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ORIGINAL ARTICLE

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Effects of high temperature kiln drying on the practical performances of Japanese cedar wood (*Cryptomeria japonica*) II: changes in mechanical properties due to heating

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Abstract Japanese cedar wood specimens were steamed at 80°, 100°, and 120°C over 14 days, and their equilibrium moisture content (M) at 20°C and 60% relative humidity, longitudinal dynamic Young's modulus (E), bending strength (σ_{max}), and breaking strain (ε_{max}) were compared with those of unheated specimens. Steaming for a longer duration at a higher temperature resulted in a greater reduction in M, σ_{max}, and ε_{max}. The E of wood was slightly enhanced by steaming at 100°C for 1–4 days and 120°C for 1–2 days, and thereafter it decreased. The slight increase in the E of sapwood was attributable to the reduction in hygroscopicity, while sufficient explanation was not given for a greater increase in the heartwood stiffness. Irrespective of the steaming temperature, the correlations between M and the mechanical properties of steamed wood were expressed in terms of simple curves. M values above 8% indicated a slight reduction in E and σ_{max}, whereas M values below 8% indicated a marked decrease in the mechanical performances. In addition, the ε_{max} decreased almost linearly with a decrease in the value of M. These results suggest that hygroscopicity measurement enables the evaluation of degradation in the mechanical performances of wood caused by steaming at high temperatures.

Key words Kiln drying · Steaming · Japanese cedar · Thermal degradation · Hygroscopicity

Introduction

Our previous article[1] suggested that the hygroscopicity of wood could be an indication of the thermal degradation resulting from steaming, i.e., heating in the presence of moisture. Furthermore, the results of hygroscopicity measurements showed that the thermal degradation of the inner part of wood was greater than that of the outer part when large-dimension lumbers were kiln-dried at 120°C.

On the other hand, many researchers have concluded that the mechanical performances of wood are not significantly reduced by high-temperature kiln drying.[2,3] In several cases, green or rewetted wood samples were kiln-dried under atmospheric pressure, and their mechanical properties were compared with those of unheated wood samples. However, in these cases, the local parts of a sample were exposed to different temperature–moisture conditions during drying: the inner part of the sample was "steamed" for a long duration, while its surface was rapidly dried and heated with a small amount of moisture. Such a nonuniform thermal history makes it difficult to determine the effect of heating temperature and duration on wood performance.

In order to clarify the effects of heating temperature and duration on the mechanical performances of kiln-dried wood, we examined the dynamic Young's modulus, strength, and breaking strain of small wood strips that were treated with saturated water vapor at constant temperatures. In an attempt to practically evaluate the kiln-dried wood on the basis of hygroscopicity measurement, the mechanical properties were related to the equilibrium moisture content of wood.

Materials and methods

A log of green Japanese cedar (*Cryptomeria japonica* D. Don), 50 years old, was separated into sapwood (18–28 rings from the pith) and heartwood (5–13 rings) portions.

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The annual ring width ranged from 3.6 to 4.8 mm (average: 4.2 mm) in the sapwood portion, and from 5.6 to 7.1 mm (average: 6.3 mm) in the heartwood portion. The portions were air-dried at room temperature and subsequently cut into specimens with dimensions of 150 × 15 × 3 mm (longitudinal L × radial R × tangential T). The specimens were completely dried in vacuo over P_2O_5 at room temperature to determine their original dry weights, conditioned at 20°C and 60% relative humidity (RH) for 2 months, and then their dynamic Young's modulus (*E*) along the L direction were determined by a free–free flexural vibration method.[4]

Approximately 2 weeks prior to steam treatment, the wood specimens were conditioned at 20°C and 100% RH, where their moisture content reached 28%–31%. Six wood specimens were steamed at 80°, 100°, and 120°C for 1, 2, 4, 7, and 14 days, in a steel autoclave (inner volume: 200 cm^3) heated at a prescribed temperature. Wet glass filters were inserted between the wood specimens to ensure a sufficient supply of water vapor. The treated specimens were then cooled at 100% RH, dried at 60% RH, and vacuum-dried over P_2O_5 at room temperature. After determining their dry weights, the treated specimens were conditioned at 20°C and 60% RH for 2 months, and their *E* values were measured again. Twelve sapwood specimens and six heartwood specimens were used for each treatment condition.

