Tumenjargal *et al. J Wood Sci* (2020) 66:17
https://doi.org/10.1186/s10086-020-01863-6

Journal of Wood Science

ORIGINAL ARTICLE

Open Access

Bending properties of dimension lumber produced from Siberian larch (*Larix sibirica*) in Mongolia

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Abstract

The modulus of elasticity (MOE) and modulus of rupture (MOR) were evaluated for 190 pieces of dimension lumber (2 by 4 lumber, 38 by 89 mm in cross-section) produced from *Larix sibirica* trees grown in Mongolia. The 5% tolerance limits of the MOE and MOR were 5.70 GPa and 15.1 MPa, respectively. The value of the 5% tolerance limit of the MOR exceeded the characteristic value of 2 by 4 lumber in visual grading class No. 3 of the Japanese Agricultural Standard for the D. fir-L, Hem-Tam, JS-III and S-P-F softwood species groups. A significant positive correlation was found between the MOE and MOR, although air-dry density was weakly correlated with bending properties in *L. sibirica*.

Keywords: *Larix sibirica*, Modulus of elasticity, Modulus of rupture, 5% tolerance limit, Visual grading, Juvenile wood

Introduction

Structural lumber is one of the world's main construction materials, and graded lumber is the highest value product from trees [1]. When structural lumber is produced, the mechanical properties need to be assessed to ensure structural safety.

The mechanical properties of lumber vary considerably, because it is a natural material. Numerous studies have focused on mechanical properties, especially the modulus of elasticity (MOE) and modulus of rupture (MOR) in bending for structural lumber sawn from softwood species grown in plantations and natural forests [2–19]. Characteristic values, such as the lower tolerance limits of the MOE and MOR, are very important for structural lumber in construction [10, 13, 20–22]. The 5th percentile ultimate stress value is used to calculate allowable design stress [4]. For example, França et al. [22] estimated allowable design bending strength for Southern pine (*Pinus* spp.) and found a value of 10.3 MPa for 2 by 4 lumber. Zhong and Ren [21] reported that design values for the bending strength of *Larix gmelinii* 2 by 4 lumber were 18.4 MPa for select structural (SS), 11.6 MPa for No. 1, 12.7 MPa for No. 2, and 10.3 MPa for No. 3 grade.

Sawing patterns in relation to the presence of juvenile wood have been investigated for softwood species [14, 16, 17, 19, 20, 23–25]. Problems of juvenile wood used as structural lumber are derived from inferior mechanical properties and inconsistent stability compared to mature wood [3]. Matsumura et al. [23] examined the influence of the sawing patterns of lumber (center, inner, and outer) on dynamic Young's modulus in Japanese cedar (*Cryptomeria japonica*) logs and found the lowest values of the modulus of the lumber to be in both the center and inner positions that contained juvenile wood.

In Mongolia, Siberian larch (*Larix sibirica* Ledeb.) is a major softwood species, and wood from this species is mainly used for structural lumber in construction due to its high mechanical strength properties [18, 19, 26]. We previously examined the geographical variations of wood properties and the quality of dimension lumber (2 by 4 lumber) for *L. sibirica* collected from five different provenances in Mongolia. Significant differences were found in the wood and the bending properties of the lumber

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between the provenances [18, 27]. However, there are limited available data on the characteristic values of the bending properties of dimension lumber for this species grown in Mongolia.

The objectives of this study were to determine the 5% lower limit with a 75% confidence level of the bending properties of 2 by 4 lumber produced from *L. sibirica* trees in Mongolia. Differences in bending properties were also examined between the visual grading classes and different types of sawing pattern, and the relationships between the air-dry density and bending properties of the lumber were investigated.

