Analysis of the Relationship between Specific Gravity, Average Annual Ring Width, and Mechanical Properties in Major Conifers in Korea

Kug-Bo Shim [a], Min-Soon Park [b], Chul-Ki Kim [c], Yonggun Park [c], and Hyun Mi Lee [c,*]

This study investigated the relationships between air-dry specific gravity, average annual ring width, and mechanical properties, including bending strength, compressive strength, and shear strength, in seven major coniferous species in Korea: *Pinus densiflora*, *Pinus koraiensis*, *Larix kaempferi*, *Pinus rigida*, *Pinus rigida* × *taeda*, *Chamaecyparis obtusa*, and *Cryptomeria japonica*. Specimens were tested according to KS standards, and correlation and regression analyses were conducted for each species. The results showed that air-dry specific gravity had significant positive correlations with mechanical strength in most species, indicating that it is the most reliable predictor of strength. In particular, *Larix kaempferi*, *Pinus rigida*, and *Pinus rigida* × *taeda* exhibited relatively clear positive correlations with bending, compressive, and shear strengths, confirming that air-dry specific gravity serves as a key indicator for explaining the strength properties of these species. Average annual ring width generally showed negative correlations with bending and compressive strengths; however, the statistical significance varied depending on species and growth region. Therefore, for analyzing the mechanical properties of domestic coniferous wood, air-dry specific gravity should be used as the primary predictive factor, while average annual ring width and species-specific wood characteristics should also be considered.

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Contact information: a: Department of Wood and Paper Science, College of Agriculture, Life and Environment Science, Chungbuk National University, 1, Chungdae-ro, Seowon-gu, Chengju-si, Chungcheongbuk-do 28644, Korea; b: Department of Forest Product, College of Agriculture, Life and Environment Science, Chungbuk National University, 1, Chungdae-ro, Seowon-gu, Chengju-si, Chungcheongbuk-do 28644, Korea; c: Division of Wood Engineering, Forest Products and Industry Department, National Institute of Forest Science, Seoul 02455, Republic of Korea;
** Corresponding author: leehm2986@korea.kr*

INTRODUCTION

Wood is one of the most established natural materials that has been used for a long time in various fields including architecture, civil engineering, and furniture manufacturing. In recent years, its importance has been further emphasized from the perspectives of environmental friendliness and sustainability (Goldhahn *et al.* 2021; Lestari and Ikaputra 2024). In particular, as the transition toward a carbon-neutral society accelerates, wood has gained increasing attention as a sustainable construction material due to its carbon storage capacity and relatively low energy consumption during production (Falk 2021; Gu *et al.* 2021). Against this background, the demand for timber structures has

expanded, and the need for research to simultaneously ensure structural safety and efficient resource utilization has increased (Huang *et al.* 2025). Therefore, developing property-based models that quantitatively describe and predict the mechanical properties of wood is an important task from both academic and industrial perspectives (Wang *et al.* 2024).

The mechanical strength of wood is influenced not only by species-specific characteristics but also by various factors such as growth conditions, anatomical structure, moisture content, and loading direction (Schimleck *et al.* 2018; Arriaga *et al.* 2023). Among these factors, density and average annual ring width have been widely used as key indicators to explain the strength properties of wood (Romagnoli *et al.* 2014; Dahlen *et al.* 2018). Air-dry density reflects the amount of cell wall material and porosity and thus shows a strong correlation with overall mechanical properties. Average annual ring width is related to growth rate and structural characteristics such as the proportion of earlywood and latewood and cell wall thickness, which contribute to variations in mechanical strength (Miyoshi *et al.* 2018; Wang *et al*. 2022; Ahmad *et al.* 2023). In general, wood with a higher latewood proportion and narrower annual rings tends to exhibit superior strength properties due to a higher cell wall content (Wang *et al.* 2022).

Although numerous studies have investigated the relationships between these physical properties and mechanical strength, most have been limited to specific species or restricted environmental conditions, which constrains the generalization of the results (Park *et al.* 2024). Moreover, compared with studies focusing on exotic species, systematic comparative research on major Korean coniferous species remains relatively scarce. Given that coniferous species account for a large proportion of domestic forest resources in Korea, clarifying the interrelationships among specific gravity, annual ring width, and strength with respect to forest management practices and growth conditions can provide practical contributions to resource management and structural timber selection (Shim *et al.* 2025).

This study investigated seven representative Korean coniferous species—*Pinus densiflora*, *Larix kaempferi*, *Pinus koraiensis*, *Pinus rigida*, *Pinus rigida* × *taeda*, *Chamaecyparis obtusa*, and *Cryptomeria japonica*. Air-dry specific gravity and average annual ring width were measured, and their relationships with bending strength, shear strength, and compressive strength were comprehensively analyzed.

EXPERIMENTAL

Wood Species for Testing

Among tree species growing in Korean forests, seven coniferous species with high standing volume or high potential for timber utilization were selected for this study. The selected species were *Pinus densiflora*, *Pinus koraiensis*, *Larix kaempferi*, *Pinus rigida*, *Pinus rigida* × *taeda*, *Chamaecyparis obtusa*, and *Cryptomeria japonica*. The origins and average growth year of the selected species are summarized in Table 1.

Bending Strength

Bending strength tests were conducted in accordance with KS F 2208 (2025). Clear and straight-grained specimens were prepared with dimensions of 20 mm in the tangential direction, 20 mm in the radial direction, and 300 mm in the longitudinal direction. Prior to testing, specimen dimensions were measured and recorded to the nearest 0.01 mm using a vernier caliper.

Table 1. Information on Habitats and Average Ages of Selected Wood Species

Generic Name	Scientific Name	Location	Commercial Forest tType	Average Years
Korean red pine	*Pinus densiflora* Siebold & Zucc.	San 80-1, Jinjo-ri, Bongpyeong-myeon, Pyeongchang-gun, Gangwon-do	National forest	42
		San 37-1, Seobu-ri, Yeongyang-eup, Yeongyang-gun, Gyeongsangbuk-do	National forest	32
Korean pine	*Pinus koraiensis* Siebold & Zucc.	San 1, Baegam-ri, Baegun-myeon, Jinan-gun, Jeollabuk-do	National forest	37
Japanese larch	*Larix kaempferi* (Lamb.) Carriere	San 80-1, Guhak-ri, Bongyang-eup, Jecheon-si, Chungcheongbuk-do	Private forest	41
Pitch pine	*Pinus rigida* Mill.	San 87, Yeongdong-ri, Maryang-myeon, Gangjin-gun, Jeollanam-do	Public forest	39
Rigitaeda pine	*Pinus rigida* Mill. *x P. taeda* L.	San 12, Handae-ri, Yeongam-eup, Yeongam-gun, Jeollanam-do	National forest	24
Japanese false cypress	*Chamaecyparis obtusa* (Siebold & Zucc.) Endl.	San 96, Jang'an-ri, Songgwang-myeon, Suncheon-si, Jeollanam-do	Private forest	51
Japanese cedar	*Cryptomeria japonica* (Thunb. ex L.f.) D.Don	San 5-2, San 2-1, Hannam-ri, Namwon-eup, Seogwipo-si, Jeju-do	National forest	37

All specimens were conditioned in a constant temperature and humidity chamber (TS-AZN-15, Tae Kwang Eng. & Service Co., Korea) at 20 °C and 65% relative humidity, corresponding to a target equilibrium moisture content of approximately 12%, until a constant mass was reached. The air-dry specific gravity was determined at this moisture condition. The tests were conducted in accordance with KS F 2201, General requirements for testing of wood, at temperatures ranging from 20 to 25 °C and relative humidity 60 %. A universal testing machine with a maximum capacity of 20 kN was used, and a three-point bending configuration with a span of 280 mm was applied. The load was applied in the radial direction from bark to pith. The loading rate was set to occur failure within 5 min.

