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GRADES AND STRENGTH CHRACTERISTICS OF LOW-DENSITY HARDWOOD, YELLOW POPLAR

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ABSTRACT: The Yellow poplar tree is well-suited to the climate and soil of Korea and exhibits high growth characteristics. In Korea, however, Yellow poplar trees are consumed as low-value materials such as wood pellets, pulp, mushroom logs, and so on. Efforts have been underway to enhance its value by investigating its potential as a structural material in Korea. This study was conducted to confirm the feasibility of Yellow poplar usage as a structural member by investigating the characteristic value of bending and tensile strength. Full-size lumber was graded by machine grading. The majority of grades of Yellow poplar lumber having a cross-section of 89 × 38 mm^2 were E8, E9, E10, E11, and E12. In the lowest grade, E8, among the majority of grades, the characteristic value of the modulus of rupture was smaller than the allowable stress in the Korean Design Standard. It was needed to restrict the diameter ratio of knot in wide side of the lumber, and the value of the diameter ratio of knot was 0.5. With the restriction, all of characteristic values of strength of Yellow poplar were larger than the allowable stress. In further studies, other properties for structural purposes will be investigated.

KEYWORDS: Yellow polplar, grade, characteristic value, diameter ratio of knot, allowable stress

1 – INTRODUCTION

Due to the global climate crisis, interest in wood, an eco-friendly material, is increasing. Wood is not only a carbon storage material recognized by UNCCD, but also emits less carbon dioxide during production and transportation compared to other building materials. However, wood is a natural material and a heterogeneous material, so in order to be used as a building material, it must be properly graded and design values must be presented according to the grade.

Grading is a basic and important indicator that can distinguish the quality and strength of wood [1]. Lumber used as engineered wood plywood or structural materials for light frame wood structures can be graded visually or mechanically [2, 3]. Visual grading is a method of assigning grades by evaluating the knots and bends present in the four cross sections of lumber. Mechanical grading is a method of assigning grades by measuring the MOE of lumber using equipment such as MSR [4]. Mechanical grading is more expensive than visual grading, but has the advantage of measuring MOE, which is one of the best indicators for predicting the strength of lumber. Uzcategui *et al.* (2023) [5] reported that the use of MSR in sawmills helps maintain or improve the quality of lumber.

Most of species used for structural purposes are softwood. Therefore, research on the grading of softwood has been traditionally and consistently conducted. On the other hand, research on the use of hardwoods as structural materials is insufficient. To use hardwood as structural materials, one of the first studies is that the grading method and the derivation of characteristic values accordingly should be conducted in advance. Weidenhiller *et al.* (2019) [6] applied microwave to grade not only conifers but also hardwoods. Green (1997) [7] applied MSR to grade hardwoods. Faust *et al.* (1990) [8] argued that it is necessary to compare and study the relationship between strength and stiffness when applying MSR to hardwoods.

Yellow poplar (*Liriodendron tulipifera*) tree, meanwhile, was selected as a major species and planted extensively for the bio-circulation forest launched by the Korea Forest Service in 2008. The total amount of Yellow poplar tree was 21,237 ha in 2019. Yellow poplar tree is well-suited to

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the climate and soil of Korea and exhibits high growth characteristics. Compared to other major tree species for afforestation, Yellow poplar tree also can absorb 1.2 to 1.7 times more carbon annually, making them advantageous for achieving carbon neutrality by 2050.

Ryu *et al.* (2014) [9] reported that while other economic tree species have an average cutting age of 50 years, Yellow poplar can be cut down in an average of 38 years, making it an economic species. In addition, Yellow poplar was found to have superior carbon capture and sequestration capabilities compared to trees commonly planted in Korea, such as Japanese larch and Pine. Kim *et al.* (2010) [10] conducted a study on the application of heat treatment technology to reduce the color difference between the heartwood and sapwood of Yellow poplar and the resulting physical and mechanical performances. Lim *et al.* (2010) [11] applied the visual grading method for softwood to grade Yellow poplar lumber and confirmed that Yellow poplar can be used as structural lumber. In addition, Mettanurak *et al.* (2010) [12] reported that Yellow poplar can be used as structural lumber except during periods of extreme growth inhibition.

Yellow poplar, however, has primarily been used for low-value materials such as wood pellets, pulpwood, and mushroom logs. Efforts are underway to enhance its value by exploring its potential as a structural material in Korea. To do this, principal research is needed on the grading distribution and structural performance of Yellow poplar timber. This study presents the results of machine grading distribution and characteristic strength of Yellow poplar timber.