Materials and methods

Lumber production

Figure 1 shows the experimental procedures used in the present study. A total of 111 logs were obtained from 25 trees (from 3 to 6 logs per tree) harvested from five different natural forests in Mongolia [18, 27]. The logs were sawn into as many 100-by-50 mm cross-sections as possible. A total of 190 pieces of lumber were thus obtained from the logs [18]. The lumber was air-dried in a laboratory without an air conditioner or heater in Ulaanbaatar, Mongolia, for 1 year, and the lumber was then planed into 38-by-89 mm cross-sections [18]. After planning, the lumber was classified into three types: lumber including pith at almost the center position in cross-section (I), lumber obtained near the pith (sometimes including pith on the surface area of the lumber) (II), and lumber obtained from the outer part of the logs (without pith) (III) (Fig. 1).

Bending properties of lumber

Before the bending test, the air-dry density at testing was determined by measuring the weight, length, and cross-section dimensions of the lumber using a portable electric balance (SL-20 K, A&D), a laser measure (GLM-50C, Bosch), and digital calipers (CD-15CX, Mitutoyo), respectively.

The bending test was conducted using a material testing machine (WDW-20E, Jinan Kason Testing Equipment). Load speed, support span, and distance between the load points were 14 mm/min, 1602 mm, and 534 mm, respectively [18]. The specimen was set randomly on the supports. The load was applied in the edgewise direction. The MOE and MOR of the lumber were determined by the following equations:

$$\text{MOE (GPa)} = \frac{\Delta P\left(l - l'\right)\left[3l^2 - 2\left(l - l'\right)^2\right]}{8\Delta y b h^3}$$

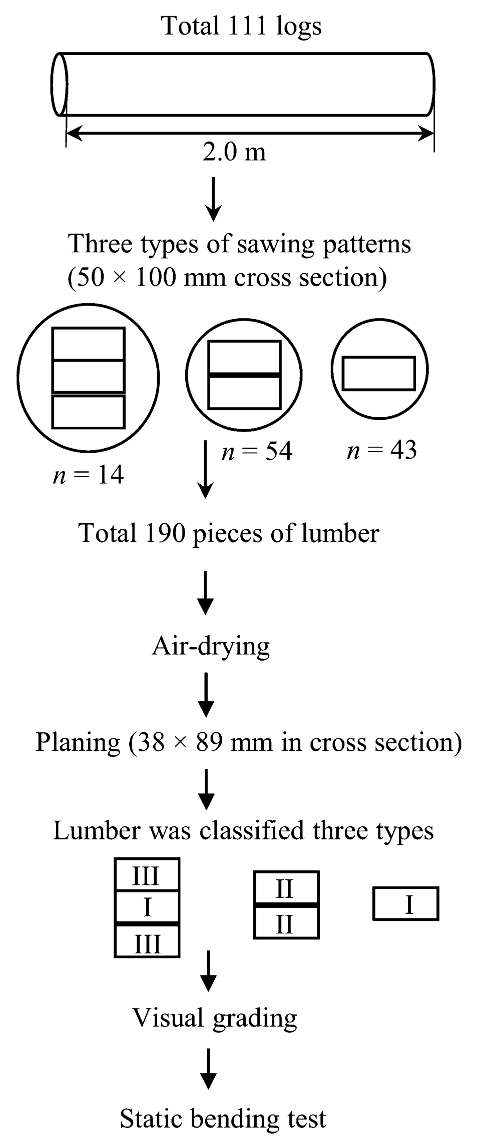

Fig. 1 Illustration of the experimental procedure. *n* number of logs. Among the large diameter logs, four lumber (one lumber was type I, and three pieces of lumber were type III) were obtained from one log. Totally, 194 pieces of lumber were obtained from 111 logs. However, we failed to collect the data of bending tests for four pieces of lumber. Thus, totally 190 pieces lumber data were used

$$\text{MOR (MPa)} = \frac{3P_{\max}\left(l - l'\right)}{2bh^2}$$

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

After the bending test, small specimens (2.5 cm in longitudinal direction) without any defects were obtained from the lumber. The specimens were used to measure the annual ring width and to determine the moisture content using an oven-drying method. The moisture content of the lumber was found to be 12.7 ± 0.7%. The MOE and MOR values were therefore adjusted to those at 15% moisture content using the following formula [28]:

$$P_2 = P_1(\alpha - \beta 15)/(\alpha - \beta M)$$

where P_2 is the MOE or MOR value at a moisture content of 15%, P_1 is the MOE or MOR value at testing, M is the moisture content at testing, α is 1.44 and 1.75 for MOE and MOR, respectively, and β is 0.0200 and 0.0333 for MOE and MOR, respectively.