After testing, small specimens measuring 20 mm × 20 mm × 20 mm in the tangential, radial, and longitudinal directions were prepared at a location 20 mm away from the failure point to determine moisture content, specific gravity, and average annual ring width. Dimensions were measured to the nearest 0.01 mm and weight to the nearest 0.01 g. Oven-dry weight was determined after drying at 103 ± 2 °C until constant weight was achieved. The moisture content was recorded. Air-dry specific gravity and bending strength were calculated follows,

$$Air\ -\ dry\ Specific\ gravity = \frac{w_0}{b \times h \times l \times \rho_w} \times 1000 \quad (1)$$

$$Bending\ strength(MPa) = \frac{3 \times P_{max} \times l_s}{2 \times b \times h^2} \quad (2)$$

where b is tangential length (mm), h is radial length (mm), l is longitudinal length (mm), ρ_w is density of water, w_0 is oven-dry weight (g), l_s is Span length (mm), and P_{max} is maximum load (N). The average annual ring width was measured in accordance with KS F 2202, as illustrated in Fig. 2.

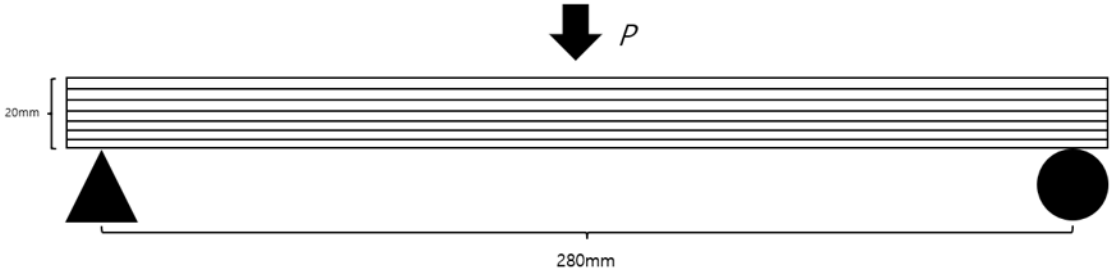
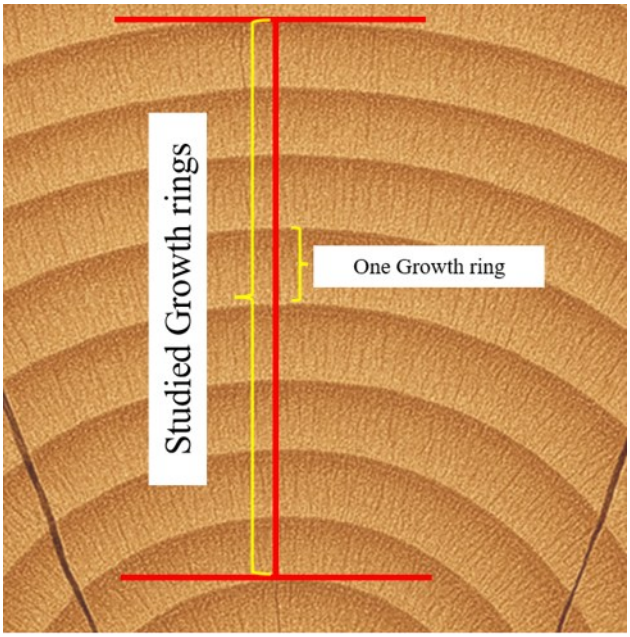


Fig. 1. Schematic diagram of bending test



Total length/Number of measured rings

Fig. 2. Measurement of the number of growth rings

Compressive Strength

Compressive strength tests were performed in accordance with KS F 2206 (Method of compression test for wood). Specimens with dimensions of 20 mm (tangential) × 20 mm (radial) × 60 mm (longitudinal) were prepared, ensuring that at least five annual rings were included in the cross section. Specimen dimensions were measured to the nearest 0.01 mm prior to testing.

Specimens were conditioned at 20 °C and 65% relative humidity until equilibrium moisture content or constant mass was reached. The tests were conducted at temperatures of 20 to 25 °C and relative humidity of 60%. Compression tests were carried out using a universal testing machine with a maximum capacity of 20 kN, maintaining a constant loading rate. Loads were applied using loading blocks larger than the specimen cross section.

For compression parallel to the grain, the loading rate was set to bring about failure within 5 min. After testing, specimens were oven-dried at 103 ± 2 °C until constant weight was reached to determine oven-dry weight, from which specific gravity was calculated (Eq. 1). Average annual ring width was measured following the method illustrated in Fig. 2. Compressive strength was calculated as follows,

$$Compressive\ strength(MPa) = \frac{P_{max}}{b \times h} \quad (3)$$

where b is tangential length (mm), h is radial length (mm), and P_{max} is maximum load (N).

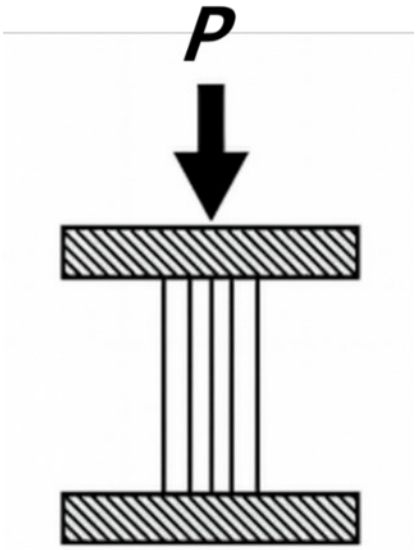


Fig. 3. Schematic diagram of compressive strength test

Shear Strength

Shear strength tests were conducted in accordance with KS F 2209 (2025). Specimens with dimensions of 50 mm (tangential) × 50 mm (radial) × 60 mm (longitudinal) were prepared to make shear plane of tangential cross section with 50 mm × 50 mm. Only clear specimens without knots or grain deviation were used. Dimensions were measured to the nearest 0.01 mm prior to testing.

Specimens were conditioned at 20 °C and 65% relative humidity until equilibrium moisture content or constant weight was achieved. Tests were performed under environmental conditions of 20 to 25 °C and 60% relative humidity. A universal testing machine with a maximum capacity of 20 kN was used, and displacement and load data were simultaneously recorded at a frequency of at least 10 Hz while maintaining a constant loading rate.

Shear tests were conducted at a location 3 mm away from the end face of the support fixture. The loading rate was set to occur failure within 5 min. After testing, small specimens measuring 50 mm (tangential) × 20 mm (radial) × 60 mm (longitudinal) were prepared at a location 10 mm away from the failure point to measure moisture content and specific gravity (Eq. 1). Dimensions and weight were measured to the nearest 0.01 mm and 0.01 g, respectively. Oven-dry weight was determined after drying at 103 ± 2 °C until constant weight, and average annual ring width was measured as shown in Fig. 2. Shear strength was calculated as follows,

$$Shear\ strength(MPa) = \frac{P_{max}}{b \times l_s} \quad (4)$$

where b is tangential length (mm), l_s is shear length along the fiber direction (mm), and P_{max} is maximum load (N).