2 – MATERIALS AND METHODS

2.1 MATERIALS

Eighty-three logs were harvested in Gangjin, Jeollanam-do, Korea, and lumber with a cross-sectional size of 89 (width) × 38 (thickness) mm^2 was produced. Table 1 shows information about the number of logs and lumbers according to a range of log's diameter at breast height (DBH). A total of 1044 pieces of lumber were produced, the number of 1017 pieces of lumber were tested for bending and tensile properties. After the structural performance tests, clear wood were made from some of the specimens to measure the moisture content and specific gravity. The moisture content and air-dry specific gravity of Yellow poplar wood were 11.5 ± 2.3% and 0.49 ± 0.05, respectively.

2.2 MACHINE GRADING

Yellow poplar lumbers were mechanically graded by using the equipment named MGFE-251 (JWM, Japan). The machine grades were classified by following KS F 3020 (2023) [13]. In the KS F 3020, the grading classifications are from E6 to E14, with E6 meaning an MOE of 6 GPa or more and less than 7 GPa. Because of lack of hardwood grading rule in Korea, machine grading rule for softwood was applied. After machine grading, defects on the wide surface of Yellow lumber were checked. In case of knot, knot was measured by using the knot diameter which is ratio of wide side of lumber and the knot diameter ratio. The knot diameter ratio can be measured as the distance between the tangential lines at each end of knot, the lines were parallel to the longitudinal direction of the face of lumber. It can be found the detailed methods to determine the knot diameter ratio in ASTM D3737 (2018) [14] and KS F 3020.

2.3 FULL SIZE TEST

2.3.1 Bending Test

Fig. 1a shows schematic diagram to evaluate a bending performance of Yellow poplar lumber. The load applied on an edge-wise lumber at a loading rate of 10 mm/min by using the universal testing machine (MTS, USA). The modulus of rupture (MOR) and modulus of elasticity (MOE) as bending performance were calculated using (1) and (2).

Table 1: Number of Lumber Pieces and Logs in Various Logs Diameter

Diameter of Log (mm)	Bending Test		Tensile Test	
	Number of Log (EA)	*Number of Lumber (EA)*	*Number of Log (EA)*	*Number of Lumber (EA)*
200 ≤ Diameter < 300	1	4	16	152
300 ≤ Diameter < 400	21	176	14	201
400 ≤ Diameter < 500	11	163	3	86
Diameter ≥ 500	9	198	8	64
Total	**42**	**541**	**41**	**503**

$$\mathrm{MOR} = P_m l / wd \quad (1)$$

$$\mathrm{MOE} = 23Pl^3 / 108td^3\Delta \quad (2)$$

where, p_m is the maximum load (N), w is width of lumber (mm), and d is depth of lumber (mm), l is span of lumber (mm), P is increment of load below proportional limit (N), and Δ is increment of deflection of lumber's neutral axis measured at midspan over distance l and corresponding load P (mm).

2.3.2 Tensile Test

Tensile tests were done by using the order-made equipment (Kyoungsung, Korea). In the tensile test, the spacing of a specimen was 2500 mm excluding the gripped part of 550 mm at both ends of the specimen with hydraulic apparatus as shown in Fig. 1b. The test speed was 8 mm/min to ensure the finish test within 5 min. The tensile strength was calculated from the maximum load and the cross-sectional area of the specimen as follows,

$$f_t = P_m / wd \quad (3)$$

2.3.3 Calculation of Characteristic Value

Characteristic value of Yellow poplar in various machine grades was calculated. The characteristic values for MOR and tensile strength were determined using 5th percentile values and allowable stress. The 5th percentile value was calculated using parametric and non-parametric methods. In the case of the parametric method, the Weibull distribution was used as shown in (4).

$$f(x|a,b) = (b/a)(x/a)^{b-1}e^{-(x/a)^b} \quad (4)$$

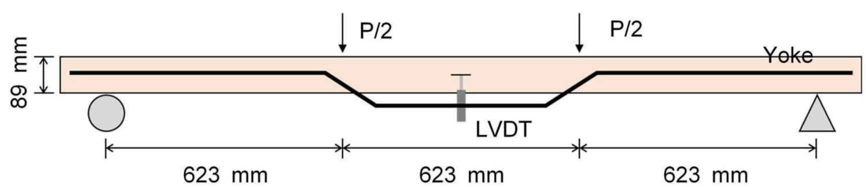
where, e is Euler's constant, a is scale parameter, and b is shape parameter. For the non-parametric method, the order statistic based on the number of specimens was used to obtain a 5th percentile value at the 75% confidence level.