Visual grading

All pieces of lumber were graded according to the Japanese Agriculture Standard (JAS) for structural lumber for wood frame construction [29]. For grading, the typical visual sorting criteria, such as annual ring width, knot size, existence and size of holes, slope of grain, deformation (bow, crook, and twist), wane, and crack, were measured on the surfaces of all pieces of lumber as described in the JAS. Based on the measurements, the lumber was classified into five grades (select structural, No. 1, No. 2, No. 3, and out grade) according to the JAS for structural lumber for wood frame construction.

Data analysis

Data analyses were conducted using Excel 2016 (Microsoft) and R [30] software. The 5% lower tolerance limits with a 75% confidence level ($\mathrm{TL}_{75\%,95\%}$) of the MOE and MOR were calculated using the following formula [28]:

$$\mathrm{TL}_{75\%,95\%} = \mu - K\sigma$$

where μ is the mean value, K a constant (1.7247, $n = 190$), and σ the standard deviation.

Significant differences in air-dry density, MOE, and MOR between the visual grades of three wood types were analyzed using the Tukey–HSD test at a 5% significance level, and the relationships between the measured properties were determined using Pearson's correlation coefficient.

Results and discussion

Bending properties

The statistical values of the annual ring width, air-dry density at testing (moisture content at 12.7 ± 0.7%), MOE, and MOR of the lumber are presented in Table 1. Annual ring width and air-dry density at testing ranged from 0.3 to 5.2 mm and 0.50 to 0.74 g/cm^3, respectively. The adjusted MOE and MOR mean values at 15% moisture content were 9.89 GPa and 50.3 MPa, respectively.

Figure 2 shows the distributions of the MOE and MOR of lumber for *L. sibirica* in the present study. The distribution patterns for the MOE and MOR fit well to a normal distribution. The 5% tolerance limits were calculated using the mean and standard deviation and found to be 5.70 GPa and 15.1 MPa for the MOE and MOR, respectively (Table 1). In the present study, we compared the characteristic values of MOR in three species groups including *Larix* species (D. fir-L, Hem-Tam, and JS-III), and a major dimension lumber species group, S-P-F [31]. The value of the 5% tolerance limit of the MOR exceeded the characteristic value of the MOR of 2 by 4 lumber in visual grading class No. 3 of the JAS for structural lumber for wood frame construction for the D. fir-L, Hem-Tam, S-P-F species groups, and JS-III (Table 2). In addition, the MOR values of over 90% of the tested lumber in the present study fit the characteristic values of the MOR of 2 by 4 lumber in visual grading class No. 1 or upper grade of the JAS for the D. fir-L, Hem-Tam, S-P-F, and JS-III species groups [31] (Table 2). Furthermore, the 5% tolerance limit was also calculated in each visual grade, such as SS, SS + No.1, SS + No.1 + No.2, and SS + No.1 + No.2 + No.3 (Table 3). The values of the 5% tolerance limit of the MOR in each grade were higher than characteristic values of the MOR of 2 by 4 lumber in visual grading class No. 3 in D. fir-L, Hem-Tam, S-P-F, and JS-III species groups.

Table 1 Mean statistical values of lumber properties in *L. sibirica*

Properties	*n*	Mean	SD	Max.	Min.	$\mathrm{TL}_{75\%,95\%}$
ARW (mm)	190	2.0	1.1	5.2	0.3	–
AD (g/cm^3)	190	0.61	0.05	0.74	0.50	–
MOE (GPa)	190	9.89	2.43	21.08	4.11	5.70
MOR (MPa)	190	50.3	20.4	110.9	13.6	15.1