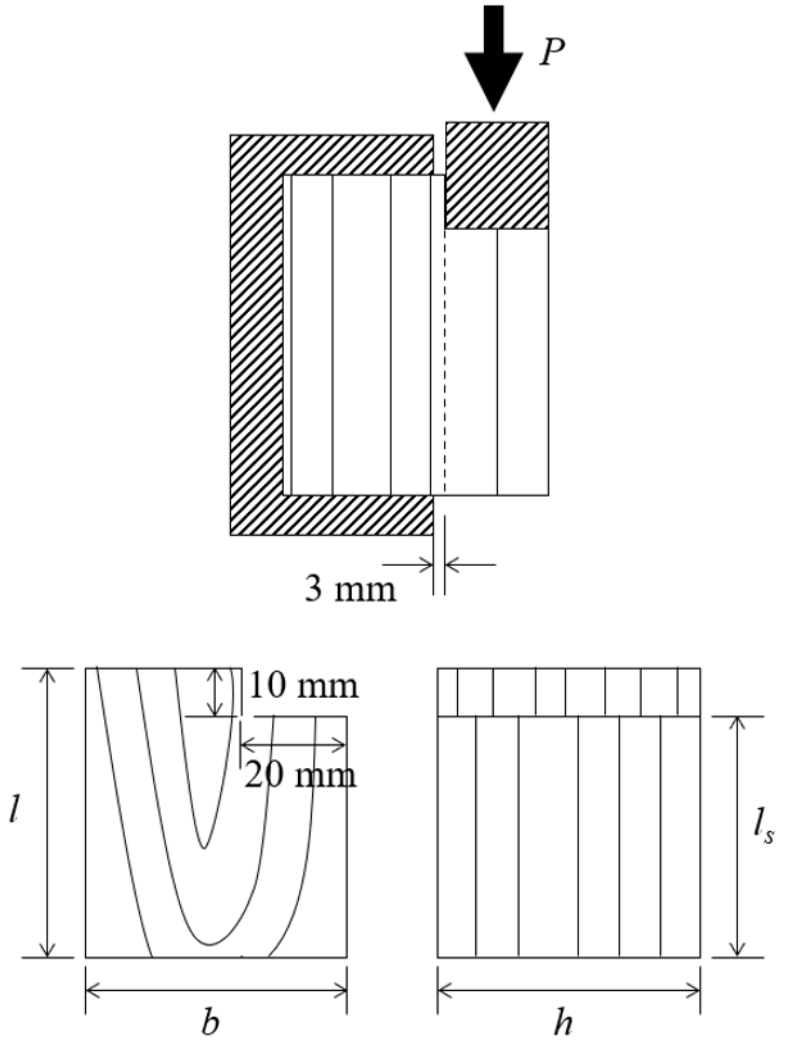


Fig. 4. Schematic diagram of shear strength test

Correlation Analysis

Statistical analyses of the relationships between air-dry specific gravity, average annual ring width, and mechanical properties (bending strength, compressive strength, and shear strength) were performed using SPSS Statistics software. Air-dry specific gravity and average annual ring width were used as independent variables, while bending strength, compressive strength, and shear strength were used as dependent variables.

Pearson's correlation coefficient was applied to evaluate the strength of linear relationships, and statistical significance was assessed at a significance level of 0.05. Linear regression analysis was performed using the SPSS linear regression module. Residual analysis and diagnostic statistics were enabled to evaluate model adequacy, with the significance level set at 0.05.

RESULTS AND DISCUSSION

Correlation Analysis between Bending Strength and Specific Gravity, Average Annual Ring Width

The number of specimens, average annual ring width, air-dry specific gravity, and bending strength, together with their means and standard deviations for the coniferous species, are presented in Table 2. The results of correlation and regression analyses between air-dry specific gravity and bending strength are shown in Table 3 and Figs. 5 and 6. The corresponding results for average annual ring width and bending strength are presented in Table 4 and Figs. 7 and 8.

For *Pinus densiflora*, a positive correlation between air-dry specific gravity and bending strength was observed in both Gangwon-do and Gyeongsangbuk-do, and the relationship was statistically significant at the 0.05 significance level. In contrast, a negative correlation was found between average annual ring width and bending strength, but this relationship was not statistically significant. Kim *et al.* (2014) reported a positive correlation between specific gravity and bending strength in *P. densiflora*, while Han *et al.* (2016) observed a significant positive correlation in trees from Sokwang-ri but did not find a statistically significant relationship in those from Anmyeondo. These results suggest that even within the same species, correlations among physical and mechanical properties can vary depending on growth region and environmental conditions.

In *Pinus koraiensis*, air-dry specific gravity showed a positive and statistically significant correlation with bending strength at the 0.05 level. Average annual ring width exhibited a negative correlation with bending strength; however, the relationship was not statistically significant.

For *Larix kaempferi*, air-dry specific gravity was positively correlated with bending strength, while average annual ring width showed a negative correlation. Both relationships were statistically significant at the 0.05 level. Tumenjargal *et al.* (2019) reported a positive correlation between density and bending strength in two out of three regions examined, and Wang *et al.* (2022) reported a positive correlation between air-dry density and bending strength as well as a negative correlation between average annual ring width and bending strength. Kim *et al.* (2021) also observed similar trends in *Larix gmelinii*, a species closely related to *L. kaempferi*. The results of the present study were consistent with these previous findings.

Table 2. Average Annual Ring Width, Air-Dry Specific Gravity and Bending Strength of Tested Species

Species	Number of Specimens	Average Annual Ring Width (mm)	Air Dry Specific Gravity	Bending Strength (MPa)
Korean red pine (Gangwon-do)	15	5.09 (1.04)	0.39 (0.03)	63.50 (4.74)
Korean red pine (Gyeongsangbuk-do)	20	3.12 (0.54)	0.42 (0.04)	65.57 (10.98)
Korean pine	25	5.44 (1.15)	0.42 (0.03)	68.03 (7.89)
Japanese larch	22	5.89 (1.46)	0.45 (0.06)	82.40 (16.03)
Pitch pine	20	4.94 (1.16)	0.42 (0.05)	83.91 (14.63)
Rigitaeda pine	20	4.65 (1.06)	0.47 (0.06)	83.80 (15.76)
Japanese false cypress	10	3.86 (1.71)	0.37 (0.03)	72.49 (10.57)
Japanese cedar	30	5.35 (1.74)	0.34 (0.04)	50.30 (11.79)

() standard deviation

Table 3. Correlation and Regression Analysis Between Air-dry Specific Gravity and Bending Strength by Species

Species	Pearsons' r	p-value	R^2	Eq.
Korean red pine (Gangwon-do)	0.525	0.044	0.276	y = 90.7x + 32.043
Korean red pine (Gyeongsangbuk-do)	0.799	0.001	0.638	Y=244.127x - 36.843
Korean pine	0.406	0.044	0.165	y = 104.77x + 29.34
Japanese larch	0.798	0.001	0.637	y = 207.71x - 10.05
Pitch pine	0.608	0.004	0.370	Y=165.21x + 2.495
Rigitaeda pine	0.907	0.001	0.822	Y=241.828x - 29.856
Japanese false cypress	0.165	0.648	0.027	y = 52.448x + 55.18
Japanese cedar	0.256	0.172	0.066	Y=56.334x + 23.647
Pooled data of all species	0.784	0.001	0.615	Y=231.506x-26.171

Table 4. Correlation and Regression Analysis Between Average Annual Ring Width and Bending Strength by Species

Species	Pearsons' r	p-value	R^2	Eq.
Korean red pine (Gangwon-do)	-0.243	0.382	0.059	Y=-1.113x+69.165
Korean red pine (Gyeongsangbuk-do)	-0.010	0.968	0.0001	Y=-0.197x+66.182
Korean pine	-0.327	0.110	0.107	Y=-2.254x+80.289
Japanese larch	-0.583	0.007	0.340	Y=-7.354x+120.254
Pitch pine	-0.345	0.137	0.119	Y=-5.131x+107.657
Rigitaeda pine	-0.289	0.181	0.084	Y=-3.176x+101.109
Japanese false cypress	0.251	0.180	0.063	Y=1.705x+41.166
Japanese cedar	0.053	0.885	0.003	Y=0.325x+71.229
Pooled data of all species	-0.080	0.313	0.006	Y=-0.900x+74.657

