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NOTE

Strength properties and effect of moisture content on the bending and compressive strength parallel to the grain of sugi (*Cryptomeria japonica*) round timber

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Abstract Static bending tests and compressive test parallel to the grain of sugi (Japanese cedar, *Cryptomeria japonica*) green round timber were conducted to confirm whether its strength would satisfy the referenced strength determined by the Construction Ministry. The strength of green round timber and air-dried round timber were compared for bending and compression parallel to the grain. The strength change ratio in response to a 1 % change in the moisture content of round timber was compared with that of small clear specimens and timber. The results revealed that a 5 % parametric tolerance limit of bending and compressive strength parallel to the grain satisfied the referenced strength, even when using green round timber. The average strength of air-dried round timber was higher than that of green round timber, in both bending and compression parallel to the grain, with significant differences indicated at a 5 % significance level. The relation between the cross-section area that includes round timber, timber and the small clear specimens, and the strength change ratio in response to a 1 % change in moisture content change was fitted to a logarithm curve. Thus, the size of the specimen was considered to affect the strength change ratio.

Keywords Moisture content · Bending strength · Compressive strength parallel to the grain · Sugi · Round timber

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Introduction

To expand the use of wood that includes thinned round timber, wood should be used not only for construction products but also for civil engineering products. One use of wood products for civil engineering would be for underground bearing piles. Wooden bearing piles would be used in the form of round timber without lumbering. When round timber is used underground, it must always be under a green condition. The strength of a small clear specimen and that of timber are known to decrease in line with higher moisture content [1]. The strength data of green round timber was very poor, however, when compared with that of a small clear specimen and timber. In this study, static bending tests and compressive tests parallel to the grain of sugi (Japanese cedar, *Cryptomeria japonica*) green round timber were conducted to confirm whether its strength would satisfy the referenced strength determined by the Construction Ministry. The strength of green round timber and air-dried round timber were also compared for bending and compression parallel to the grain. The strength change ratio in response to a 1 % change in the moisture content of round timber was compared with that of small clear specimens and timber.

Materials and methods

Materials and sorting

Eighty green round timbers (each measuring 16–20 cm in diameter at the top end, and about 5 m in length) were procured. The dynamic Young's modulus for all green round timbers was obtained by using the longitudinal vibration method. The density of round timber was

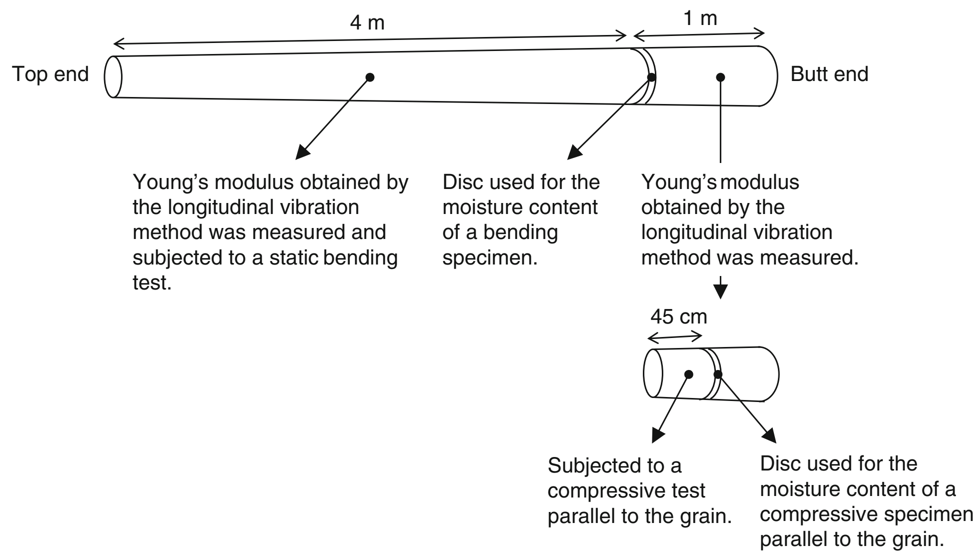

Fig. 1 Flow of the testing

calculated according to the Japanese Agricultural Standard for logs [2]. The average Young's modulus obtained by the longitudinal vibration method was 8.20 kN/mm^2, with minimum and maximum values of 5.88 and 9.71 kN/mm^2, respectively. Green round timbers were divided into two groups of 40 specimens by the Young's modulus obtained by the longitudinal vibration method for that average, with largely uniform standard deviation. One group was tested as green round timber and the other group as air-dried round timber.