The allowable stress for either tensile strength or MOR was determined by multiplying a reduction factor of 0.475 by 5th percentile values, and the reduction factor considers the normal load duration and safety factor. The allowable stresses of either tensile strength or MOR were compared with the allowable properties according to the mechanical grades of softwood lumber in KS F 3020.

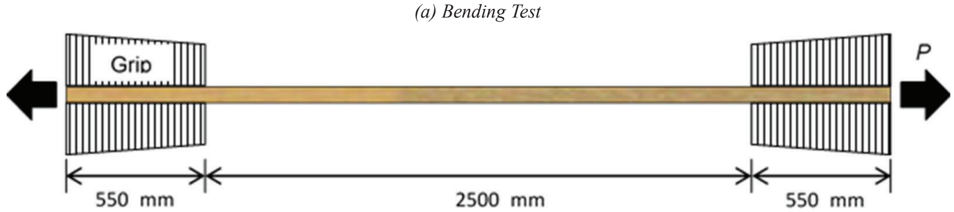
3 – RESULTS AND DISCUSSION

3.1 GRADING RESULTS

Fig. 2 shows the results of machine grading of Yellow poplar lumber. The majority of Yellow poplar grades were E8, E9, E10, E11, and E12 and the percentage were 12%, 21%. 23%, 23%, and 11% in order. Compared to the proportion of lumber pieces according to test types, the proportion of machine grades was different even though the lumbers were produced from the same harvested area. It was considered that the difference occurred because of the diameter of logs used to make lumber, as listed in Table 1. In the case of lumbers for tensile test, the largest number of lumber pieces was produced from logs with a diameter of 300 mm to 400 mm. The largest number of lumber pieces for the bending test, on the order hands, was made by using logs with a diameter of 500 mm or over.



(a) Bending Test



(b) Tensile Test

Figure 1. Schematic diagram for full size test.

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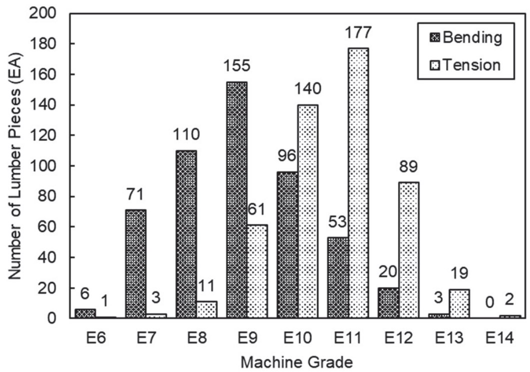
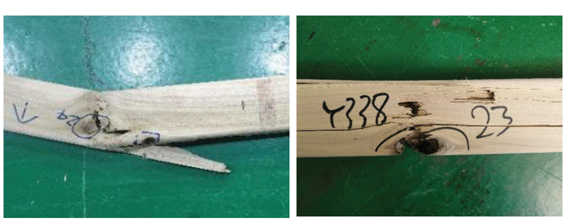


Figure 2. Machine grade distribution of Yellow poplar for each test.

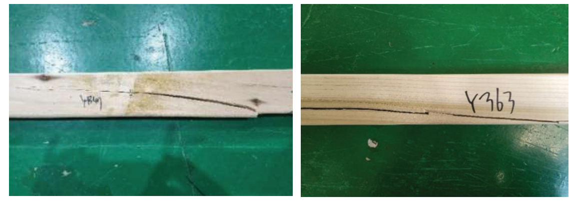
The relationship between log diameter and lumber grades is not revealed clearly. Øvrum *et al.* (2009) [15] reported that the proportion of lumber with high machine grade increased as the diameter of logs decreased for Norway spruce. This was because the log with a small diameter tended to have high density with small knots and a narrow width of the annual ring. On the contrary, there was a report that a strong relationship between visual log classification and machine grades could not be found. Therefore, It is needed that additional research on log classifying and lumber grading to establish production planning for Yellow poplar lumber.