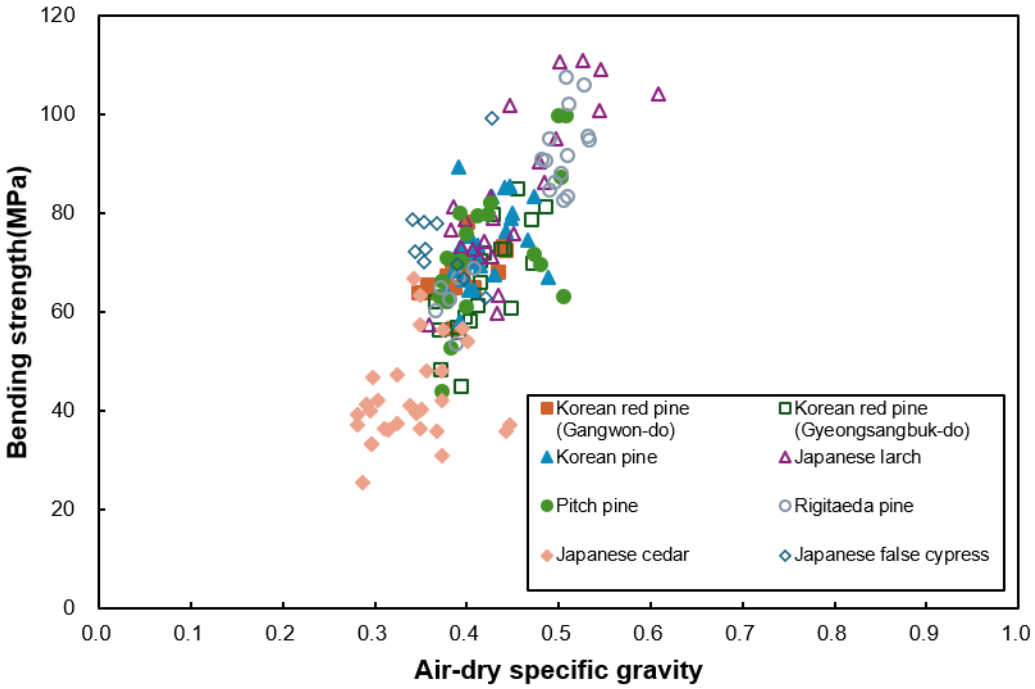


Fig. 5. Relationship between bending strength and air-dry specific gravity by species

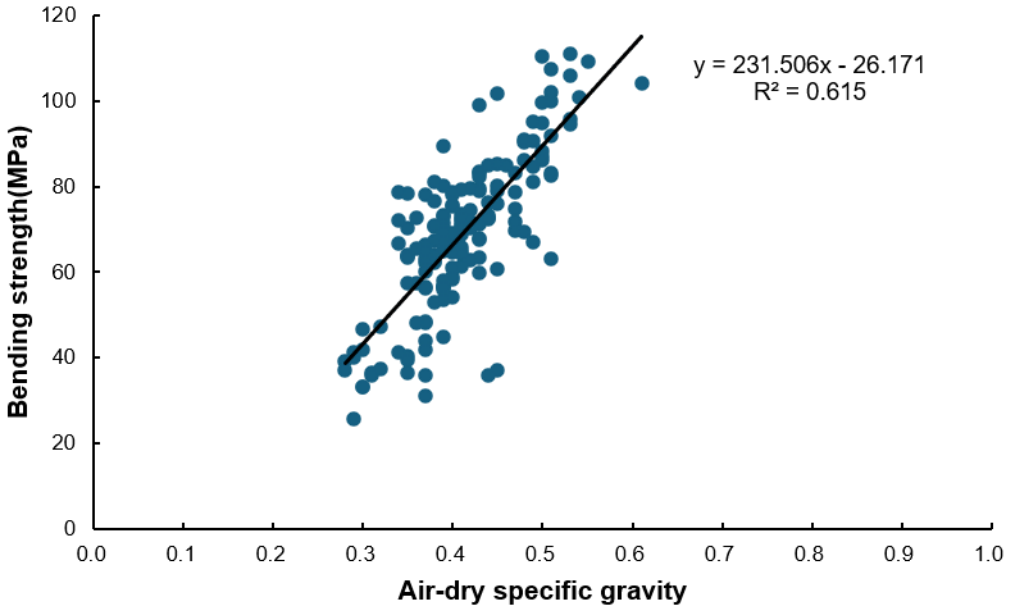


Fig. 6. Relationship between bending strength and air-dry specific gravity pooled data of all species

For *Pinus rigida*, a positive correlation between air-dry specific gravity and bending strength was observed and found to be statistically significant at the 0.05 level. Although a negative correlation was observed between average annual ring width and bending strength, this relationship was not statistically significant. Lim *et al.* (2011) reported that bending strength increased with increasing density in *P. rigida*, and Esteban *et al.* (2020) also reported a positive correlation between density and bending strength, as

well as higher bending strength associated with narrower annual rings.

Similarly, *Pinus rigida* × *taeda* showed a positive and statistically significant correlation between air-dry specific gravity and bending strength at the 0.05 level. Average annual ring width exhibited a negative correlation with bending strength, but the relationship was not statistically significant. Amateis *et al.* (2013) and Pradhan *et al.* (2024) reported significant positive correlations between density and bending strength in *Pinus taeda*, which is consistent with the density–strength relationship observed in this study.

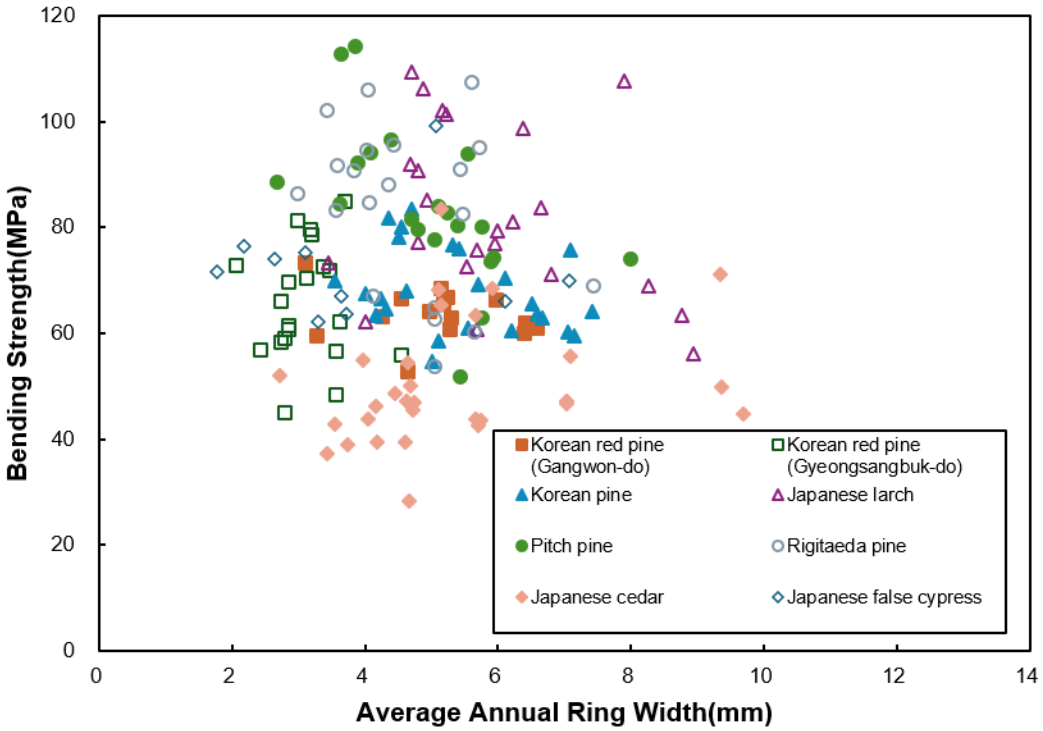


Fig. 7. Relationship between bending strength and average annual ring width by species