Values of the MOE and MOR were adjusted to those at 15% moisture content by the method of the Japan Housing and Wood Technology Center [28]

n number of lumber pieces, *ARW* annual ring width, *AD* air-dry density at testing (moisture content at 12.7 ± 0.7%), *MOE* modulus of elasticity, *MOR* modulus of rupture, *SD* standard deviation, *Max.* maximum, *Min.* minimum, $\mathrm{TL}_{75\%,95\%}$, 5% lower limit with a 75% confidence level (5% tolerance limit)

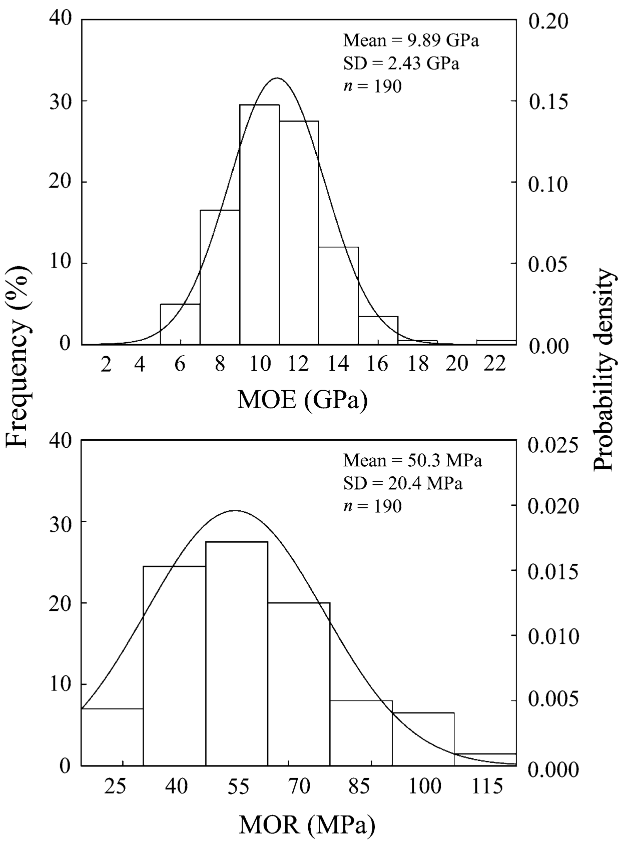

Fig. 2 Distribution of the MOE and MOR of lumber in *L. sibirica*. *SD* standard deviation, *n* number of lumber

Based on the results, it is considered that dimension lumber produced from *L. sibirica* harvested from Mongolia has almost the same bending properties as that produced from other *Larix* species belonging to the D. fir-L Hem-Tam, and JS-III groups, such as *L. occidentalis*, *L. gmelinii*, *L. kaempferi*, and *L. laricina*.

Visual grading

The mean values of the air-dry density, MOE, and MOR of the lumber in each visual grade are listed in Table 4. According to visual grading based on the JAS for structural lumber for wood frame construction, 56.8% ($n = 108$), 6.3% ($n = 12$), 10% ($n = 19$), 10.5% ($n = 20$), and 16.3% ($n = 31$) of the pieces of lumber were graded as SS, No. 1, No. 2, No. 3, and out grade, respectively. Zhou et al. [15] analyzed the mechanical properties of visually graded 2 by 4 lumber for *L. gmelinii* and reported that the highest MOE (10.16 GPa) and MOR (38.4 MPa) values were found in SS grade and the lowest in No. 3 grade (MOE = 8.45 GPa and MOR = 19.6 MPa). In addition, Zhong and Ren [21] evaluated the bending strength of 2 by 4 lumber for *L. gmelinii* and found that the mean value of the MOR for SS grade was 65.1 MPa, which was higher than those of other grades. Similar results were also found in lumber for 50-, 73-, and 90-year-old *Pinus banksiana* [10]. In the present study, the highest mean values of the MOE and MOR were found in No. 1 grade (10.90 GPa and 54.2 MPa, respectively) and the lowest in out grade lumber (8.38 GPa and 40.2 MPa, respectively). No significant differences in either the MOE or MOR were found between SS, No. 1, No. 2, and No. 3 grade lumber, while the MOE and MOR in out grade lumber showed notably lower values (Table 4). These results indicate that visual grading for dimension lumber produced in this species is effective for eliminating lumber with extremely low strength properties, such as out grade. In addition, downgrading factors in the visual grading were evaluated for lumber (Table 5). Among evaluated factors, annual ring width, fiber orientation, and crack were not considered as downgrading factors in the visual grading class. On the other hand, knot, wane, and twist were major defects to downgrade for visual grading class in this species (Table 5).