3.2 CHARACTERISTIC VALUES

The most frequent failure modes were observed as a round knot and grain angle as shown in Fig. 3. Brittle failure mainly took place in both tensile and bending tests because failures in the bending test occurred on the side in tension, the opposite of the loading point. Therefore, it was considered that the characteristic values could be determined by using the Weibull distribution for the parametric method. Weibull's weakest link theory assumes that the probability of defects in a larger body increases and the likelihood of brittle failure at low stress is higher [16].



(a) Knot (left: bending, right: tension)



(b) Grain angle (left: bending, right: tension)

Figure 3. Failure modes in tests.

To obtain statistically significant results, machine grades having a high number of repetitions were analyzed for tensile and bending allowable properties. The machine grades used to determine allowable bending strength (MOR) for Yellow poplar were E8, E9, and E10. For allowable tensile strength, the machine grades of E10, E11, and E12 were used.

The 5th percentile values of MOR for E8, E9, and E10 were 17.8, 27.5, and 33.4 MPa, when the values were calculated by the parametric method. On the other hand, the 5th percentile values of MOR were 12.3, 22.9, and 26.6 MPa in the case of the non-parametric method in the same order. As shown in Fig. 4, the values by the non-parametric method were lower than those by the parametric method under a cumulative frequency of 0.2.

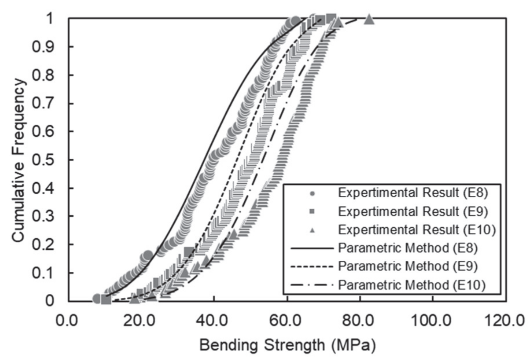


Figure 4. Cumulative distribution of experimental value and value from parametric method in MOR according to machine grades.

Table 2 presents the results of the allowable MOR for Yellow poplar lumber. The allowable MORs were determined by multiplying the 5th percentile values by 0.475. The final allowable MORs of Yellow poplar in E8, E9, and E10 were 5.8, 10.9, and 12.6 MPa, respectively. The allowable MOR of E8 was lower than in the literature when the allowable values for each machine grade were compared with KS F 3020.

Table 2: Allowable MOR in Various Grades (Unit: MPa)

Grade	Parametric	Non[a]	KS F 3020
E8	8.5	5.8	8.2
E9	13.1	10.9	9.0
E10	15.9	12.6	10.0

[a] Non-parametic method

The 5th percentile values of tensile strength for E10, E11, and E12 were 12.7, 19.6, and 27.2 MPa in the parametric method. In the cases of the non-parametric method, the 5th percentile values of tensile strength were 12.8, 17.1, and 23.7 MPa in the same order. Without machine grade of E10, the values calculated by using the non-parametric method lower than those by the parametric method. It was consistence with the result of the 5th percentile values of MOR. Ravenshorts(2015) also reported a consistent result about differences according to calculating methods. Fig. 5 shows the cumulative distribution of tensile test results and results calculated by using the parametric method.

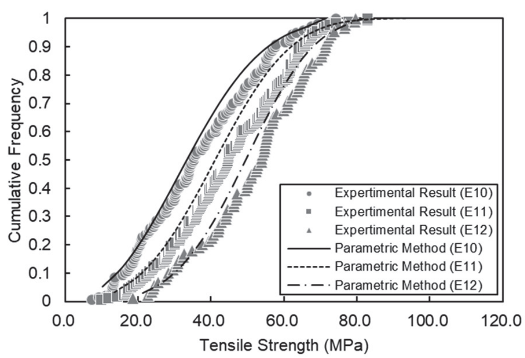


Figure 5. Tensile strength cumulative distribution of experimental value and value from parametric method in various grades.

Results of the allowable tensile strength are listed in Table 3. The final allowable tensile strengths of Yellow poplar in E10, E11, and E12 were 6.0, 8.1, and 11.3 MPa, and all the strengths were higher than the literature, KS F 3020.