The control and steamed specimens were subjected to a three-point flatwise bending test to measure their strength (σ_{max}). The effective span and crosshead speed were 100 mm and 5 mm/min, respectively. In order to measure the tensile breaking strain (ε_{max}), strain gauges (Kyowa Dengyo, KFG-30-120-C1-11 L1M2R) were attached on the back surface of the loading point of half of the sapwood specimens. The mechanical restriction due to the strain gauge was examined by the following method: 20 sapwood specimens having almost identical *E* values were selected by vibration testing, and strain gauges were attached to half the number of the specimens. These specimens were then subjected to the static bending test. Because no significant difference was found between the strength of specimens with and without the strain gauge, the mechanical restriction due to the strain gauge was considered to be negligible.

Results and discussion

Figure 1 shows the relative weight (W_t/W_u) and equilibrium moisture content (*M*) at 20°C and 60% RH of the steamed wood specimens as a function of the steaming duration. The relative weight is defined as the ratio of the weight of steamed wood (W_t) to the original weight (W_u). Steaming for a longer duration and at a higher temperature resulted in greater weight loss and lower hygroscopicity of wood. In Fig. 2, the *M* values of unheated and steamed wood are plotted against their W_t/W_u values. All data were located around a curve, irrespective of the steaming temperature. This suggests that a lower *M* value can be a simple indication of greater thermal degradation due to steaming.

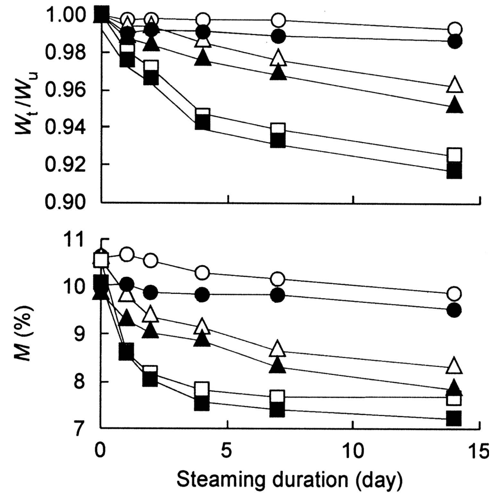

Fig. 1. Changes in relative weight (weight of steamed wood/original weight; W_t/W_u) and equilibrium moisture content (*M*) at 20°C and 60% relative humidity (RH) of wood specimens due to steaming. *Open plots*, sapwood; *filled plots*, heartwood; *circles*, steamed at 80°C; *triangles*, steamed at 100°C; *squares*, steamed at 120°C

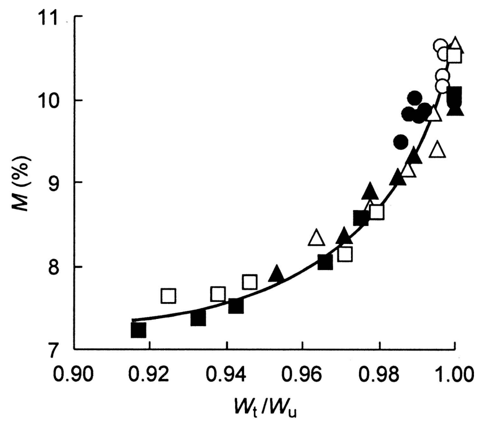

Fig. 2. Relationship between *M* and W_t/W_u of unheated and steamed wood specimens