Figure 1 shows the flow of the testing. Green round timber was cut to a length of 4 m, including the top end used as a bending specimen. At the same time, a disc about 2-cm thick was cut from the green round timber. The moisture content of the disc was measured by using a oven dry method and thus considered the moisture content of the bending specimen. The Young's modulus obtained by the longitudinal vibration method was measured for bending specimens 4 m in length. After dynamic Young's modulus was measured, a bending test was promptly conducted. A compressive specimen parallel to the grain was prepared using the remaining green round timber about 1 m in length. At the 1-m length, Young's modulus obtained by the longitudinal vibration method was measured and thus considered the Young's modulus of the compressive specimen parallel to the grain. After dynamic Young's modulus was measured, the green round timber was cut using a band saw to a length of 45 cm, in order to make each cross-section parallel. This round timber (45 cm in length) was used for the compressive test parallel to the grain. At the same time, a disc about 2-cm thick was cut from the green round timber. The moisture content of the disc was measured by a oven dry method and thus considered the moisture content of the compressive specimen.

The air-dried round timbers were air-dried outdoors for 8–9 months. After being air-dried, the air-dried round timbers were subjected to the test using the same method as for the green round timbers.

Method of testing bending and compression parallel to the grain

For the static bending test, a universal testing machine of 200-kN capacity (made by Tokyokoki Seizosho Ltd.) was used for the 100-kN range. Third-point loading was applied with a total span of 360 cm. The total span deflection of green round timber was measured using the CDP-100 displacement gauge with 10-cm capacity (made by Tokyo Sokki Kenkyujo Co., Ltd.). The displacement gauge was mounted on a yoke to measure the neutral axis deflection. The targeted duration of testing was 5 min. The apparent Young's modulus was obtained based on the total span deflection, and calculated at the middle circumference of the round timber. The bending strength was calculated at the circumference of a failure part from the ratio of the mid-length circumference to the circumference at the loading point. However, 9 of the 40 green round timbers did not show failure, even at the extension limit of the testing machine's ram cylinder. For these specimens, load at the extension limit of the test machine's ram cylinder was considered the maximum load. For the air-dried round timber, the total span deflection was measured using the rolled-in type DP-500E displacement gauge with 50-cm capacity (made by Tokyo Sokki Kenkyujo Co., Ltd.). The displacement gauge was mounted on a yoke to measure the neutral axis deflection of air-dried round timber. All air-dried round timbers failed within the extension limit of the ram cylinder.

Table 1 Results of the bending test

	MC (%)	Density (kg/m^3)	E_{fr} (kN/mm^2)	App. E_b (kN/mm^2)	σ_b (N/mm^2)	5 % PTL (N/mm^2)
Green round timber	75.8 (13.6)	727 (7.64)	8.32 (9.14)	7.75 (8.97)	56.0 (7.31)	48.5
Air-dried round timber	17.6 (6.07)	491 (5.28)	8.60 (9.14)	7.93 (11.1)	59.8 (8.87)	50.1

The values denote average with parenthesized values denoting the coefficients of variation (%)

MC moisture content, E_{fr} the Young's modulus obtained by the longitudinal vibration method, *App.* E_b the apparent bending Young's modulus, σ_b the bending strength, *5 % PTL* the 5 % parametric tolerance limit

Table 2 Results of the compressive test parallel to the grain

	MC (%)	Density (kg/m^3)	E_{fr} (kN/mm^2)	σ_c (N/mm^2)	5 % PTL (N/mm^2)
Green round timber	80.3 (14.1)	715 (8.58)	8.07 (11.5)	23.8 (7.98)	20.3
Air-dried round timber	20.8 (3.59)	493 (14.5)	8.26 (12.7)	26.8 (7.09)	23.3

The values denote average with parenthesized values denoting the coefficients of variation (%)

MC moisture content, E_{fr} the Young's modulus obtained by the longitudinal vibration method, σ_c the compressive strength parallel to the grain, *5 % PTL* the 5 % parametric tolerance limit

For the compressive test parallel to the grain, a compressive testing machine of 3000-kN capacity (made by Maekawa Testing Machine Mfg Co., Ltd.) was used. Load was applied up to the maximum load and the targeted duration of testing was 5 min. Compressive strength parallel to the grain was calculated by maximum load divided into the cross-section area measured at the butt end circumference.

