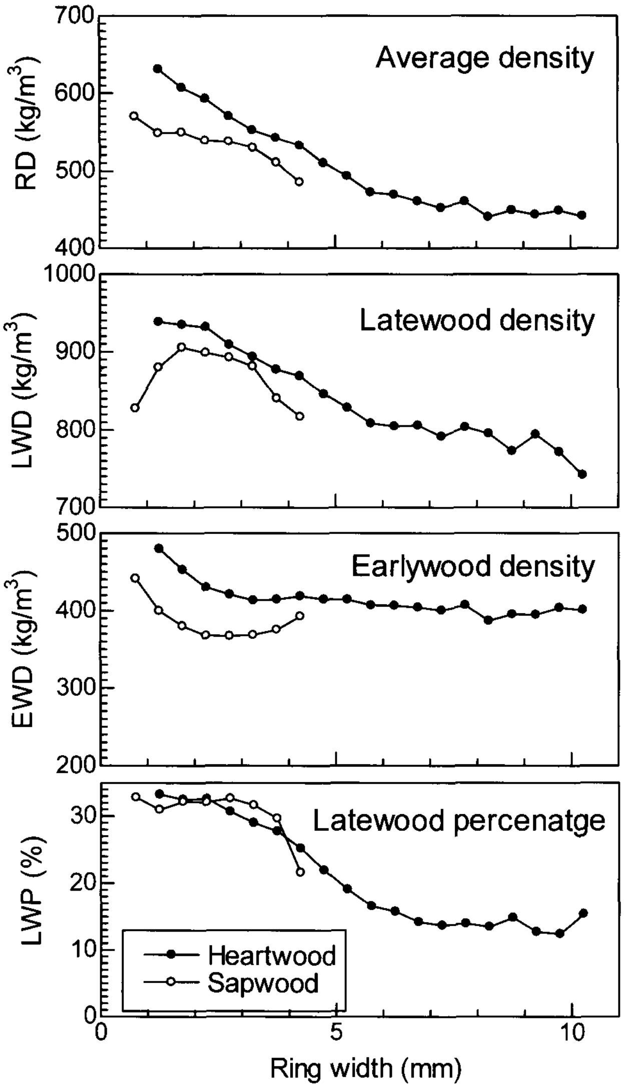

Fig. 4. Relationship between growth ring parameters and ring width classes RD, EWD, LWD, LWP are defined in Fig. 2.

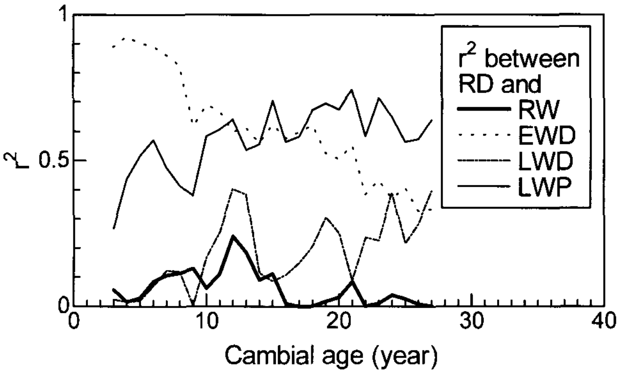

Fig. 5. Trends for coefficients of determination (r^2) between RD and RW, EWD, LWD, and LWP associated with cambial age.

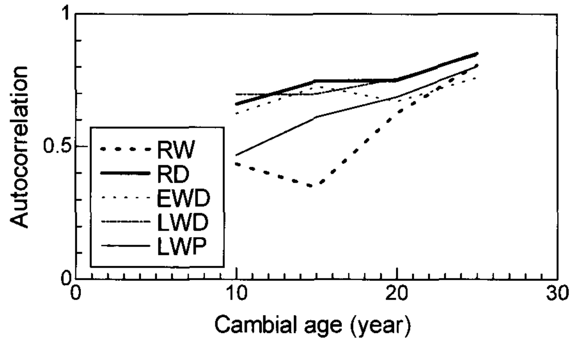

Fig. 6. Autocorrelation of growth-ring parameters over 5-year periods with those of the preceding 5-year period.

The relationship between the RW and other wood-density parameters of heartwood and sapwood are shown separately in order to consider the differences in their densities (Fig. 4) because unextracted specimens were used for X-ray densitometry; each plot represents the average value for the corresponding 0.5 mm ring-width class. As a general trend, RD decreased as RW increased; this trend may be attributed to negative correlations between LWD or LWP and RW in the juvenile stage.

The average RD of heartwood corresponding to the ring-width classes was higher than that of sapwood by 50.0 kg/m^3; this high density may be attributed to the presence of arabinogalactan in the heartwood of several species of larch (Côté *et al.* 1989). The differences between heartwood and sapwood with regard to the EWD and LWD were 54.0 kg/m^3 and 33.9 kg/m^3, respectively. These results suggest rich deposits of arabinogalactan in the large lumens of earlywood.

Figure 5 shows the trends of the coefficients of determination (r^2) of RD with RW, EWD, LWD, and LWP in relation to cambial age in order to consider the effects of maturity or age on the relationship between RD and other growth ring parameters. EWD was observed to be the prominent source of variation in RD in the corewood section, whereas LWP had a major effect on RD in the outerwood section. The contribution of RW to RD was very small across all cambial ages. The correlation coefficients of RD with LWP, LWD, EWD, and RW for all growth rings were 0.829, 0.629, 0.600, and −0.517, respectively.

In order to discuss the stability or continuity of the growth ring parameters from the juvenile to mature stage with regard to the chronological sequence of growth rings, autocorrelations (coefficients for age correlation) between the parameters for a given

Table 2. Variance ratios (*F*) for mechanical properites of small clear specimens among the provenances.

	WD	MOE	MOR	CS	SS
Outerwood	2.19**	1.54	1.26	2.12**	2.40**
Corewood	1.51	0.97	0.83	1.37	0.79

** Differences are significant at 1% level.
WD, MOE, MOR, CS, SS: Refer to Table 1.

Table 3. Correlation coefficients (*r*) between wood density and mechanical properties.

	MOE	MOR	CS	SS
Outerwood	0.425	0.663	0.729	0.496
Corewood	0.322	0.545	0.779	0.453

MOE, MOR, CS, SS: Refer to Table 1.

five-year-period and those for the preceding five-year-period were calculated (Fig. 6). For example, the value at the 10th cambial age in the figure represents the correlation coefficient between the average value obtained for the periods between 8 to 12 years and 3 to 7 years of cambial age with regard to the variables under consideration. RD showed a high autocorrelation that increased with cambial age from 0.66 in corewood to 0.86 in the outerwood, whereas RW showed a small autocorrelation within the corewood section. The high degree of continuity of the RD makes it a reliable index of the mechanical quality of Japanese larch for early selection in tree breeding programs.

Conclusion

(1) Wood density strongly affected the strength properties of small clear specimens, particularly in the outerwood section.

(2) Earlywood density had a major effect on average density in the corewood, whereas the effect of latewood percentage on average density was the largest in the outerwood.

(3) Average density within a ring was more stable across all cambial ages than other growth ring parameters and was considered to be a reliable index of wood quality for early selection in tree breeding programs.

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