Table 2 Characteristic value of the MOR in 2 by 4 lumber and the number of *L. sibirica* lumber in each grade

Grade	Characteristic value of MOR in 2 by 4 lumber (MPa)				Number of *L. sibirica* lumber in characteristic value of MOR for each grade							
	D. fir-L	Hem-Tam	S-P-F	JS-III	D. fir-L		Hem-Tam		S-P-F		JS-III	
					No.	%	No.	%	No.	%	No.	%
SS	36.0	29.4	30.0	22.5	139	73.2	163	85.8	160	84.2	180	94.7
No. 1	24.6	18.0	22.2	16.1	38	20.0	21	11.1	21	11.1	5	2.6
No. 2	21.6	13.8	21.6	15.5	6	3.2	5	2.6	2	1.1	2	1.1
No. 3	12.6	8.4	12.6	9.0	7	3.7	1	0.5	7	3.7	3	1.6

Characteristic values of the MOR in 2 by 4 lumber were cited from "Matters to determine the standard strength of wood F_c, F_t, F_b, and F_s" in Notification of Ministry of Land, Infrastructure, Transport and Tourism No. 910 [31]. Species group D. fir-L includes *L. occidentalis*, *L. gmelinii*, *Pseudotsuga menziesii*, and others; group Hem-Tam includes *L. kaempferi*, *L. laricina*, and others; and group S-P-F includes *Picea engelmannii*, *Pinus sylvestris*, *Abies balsamea*, and others; and group JS-III includes *L. kaempferi* and similar species

SS select structural

Table 3 Mean values, standard deviations, and 5% lower tolerance limits of each grade

Grade	*n*	MOE (GPa)			MOR (MPa)		
		Mean	SD	$TL_{75\%,95\%}$	Mean	SD	$TL_{75\%,95\%}$
SS	108	10.08	2.43	5.83	52.8	21.9	14.4
SS + No. 1	120	10.17	2.41	5.96	52.9	21.6	15.1
SS + No. 1 + No. 2	139	10.19	2.42	5.99	52.8	21.5	15.4
SS + No. 1 + No. 2 + No. 3	159	10.18	2.40	6.01	52.3	20.7	16.4

n number of lumber, *MOE* modulus of elasticity, *MOR* modulus of rupture, *SD* standard deviation, *SS* select structural, $TL_{75\%,95\%}$, 5% lower limit with a 75% confidence level (5% tolerance limit)

Table 4 Mean values and standard deviations of the air-dry density and bending properties of lumber in each visual grade

Grade	*n*	AD (g/cm^3)		MOE (GPa)		MOR (MPa)	
		Mean	SD	Mean	SD	Mean	SD
SS	108	0.60^{a}	0.05	10.08^{a}	2.43	52.8^{a}	21.9
No. 1	12	0.63^{a}	0.06	10.90^{a}	2.16	54.2^{ab}	19.8
No. 2	19	0.61^{a}	0.05	10.37^{a}	2.56	52.1^{ab}	21.1
No. 3	20	0.60^{a}	0.04	10.07^{ab}	2.35	48.8^{ab}	14.4
Out grading	31	0.60^{a}	0.04	8.38^{b}	2.00	40.2^{b}	14.9

The same letters (a and b) followed by mean values indicate no significance at the 5% level according to the Tukey–HSD test

n number of lumber pieces, *AD* air-dry density, *MOE* modulus of elasticity, *MOR* modulus of rupture, *SD* standard deviation, *SS* select structural