Results and discussion

Comparison with the referenced strength

Tables 1 and 2 list the results of the bending test and compressive test parallel to the grain, respectively. Figures 2 and 3 show the normalized ranks of bending strength and compressive strength parallel to the grain. In Tables 1 and 2, the 5 % parametric tolerance limit (PTL) was estimated with a content of 95 % and confidence of 75 % for normal distribution [3]. The 5 % PTL of bending strength and that of compressive strength parallel to the grain of green round timbers were compared with the referenced strength of sugi for non-graded timber determined by the Construction Ministry [4], as no referenced strength had been set for round timber. In terms of bending strength, the 5 % PTL of green round timber was 48.5 N/mm^2, thereby exceeding the referenced strength of 22.2 N/mm^2. In terms of compressive strength parallel to the grain, the 5 % PTL of green round timber was 20.3 N/mm^2, also exceeding the referenced strength of 17.7 N/mm^2. Thus, the 5 % PTL of both bending and compressive strength parallel to the grain was found to satisfy the referenced strength, even when using round timbers under a green condition.

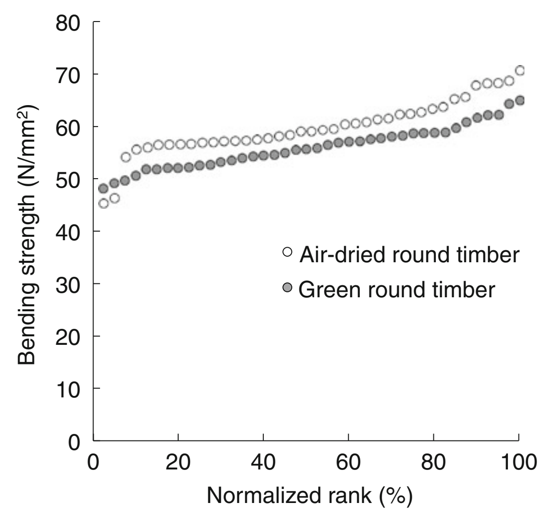

Fig. 2 Normalization of bending strength of air-dried round timbers and green round timbers

Comparison of strength properties between green round timbers and air-dried round timbers

The bending test results showed no significance at the 5 % significance level on average regarding the Young's modulus obtained by the longitudinal vibration method, and the apparent Young's modulus for green round timbers and air-dried round timbers. Meanwhile, the average bending strength showed significant differences at the 5 % significance level between green round timbers and air-dried round timbers. When considering that the average for green round timbers would actually increase because the green round timbers included those that did not show failure, it was difficult to simply conclude that there were differences between green round timbers and air-dried round timbers.

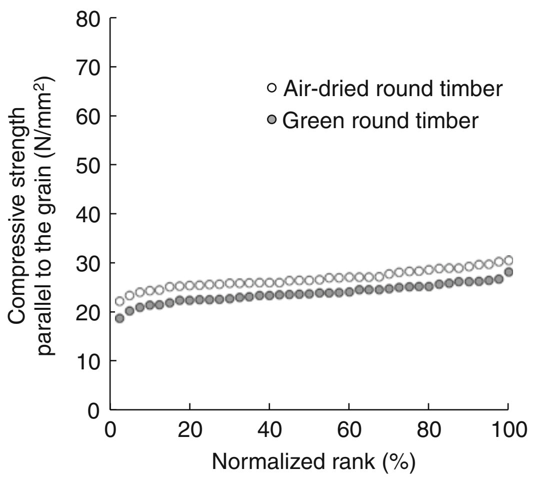

Fig. 3 Normalization of compressive strength parallel to the grain of air-dried round timbers and green round timbers

The 5 % PTL of bending strength was slightly higher for air-dried round timbers than green round timbers, although we should also consider the fact that the bending strength of green round timbers would actually increase.