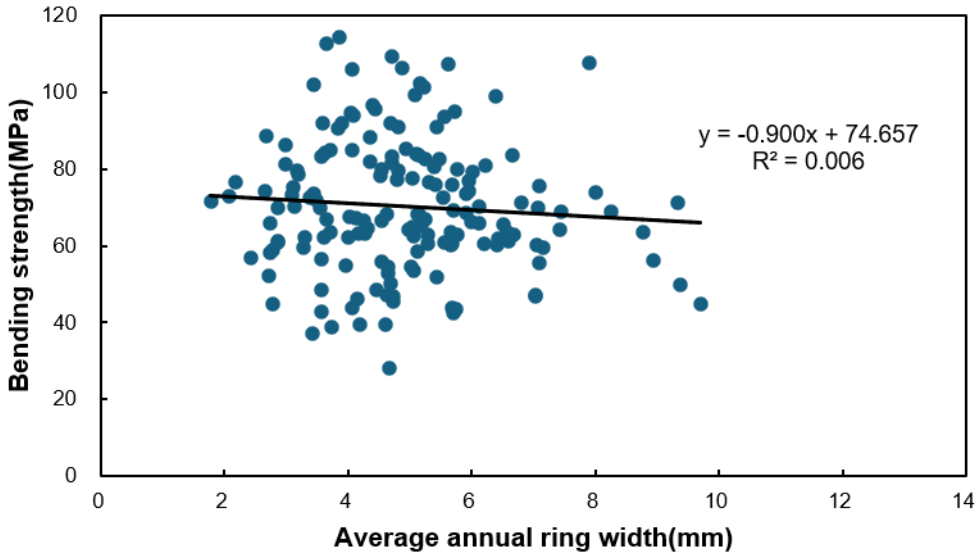


Fig. 8. Relationship between bending strength and average annual ring width pooled data of all species

In *Chamaecyparis obtusa*, a positive correlation was observed between air-dry specific gravity and bending strength, but the relationship was not statistically significant at the 0.05 level. Average annual ring width also showed a positive correlation with bending strength, which was likewise not statistically significant. Takahashi *et al.* (2022) reported a significant positive correlation between air-dry density and bending strength in *C. obtusa*, while no significant correlation was found between average annual ring width and bending strength. In addition, Khider (2013) and Ng'ang'a (1992) reported positive correlations between density and bending strength in cypress species from Mexico and East Africa, respectively. For *Cryptomeria japonica*, both air-dry specific gravity and average annual ring width exhibited positive correlations with bending strength; however, neither relationship was statistically significant at the 0.05 level. Wang and Ko (1998) reported that narrower annual rings tended to be associated with higher density and bending strength, and Zhu *et al.* (2005) found positive correlations between density and bending strength in both juvenile and mature wood. They also reported that, as wood matures, annual ring width decreases while density and strength increase.

The correlation and regression analyses conducted in this study generally confirmed the established trends that higher air-dry specific gravity is associated with greater bending strength, whereas greater average annual ring width is associated with lower bending strength across multiple species. However, these relationships were not statistically significant in some species and regions.

Correlation Analysis between Compressive Strength and Specific Gravity and Average Annual Ring Width

The number of specimens, average annual ring width, air-dry specific gravity, and compressive strength, together with their means and standard deviations for the coniferous species, are presented in Table 5. The results of correlation and regression analyses between air-dry specific gravity and compressive strength are shown in Table 6 and Figs. 9 and 10, while those between average annual ring width and compressive strength are presented in Table 6 and Figs. 11 and 12.

For *Pinus densiflora*, both groups from Gangwon-do and Gyeongsangbuk-do exhibited a positive correlation between air-dry specific gravity and compressive strength and a negative correlation between average annual ring width and compressive strength. Both relationships were statistically significant at the 0.05 significance level. These findings are consistent with those reported by Kim and Kim (2013), who also observed a positive correlation between density and compressive strength and a negative correlation between annual ring width and compressive strength in *P. densiflora*. In *Pinus koraiensis*, air-dry specific gravity showed a positive and statistically significant correlation with compressive strength at the 0.05 level. Average annual ring width exhibited a positive correlation with compressive strength; this relationship was not statistically significant.

For *Larix kaempferi*, a positive correlation was observed between air-dry specific gravity and compressive strength, which was statistically significant at the 0.05 level. A negative correlation was observed between average annual ring width and compressive strength, but this relationship was not statistically significant. Ishikura *et al.* (2012) reported that compressive strength increased with increasing density and decreasing annual ring width.

Table 5. Average Annual Ring Width, Air-Dry Specific Gravity and Compressive Strength of Tested Coniferous Species

Species	Number of Specimens	Average Annual Ring Width (mm)	Air Dry Specific Gravity	Compressive Strength (MPa)
Korean red pine (Gangwon-do)	20	6.48 (0.85)	0.40 (0.03)	26.82 (1.50)
Korean red pine (Gyeongsangbuk-do)	20	3.19 (0.61)	0.40 (0.03)	30.59 (4.58)
Korean pine	25	5.54 (0.95)	0.41 (0.03)	33.43 (4.14)
Japanese larch	30	5.30 (0.60)	0.54 (0.09)	42.20 (6.94)
Pitch pine	21	3.60 (0.98)	0.48 (0.04)	42.80 (6.10)
Rigitaeda pine	20	6.97 (1.21)	0.45 (0.04)	26.36 (2.21)
Japanese false cypress	28	4.77 (1.12)	0.44 (0.03)	43.26 (2.76)
Japanese cedar	26	7.04 (2.08)	0.35 (0.02)	25.22 (1.77)

Table 6. Correlation and Regression Analysis Between Air-dry Specific Gravity and Compressive Strength by Species

Species	Pearsons' r	p-value	R^2	Eq.
Korean red pine (Gangwon-do)	0.738	0.001	0.544	Y = 40.895x + 10.496
Korean red pine (Gyeongsangbuk-do)	0.784	0.001	0.615	Y = 115.821x - 16.197
Korean pine	0.873	0.001	0.761	Y = 134.346x – 22.140
Japanese larch	0.709	0.001	0.502	Y = 53.590x + 17.351
Pitch pine	0.653	0.001	0.426	Y = 108.635x – 8.822
Rigitaeda pine	-0.086	0.717	0.0007	Y = -4.960x + 28.590
Japanese false cypress	0.568	0.002	0.322	Y = 57.515x + 18.181
Japanese cedar	0.065	0.746	0.004	Y = 5.663x + 23.270
Pooled data of all species	0.735	0.001	0.540	Y=92.888x-5.386

Table 7. Correlation and Regression Analysis Between Average Annual Ring Width and Compressive Strength by Species

Species	Pearsons' r	p-value	R^2	Eq.
Korean red pine (Gangwon-do)	-0.462	0.040	0.213	Y=-0.817x+32.118
Korean red pine (Gyeongsangbuk-do)	-0.623	0.003	0.388	Y=-4.699x+45.607
Korean pine	0.165	0.431	0.027	Y=0.720x+29.438
Japanese larch	-0.286	0.082	0.126	Y=-3.288x+63.626
Pitch pine	0.018	0.940	0.0003	Y=0.109x+42.413
Rigitaeda pine	-0.413	0.070	0.171	Y=-0.754x+31.613
Japanese false cypress	-0.040	0.841	0.002	Y=-0.098x+43.727
Japanese cedar	-0.375	0.054	0.141	Y=-0.320x+27.479
Pooled data of all species	-0.424	0.001	0.180	Y=-2.265x+47.222