Table 3: Allowable Tensile Strength in Various Grades (Unit: MPa)

Grade	Parametric	Non[a]	KS F 3020
E10	6.0	6.1	6.0
E11	9.3	8.1	7.4
E12	12.9	11.3	8.2

[a] Non-parametic method

3.3 CHANGE OF ALLOWABLE MOR WITH LIMIT OF KNOT DIAMETER RATIO

Test results about the allowable properties of Yellow poplar must be higher than the literature, KS F 3020, to use structural purposes. However, allowable MOR of E8 from the bending test was lower than the literature. Therefore, it was needed to the characteristic value of MOR was revised by restricting the diameter ratio of the knots in the wide side of the lumber. Hong *et al.* (2015) [17] reported that reasonable grading might be possible if limiting criterial for major strength reduction defects, such as knots and grain angle, were considered in addition to the machine grading.

The changes in the number of lumbers according to the limitation of knot diameter ratio are shown in Fig. 6. The number of E8 grade lumbers with knot diameter ratios of less than 75%, 50%, and 25% were 99, 75, and 29. In the relatively higher grade, the elimination percentage according to the knot diameter ratio limitation was lower.

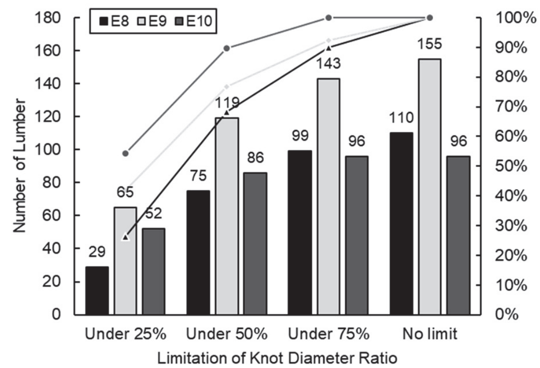


Figure 6. Number of lumber and percentage according to limitation of knot diameter ratio and grades.

Table 4 and Fig. 7 show the changes in allowable MOR of E8 depending on the limit of the knot diameter ratio. The allowable MORs increased as a limitation of the knot diameter ratio was exceeded. The allowable MORs of lumber with knot diameter ratio limits of less than 75%, 50%, and 25% were 9.1, 11.7, and 16.7 MPa, derived using the parametric method. The allowable MORs according to the knot diameter ratio limits were determined as 6.3, 8.8, and 14.5 MPa using the non-parametric method. It was confirmed that the knot diameter ratio limit of less than 75% was not appropriate because the allowable MOR of E8 grade was lower than the literature value of 8.2 MPa.

Table 4: Allowable MOR of E8 Grade in Various Limitation of Knot Diameter Ratio

Type	Allowable MOR (MPa)			KS F 3020
	< 25%	< 50%	< 75%	
Parametric	16.7	11.7	9.1	8.2
Non[a]	14.5	8.8	6.3	

[a] Non-parametic method

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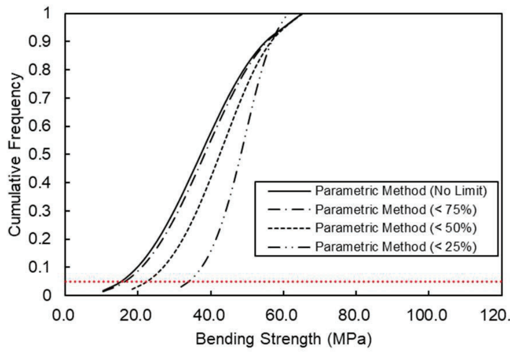

Figure 7. Change of 5th percentile value according to limitation of knot diameter ratio in E8 grade.

It was considered that Yellow poplar could be used safely as structural lumber using the 50% limitation of knot diameter ratio. The allowable MOR was higher than the literature value in that case. When the knot diameter ratio limit was less than 50%, the allowable MOR derived using the non-parametric method increased by 3 MPa compared with the case having no limitation of the knot diameter ratio. It was judged that the knot diameter ratio limit of 50% might be reasonable considering the comprehensive comparison of the acceptable number of lumbers and the tolerance of allowable MOR.

4 – CONCLUSION

It was confirmed that the feasibility of Yellow poplar as a structural material conducting a review of the allowable properties of strength according to machine grades. The machine grading rule was not established for hardwood, but it was considered that the grading rule for softwood could be applied to Yellow poplar with a limitation of the knot diameter ratio of 50%. Machine-graded Yellow poplar had better structural properties than those in the literature. In further studies, the adhesive properties for the manufacture of engineered wood and connection properties concerning fastener types will be evaluated.

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