As for the compressive test parallel to the grain results, there was no significance seen in the average Young's modulus obtained by the longitudinal vibration method for air-dried round timbers and green round timbers. Significance was seen in average compressive strength parallel to the grain at the 5 % significance level for air-dried round timbers and green round timbers. The 5 % PTL of compressive strength parallel to the grain was higher in air-dried round timber than green round timber. In terms of average, the strength ratios of dry/green round timbers were larger in compressive strength parallel to the grain than in bending strength, as well as the other timbers [5, 6] and small clear specimens [7].

Comparison of strength change ratio in response to a 1 % change in the moisture content of round timber, timber, and small clear specimens

Figures 4 and 5 show average increases in strength due to a 1 % decrease in moisture content of round timber, timber, and small clear specimens of sugi, respectively. The strength change ratio in response to a 1 % change in the moisture content was calculated with the following formula:

$$\left[\left(\sigma_{\text{dry}} - \sigma_{\text{green}}\right)/\sigma_{\text{green}}\right] / \left(\text{MC}_{\text{dry}} - \text{FSP}\right) \quad (1)$$

where, σ_{dry} denotes the strength of a dried specimen, σ_{green} the strength of a green specimen, and MC_{dry} the dried moisture content. The strength did not change over the fiber saturation point (FSP) and the FSP value was determined to be 28 [8]. The average was used in this formula. The strength change ratio of small clear specimens was highest in terms of bending strength and compressive strength parallel to the grain. This was followed by timber, specifically such as boards (20 cm width × 3.5 cm depth) [6], regular square lumber (10.5 cm width × 10.5 cm depth) [5], and square lumber (12 cm width × 24 cm depth) [9]. Round timber showed the lowest strength change ratio. It is well known that the

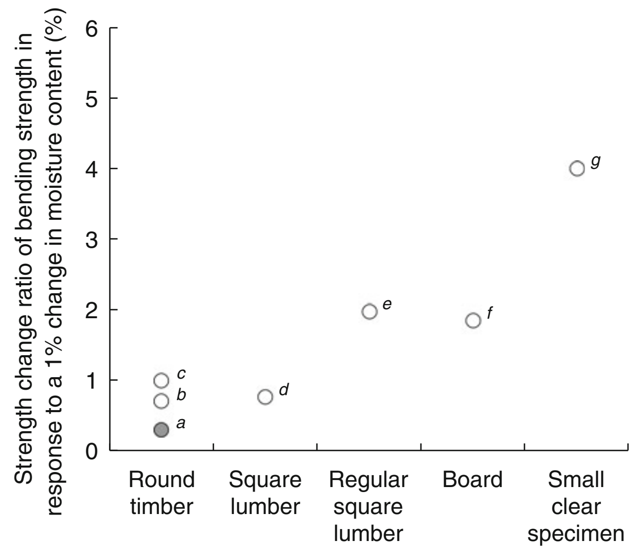

Fig. 4 Average increase in bending strength of sugi due to a 1 % decrease in moisture content. *a* This study, *b* Nakai et al. [14, 15] (18–22 cm top end diameter), *c* Nakai et al. [13] (<12, 12–14, >14 cm top end diameter), *d* Nakai et al. [9] (12 cm width × 24 cm depth), *e* Nagao et al. [5] (10.5 cm width × 10.5 cm depth), *f* Nagao et al. [6] (20 cm width × 3.5 cm depth), *g* Markwardt [7] (regardless of species)

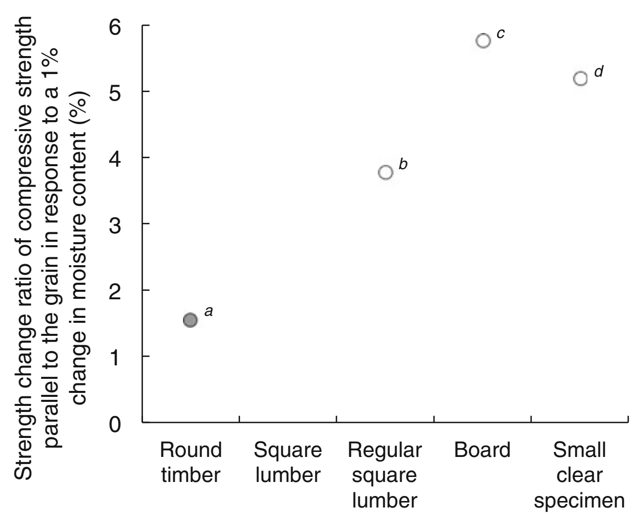

Fig. 5 Average increase in compressive strength parallel to the grain due to a 1 % decrease in moisture content. *a* This study, *b* Nagao et al. [5] (10.5 cm width × 10.5 cm thickness), *c* Nagao et al. [6] (20 cm width × 3.5 cm thickness), *d* Oda et al. [16]