Table 5 Downgrading factors in the visual grading of lumber

Factor	Quantity of downgraded lumber in each grade (%)			
	SS	No. 1	No. 2	No. 3
Knot	28.4	20.5	16.8	8.4
ARW	0.0	0.0	0.0	0.0
Wane	15.3	15.3	10.0	8.9
Fiber orientation	0.0	0.0	0.0	0.0
Crack	0.0	0.0	0.0	0.0
Crook	2.6	2.6	0.0	0.0
Bow	2.1	2.1	1.1	0.0
Twist	10.0	10.0	4.2	2.1

Mean values were calculated from the ratio of the lumber downgraded to total lumber. Total lumber = 190

ARW annual ring width, *SS* select structural

Effects of lumber type on bending properties

Butler et al. [16] reported that significant differences between lumber with pith and without pith were found in the MOE and MOR of 2 by 4 lumber in *Pinus taeda*. Dahlen et al. [20] also reported that the MOE and MOR of lumber (2 by 6, 2 by 8, 2 by 10, and 2 by 12) with pith were significantly lower than those of lumber without pith in Southern pine (*Pinus* spp.). In addition, the lumber obtained from the center of logs had lower strength classes than side lumber from *Pseudotsuga menziesii* trees [14, 17]. In the present study, 30% of the lumber overall ($n = 57$) was classified into type I lumber (Table 6). Mean values ranged from 9.28 to 10.15 GPa and from 43.2 to 57.4 MPa for the MOE and MOR, respectively, among the three lumber types. Although the mean value of the MOE for type I lumber was lower than those for types II and III, no significant differences were found among these types. The MOR of type I lumber was significantly lower than those of types II and III. These results suggest that lumber with pith has lower bending properties. In previous reports, we examined the effect of juvenile wood on the properties of 2 by 4 lumber in *L. kaempferi* and found significant differences between juvenile wood and mature wood in bending properties [19]. Shivnarain and Smith [3] reported that the percentage of juvenile wood in a piece of lumber is a good indicator of bending strength in 2 by 4 lumber from *Picea glauca* trees. Based on these results, the MOE and MOR of *L. sibirica* lumber are considered to be greatly affected by the presence of juvenile wood. Thus, when structural *L. sibirica* lumber that requires higher strength properties is needed, the sawing pattern should be carefully considered in lumber production.

Table 6 Mean values and standard deviations of lumber properties in each sawing pattern

Lumber type	*n*	ARW (mm)		AD (g/cm^3)		MOE (GPa)		MOR (MPa)	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
I	57	2.1^{a}	1.1	0.59^{a}	0.05	9.28^{a}	2.21	43.2^{a}	12.5
II	104	2.0^{a}	1.1	0.60^{a}	0.04	10.15^{a}	2.36	52.3^{b}	21.4
III	29	1.9^{a}	1.2	0.65^{b}	0.04	10.14^{a}	2.92	57.4^{b}	25.2

The same letters (a and b) followed by mean values indicate no significance at the 5% level according to the Tukey–HSD test. The values of the MOE and MOR were adjusted to the values at 15% moisture content

n number of lumber pieces, *ARW* annual ring width, *AD* air-dry density at testing, *MOE* modulus of elasticity, *MOR* modulus of rupture, *SD* standard deviation, *I* lumber including pith at an almost-center position in cross-section, *II* lumber obtained near the pith (sometimes including pith on the surface area of the lumber), *III* lumber obtained from outer part of the logs (without pith)

Table 7 Correlation coefficients between properties

Grade and lumber types	*n*	AD-MOE	AD-MOR	MOE-MOR
Total lumber	190	0.182^{*}	0.215^{**}	0.789^{**}
SS	108	0.302^{**}	0.302^{**}	0.801^{**}
No. 1	12	0.196^{ns}	0.196^{ns}	0.910^{**}
No. 2	19	-0.090^{ns}	0.021^{ns}	0.760^{**}
No. 3	20	0.222^{ns}	-0.064^{ns}	0.613^{**}
Out grading	31	-0.014^{ns}	-0.076^{ns}	0.762^{**}
I	57	0.122^{ns}	-0.057^{ns}	0.635^{**}
II	104	0.180^{ns}	0.249^{*}	0.814^{**}
III	29	0.196^{ns}	0.106^{ns}	0.879^{**}