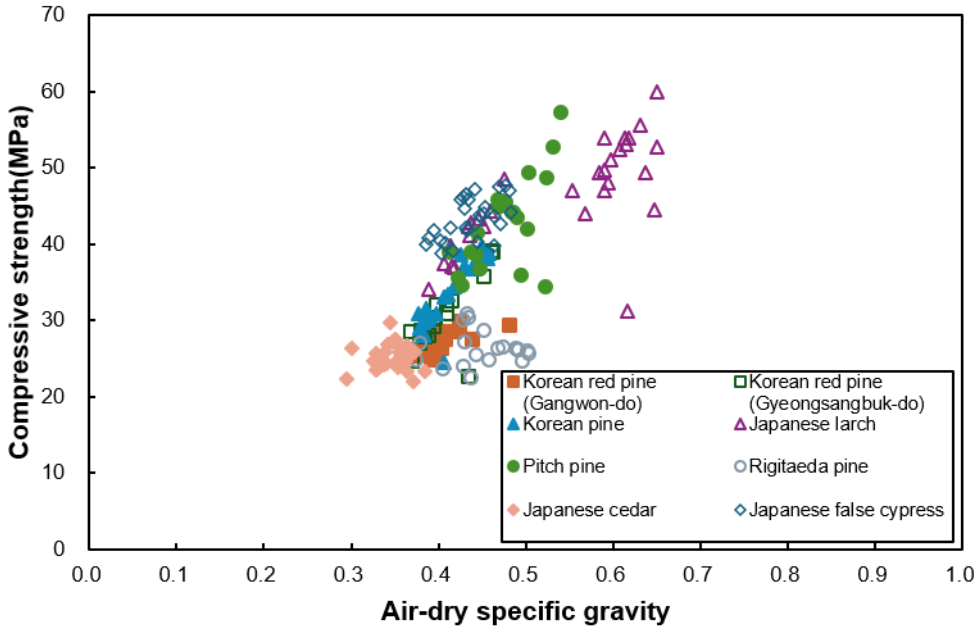


Fig. 9. Relationship between compressive strength and air-dry specific gravity by species

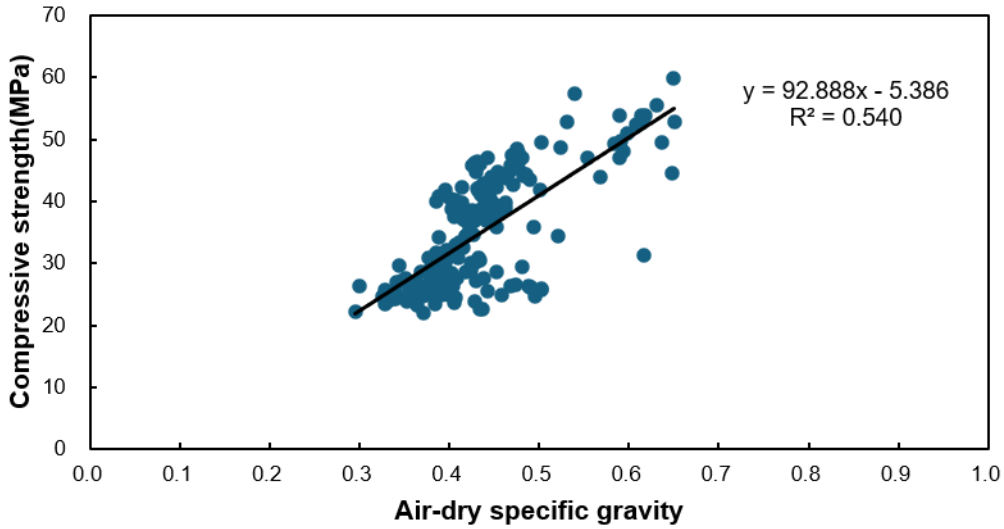


Fig. 10. Relationship between compressive strength and air-dry specific gravity pooled data of all species

Kim *et al.* (2022) also reported that in *Larix gmelinii*, a species closely related to *L. kaempferi*, compressive strength increased with increasing density, while wider annual rings were associated with a lower latewood proportion and reduced compressive strength. Zhang *et al.* (2023) reported a positive correlation between density and compressive strength similarly, supporting the trends observed in the present study.

For *Pinus rigida*, a positive and statistically significant correlation between air-dry specific gravity and compressive strength was observed at the 0.05 significance level. Although average annual ring width exhibited a negative correlation with compressive strength, this relationship was not statistically significant.

In contrast, *Pinus rigida* × *taeda* exhibited a negative correlation between air-dry specific gravity and compressive strength and a positive correlation between average annual ring width and compressive strength; however, neither relationship was statistically significant at the 0.05 level. Previous studies have consistently reported a positive correlation between density and compressive strength in *Pinus taeda*, as supported by Irby *et al.* (2020) and Pradhan *et al.* (2024). The discrepancy observed in the present study may be attributed to differences in sample characteristics or growth conditions.

For *Chamaecyparis obtusa*, a positive and statistically significant correlation was observed between air-dry specific gravity and compressive strength at the 0.05 level. Average annual ring width showed a negative correlation with compressive strength; however, this relationship was not statistically significant. Similar positive correlations between density and compressive strength have been reported in previous studies on cypress species (Zhu *et al.* 2005; Bektas and Kurt 2010), which is consistent with the trend observed in this study. In *Cryptomeria japonica*, a positive correlation between air-dry specific gravity and compressive strength and a negative correlation between average annual ring width and compressive strength were observed; however, neither relationship was statistically significant at the 0.05 level. Taniuchi (2022) reported a positive correlation between density and partial compressive strength in *C. japonica*, while Wang *et al.* (2008) suggested potential negative relationships among annual ring width, density, and compressive strength in Taiwan and Japanese cedar. These results indicate that regional differences, tree age, and material characteristics may contribute to variability in the observed relationships.

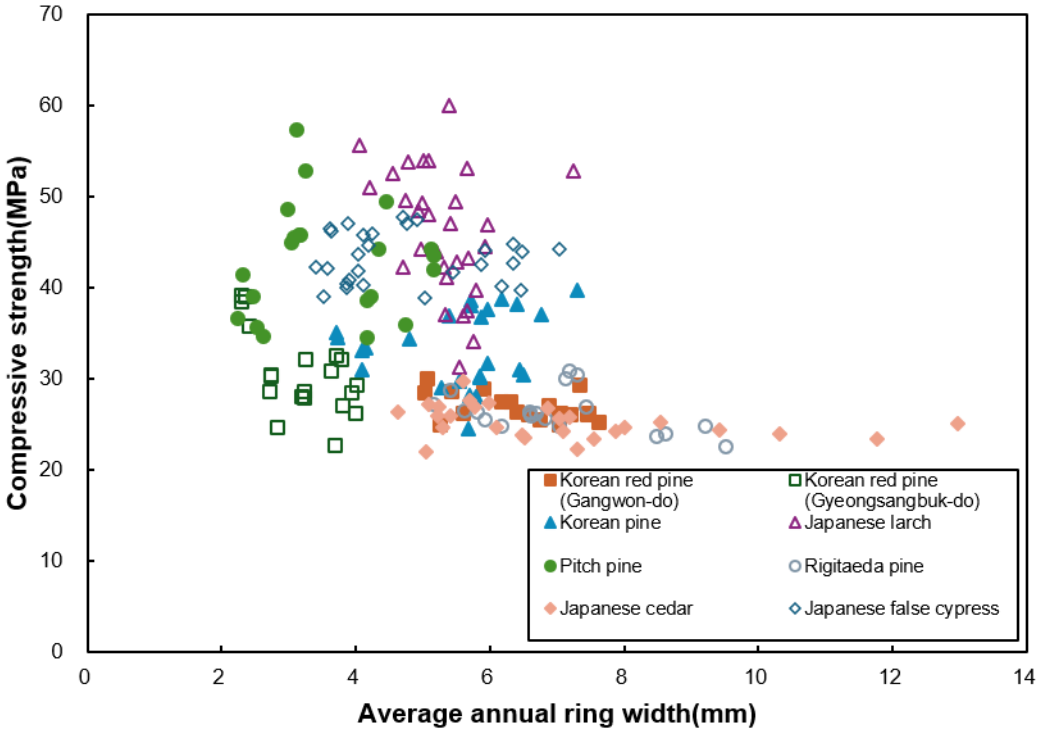


Fig. 11. Relationship between compressive strength and average annual ring width by species

Overall, the regression and correlation analyses in this study generally agree with the classical trend that compressive strength increases with increasing air-dry specific

gravity and decreases with increasing average annual ring width. However, for some species and regions, statistical significance was not achieved.