strength change ratio of small clear specimens was higher than that of timber. As for bending strength, Green and Evans [10] noted that, "although seasoning results in a significant increase in strength for small clear specimens, for timbers, the increase in bending strength resulting from drying may be offset by a weakening of timber, which is caused by the formation of splits." In addition to splits, such defects as knots and the slope of grain offset the strength change with seasoning. The Wood Handbook [1] noted that "very low quality lumber that has many large knots may be insensitive to changes in moisture content." Also for sugi timber, the strength change ratio was larger for timber having higher strength and thus fewer defects, while the strength change ratio was lower for timber having lower strength and thus many defects [5, 9]. However, from the standpoint of defects offsetting the strength change ratio, the strength change ratio of round timber would be closer to that of small clear specimens than to that of timber. The slope of grain in round timber is relatively straight. The knots in round timber are not so critical compared with timber, because round timber does not have any edge knots as in timber that more directly affect strength. Air-dried round timbers of lodgepole pine showed only a slight increase in bending strength compared with green round timbers [11]. Betts [12] showed the relation between the butt end diameter (about 8–11.5 inches or 21.6–29.2 cm) and bending strength of the round beams of various species. In particular, Betts showed that when the butt end diameter became larger, the dry/green ratio of bending strength became smaller. This suggests that the size of round timber effects the strength change ratio. In Fig. 4, the round timbers that have a smaller top end diameter [13] that included three diameter groups divided by top end diameter—smaller than 12 cm, 12–14 cm, and larger than 14 cm—showed a higher strength change ratio than those having a larger top end diameter of 16–20 cm (this study) and 18–22 cm [14, 15]. As for timber, regular square lumber (10.5 cm width × 10.5 cm depth) [5] and boards (20 cm width × 3.5 cm depth) [6] showed a higher strength change ratio than that of square lumber (12 cm width × 24 cm depth) [9]. Figure 6 shows the relation between the cross-section area and the strength change ratio of bending strength that includes round timbers, timbers, and small clear specimen together. The cross-section areas of round timbers were determined based on circumference that was the medium range of the top end diameter. Although the effect of defects was not considered, plots were fitted to a logarithm curve to some extent. The reason for these results is not apparent thus far, but one explanation is that the strength reaction to moisture content would less sensitive to the increased size of a specimen. Thus, not only the defects but also the size of a specimen was considered to affect the strength change ratio.

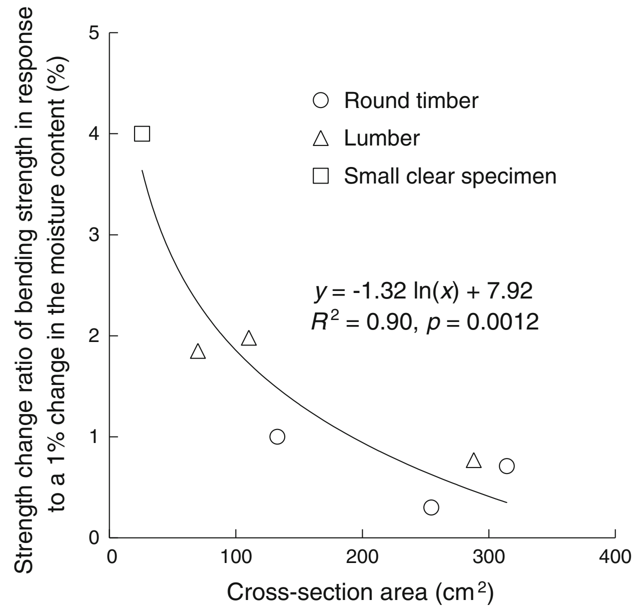

Fig. 6 Relation between cross-section area and strength change ratio of bending strength

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