For abbreviations, refer to Tables 2 and 4

ns not significant

* Significant at the 5% level; ** significant at the 1% level

Correlations between lumber properties

Correlation coefficients between the air-dry density and bending properties of lumber are listed in Table 7. With a few exceptions, no significant correlations were found between the air-dry density and the MOE or MOR. Although air-dry density showed significant relationships with both the MOE and MOR overall and in SS grade lumber, the correlation coefficients were lower. Similar weak correlation coefficients between density and MOR were found in *L. kaempferi* lamina ($r = 0.242$) [32], and 2 by 4 lumber of *C. japonica* ($r = 0.094$) [13]. In addition, the relationships between wood density and MOR might be affected by presence of large amounts of arabinogalactan in the species. In the previous study [26], we reported that arabinogalactan might be included in hot-water extracts in heartwood of *L. sibirica*, and the content of hot-water extracts was 14.1%. Thus, it is considered that wood density including arabinogalactan in this species resulted in overestimation of wood density values. Cáceres et al. [33] examined the influence of extractives on wood density in *L. kaempferi*; they found that the hot-water extractive content (mainly arabinogalactan) of *L. kaempferi* varied between 2.9 and 6.9%. Therefore, the presence of large amounts of arabinogalactan might result in lower correlation coefficients between air-dry density and bending properties. Based on the results, air-dry density is considered not to be a good predictor of the bending properties of visually graded lumber in *L. sibirica*.

Significant positive correlation coefficients were found between the MOE and MOR in all types of lumber (Table 7). Gupta et al. [8] found a positive relationship between the MOE and MOR of *L. dahurica* 2 by 4 lumber. Butler et al. [16] also found a significantly positive correlation coefficient between the MOE and MOR of loblolly pine (*Pinus taeda*) lumber. In addition, significantly positive correlations were observed between the MOE and MOR of 2 by 4 lumber from *Picea glauca* [6] and both green and dry 2 by 8 lumber from three different softwood species [4]. The results obtained in this study suggest that the MOE of lumber is a good predictor of MOR in *L. sibirica.*

Conclusions

The bending properties of 2 by 4 lumber from *L. sibirica* in Mongolia were investigated in this study. The mean values of MOE and MOR adjusted to 15% moisture content were 9.89 GPa and 50.3 MPa, respectively. The 5% tolerance limits of these properties were 5.70 GPa and 15.1 MPa, respectively. The value of the 5% tolerance limit of the MOR exceeded the characteristic value of the MOR of 2 by 4 lumber in visual grading class No. 3 of the JAS for structural lumber for wood frame construction for D. fir-L, Hem-Tam, JS-III, and S-P-F species groups. The mean MOR values were significantly higher in the lumber obtained from the outer part of the logs. A significant positive correlation was found between the MOE and MOR, although the air-dry density was weakly correlated with bending properties.

Abbreviations

MOE: Modulus of elasticity; MOR: Modulus of rupture; $TL_{75\%, 95\%}$: 5% lower tolerance limit with a 75% confidence level; SS: Select structural.

Acknowledgements

The authors thank Ms. Yui Kobayashi and Mr. Tappei Takashima (students at Utsunomiya University), and Mr. Sarkhad Murzabek and Ms. Togtokhbayar Erdene-Ochir (Mongolian University of Science and Technology) for their assistance in measuring the lumber properties.

Authors' contributions

BT contributed to experiments, data analysis, and writing the manuscript. FI designed this study and contributed to experiments, data analysis, and writing the manuscript. YT and IN contributed to experiments and data analysis. BB and GC contributed to experiments. HA-S, JO, and SY contributed to discussion on the obtained results. All authors read and approved the final manuscript.

Funding

A part of this research was financially supported by the M-JEED program of the Ministry of Education, Culture, Science, and Sports, Mongolia.

Availability of data and materials

Not applicable.

Ethics approval and consent to participate

The wood samples used in the present study were collected with the observance of Mongolian laws.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Received: 10 December 2019 Accepted: 27 February 2020
Published online: 07 March 2020

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