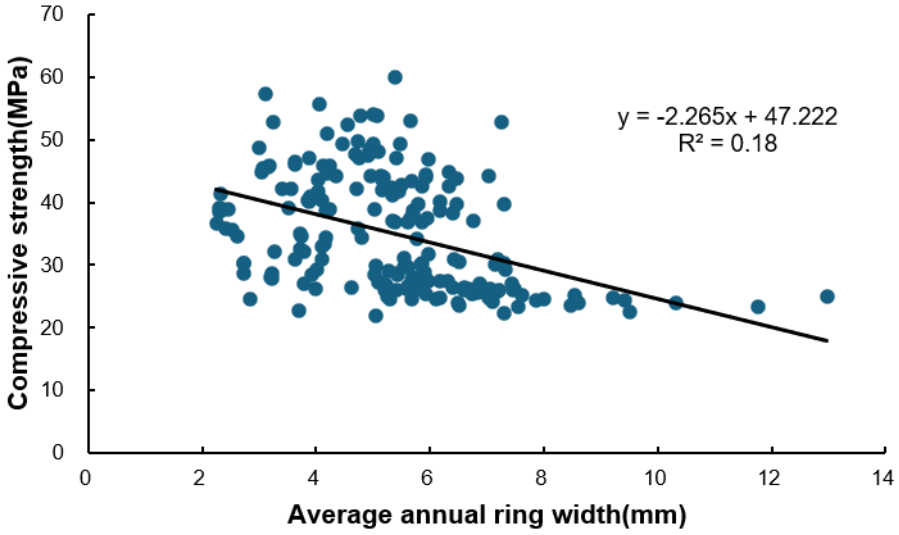


Fig. 12. Relationship between compressive strength and average annual ring width pooled data of all species

Correlation Analysis between Shear Strength and Specific Gravity, Average Annual Ring Width

The number of specimens, average annual ring width, air-dry specific gravity, and shear strength, together with their means and standard deviations for each coniferous species, are presented in Table 8.

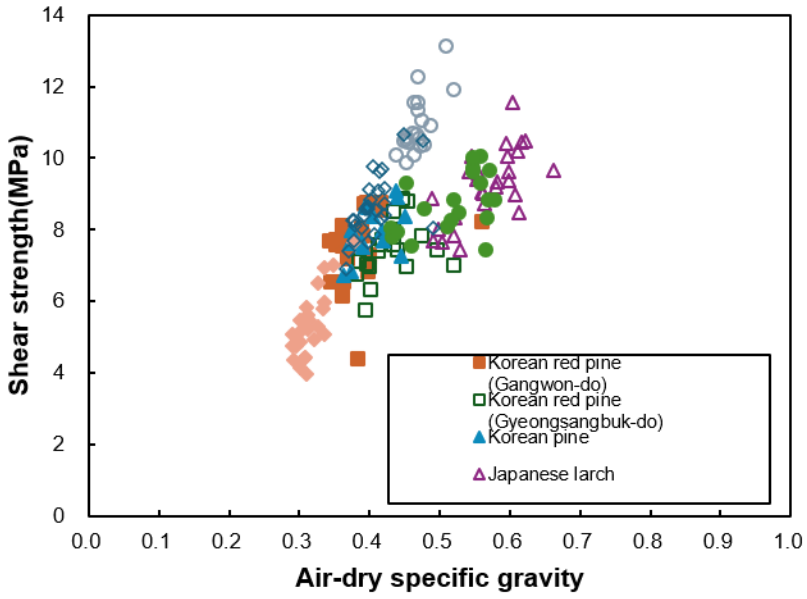


Fig. 13. Relationship between shear strength and air-dry specific gravity by species

Table 8. Average Annual Ring Width, Air-Dry Specific Gravity and Shear Strength of Tested Coniferous Species

Species	Number of Specimens	Average Annual Ring Width (mm)	Air Dry Specific Gravity	Shear Strength (MPa)
Korean red pine (Gangwon-do)	21	4.55 (0.63)	0.39 (0.05)	7.50 (1.03)
Korean red pine (Gyeongsangbuk-do)	20	3.40 (0.85)	0.43 (0.04)	7.46 (0.78)
Korean pine	15	5.00 (0.59)	0.40 (0.03)	7.95 (0.72)
Japanese larch	27	4.90 (1.54)	0.57 (0.05)	9.22 (1.00)
Pitch pine	20	3.86 (0.72)	0.52 (0.05)	8.73 (0.82)
Rigitaeda pine	20	4.73 (0.59)	0.47 (0.02)	10.92 (0.82)
Japanese false cypress	27	4.01 (0.68)	0.41 (0.03)	8.62 (0.88)
Japanese cedar	27	9.08 (1.40)	0.31 (0.02)	5.32 (0.89)

Table 9. Correlation and Regression Analysis Between Air-dry Specific Gravity and Shear Strength by Species

Species	Pearsons'r	p-value	R^2	Eq.
Korean red pine (Gangwon-do)	0.307	0.176	0.094	Y=6.815x+4.869
Korean red pine (Gyeongsangbuk-do)	0.359	0.120	0.129	Y=7.512x+4.225
Korean pine	0.509	0.053	0.259	Y=11.783x+3.194
Japanese larch	0.676	0.001	0.458	Y=14.993x+0.725
Pitch pine	0.488	0.029	0.238	Y=7.622x+4.769
Rigitaeda pine	0.679	0.001	0.461	Y=27.840x-2.136
Japanese false cypress	0.555	0.003	0.308	Y=16.817x+1.776
Japanese cedar	0.787	0.001	0.620	Y=33.063x-5.096
Pooled data of all species	0.695	0.001	0.483	Y=14.269x+1.925

Table 10. Correlation and Regression Analysis Between Average Annual Ring Width and Shear Strength by Species

Species	Pearsons' r	p-value	R^2	Eq.
Korean red pine (Gangwon-do)	0.998	0.001	0.996	Y=1.641x+0.027
Korean red pine (Gyeongsangbuk-do)	0.630	0.003	0.397	Y=0.571x+5.516
Korean pine	-0.111	0.692	0.012	Y=-0.136x+8.633
Japanese larch	0.115	0.567	0.013	Y=0.075x+8.853
Pitch pine	-0.255	0.278	0.065	Y=-0.289x+9.850
Rigitaeda pine	0.354	0.125	0.125	Y=0.495x+8.582
Japanese false cypress	0.069	0.733	0.005	Y=0.044x+4.927
Japanese cedar	0.194	0.332	0.038	Y=0.249x+7.621
Pooled data of all species	-0.463	0.001	0.215	Y=-0.408x+10.229

The results of correlation and regression analyses between air-dry specific gravity and shear strength are shown in Table 9 and Figs. 13 and 14, while those between average annual ring width and shear strength are presented in Table 10 and Figs. 15 and 16.

For *Pinus densiflora*, air-dry specific gravity and shear strength exhibited positive correlations in both surveyed regions; these relationships were not statistically significant at the 0.05 significance level. Average annual ring width showed a positive and statistically significant correlation with shear strength in both regions. These results are generally consistent with previous studies reporting a positive relationship between density and shear strength in *P. densiflora* (Kim *et al.* 2014).

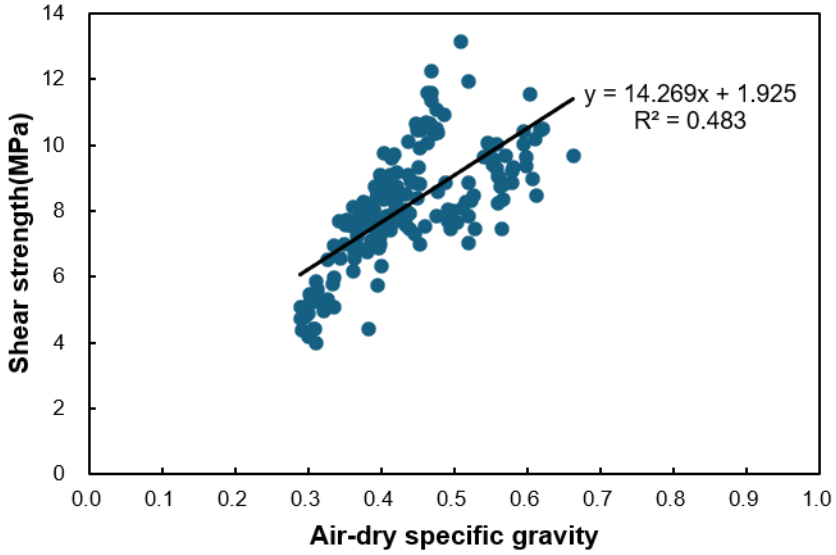


Fig. 14. Relationship between shear strength and air-dry specific gravity pooled data of all species

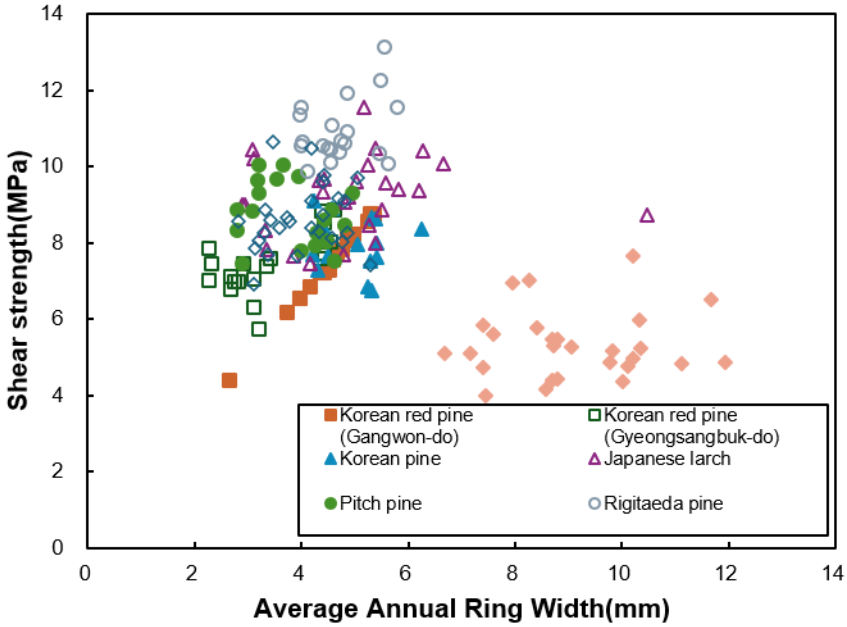


Fig. 15. Relationship between shear strength and average annual ring width by species

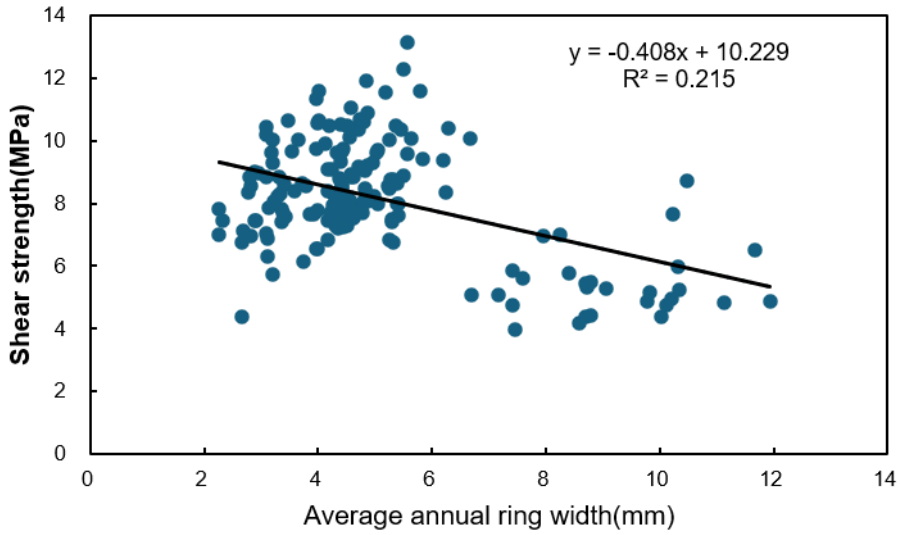


Fig. 16. Relationship between shear strength and average annual ring width pooled data of all species

In *Pinus koraiensis*, air-dry specific gravity showed a positive correlation with shear strength, while average annual ring width showed a negative correlation. However, neither relationship was statistically significant at the 0.05 level.

For *Larix kaempferi*, a positive and statistically significant correlation between air-dry specific gravity and shear strength was observed at the 0.05 level. Average annual ring width exhibited a positive correlation with shear strength, but this relationship was not statistically significant. In European larch (*Larix decidua*), a strong positive correlation between density and shear strength and a tendency for shear strength to decrease with increasing ring width have been reported (Müller *et al.* 2003). Positive correlations between density and shear strength have also been reported for *L. kaempferi* and *Larix gmelinii* (Li *et al.* 2021; Kim *et al.* 2022), with annual ring width showing a negative correlation with latewood proportion and, consequently, with shear strength.

For *Pinus rigida*, air-dry specific gravity showed a positive and statistically significant correlation with shear strength at the 0.05 level. Average annual ring width exhibited a negative correlation with shear strength, but this relationship was not statistically significant.

For *Pinus rigida* × *taeda*, a positive and statistically significant correlation between air-dry specific gravity and shear strength was observed at the 0.05 level. Average annual ring width showed a positive correlation with shear strength, but this relationship was not statistically significant. In *Pinus taeda*, a species closely related to *P. rigida* × *taeda*, a positive correlation between density and shear strength has been reported (Kretschmann 2008).

In *Chamaecyparis obtusa*, air-dry specific gravity exhibited a positive and statistically significant correlation with shear strength at the 0.05 level. Average annual ring width also showed a positive correlation with shear strength, but this relationship was not statistically significant. Similar positive correlations between density and shear strength have been reported for Japanese cypress in previous studies (Ido *et al.* 2012; Yamasuso and Kishimoto 2013).

For *Cryptomeria japonica*, air-dry specific gravity showed a positive and statistically significant correlation with shear strength at the 0.05 level. Average annual

ring width exhibited a positive correlation with shear strength, but this relationship was not statistically significant. Positive correlations between density and shear strength have also been reported for *C. japonica* glulam (Ukyo *et al.* 2010) and solid wood (Yamasuso and Kishimoto 2013).

Overall, the typical trend of increasing shear strength with increasing air-dry specific gravity was reconfirmed for most species. However, in the present dataset, some relationships did not reach statistical significance at the 0.05 level. This may be attributed to confounding factors such as sample size, growth conditions, proportions of earlywood and latewood, the presence of juvenile wood, and the sampling position within the stem.

CONCLUSIONS

1. Air-dry specific gravity showed positive correlations with bending, compressive, and shear strengths in most species. In particular, *Larix kaempferi*, *Pinus rigida*, and *Pinus rigida* × *taeda* exhibited relatively consistent positive relationships across all strength properties. These results indicate that air-dry specific gravity is a reliable physical indicator for evaluating and predicting the structural strength properties of domestic coniferous wood.
2. Average annual ring width generally showed negative relationships with bending and compressive strengths. This trend is consistent with the established understanding that narrower annual rings are often associated with a higher latewood proportion and greater cell wall content, which contribute to improved mechanical performance. However, the statistical significance of the relationships between average annual ring width and strength varied among species and growth regions, and clear relationships were not observed for some species. This suggests that average annual ring width reflects not only growth rate but also combined effects of earlywood–latewood proportion, juvenile wood distribution, tree age, and growth environment.
3. Air-dry specific gravity was identified as the primary predictor for explaining bending, compressive, and shear strengths in major domestic coniferous species. In contrast, average annual ring width is more appropriately interpreted as a supplementary indicator of wood-quality variation and growth characteristics rather than as an independent predictor of strength. Considering the observed species- and region-dependent differences, prediction models for structural utilization and grading of domestic coniferous wood should primarily incorporate air-dry specific gravity, together with average annual ring width and relevant anatomical characteristics.

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