Table 1. Density and dynamic Young's modulus (E_u) of unheated specimens at 20°C and 60% relative humidity

	Density (g/cm^3)	E_u (GPa)
Sapwood	0.340 (0.014)	8.0 (0.7)
Heartwood	0.386 (0.017)	7.7 (0.5)

Values in parentheses indicate standard deviations

Table 1 lists the average density and the *E* values of unheated wood specimens. Although the wood specimens were obtained from the same log, the *E* values varied to a certain extent, and different *E* values were obtained for sapwood and heartwood. In order to evaluate the effects of steaming, we calculated the relative stiffness (E_t/E_u), which is the ratio of the *E* of steamed wood (E_t) to the *E* in the unheated state (E_u). Figure 3 shows the E_t/E_u values of steamed wood plotted against the steaming duration. In spite of the variable E_u, the variation in E_t/E_u was small

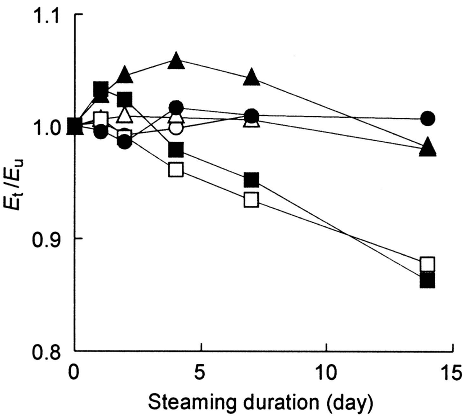

Fig. 3. Effects of steaming duration on the change ratio of dynamic Young's modulus (E_t/E_u) of wood specimens at 20°C and 60% RH

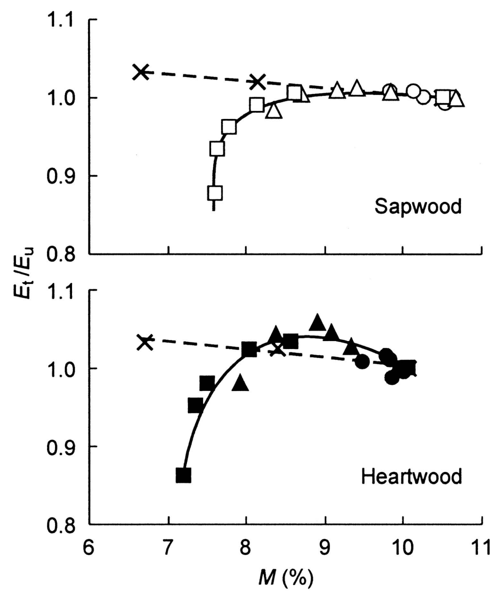

Fig. 4. The E_t/E_u values of wood specimens as a function of *M*. *Crosses* and *broken lines* indicate the trends of unheated wood equilibrated at 33%, 43%, and 60% RH

within the size of the plot. The *E* of the wood remained almost constant by steaming at 80°C. By steaming at 100°C, the *E* of the wood increased slightly during 4 days of steaming and then it began to decrease. A similar trend was observed in the wood specimens that were steamed at 120°C, while the maximum value of *E* was recorded for a shorter duration (1 day) and the subsequent reduction in stiffness was much greater.

Figure 4 shows the E_t/E_u values of unheated and steamed wood plotted against their *M* values. Prior to steaming, the *M* of the sapwood and heartwood were 10.4% ± 0.4% and 10.1% ± 0.2%, respectively. By steaming, there was a gradual decrease in the *M* of the wood, while E_t/E_u increased slightly and then dropped regardless of the steaming temperature. The values of E_t/E_u of the unheated wood equilibrated at 33%–60% RH are indicated by crosses and broken lines in Fig. 4. Both sapwood and heartwood exhibited a slight increase in *E* with decreasing values of *M*. For *M* values above 9%, the *E* of the steamed sapwood followed the same trend as the unheated sample. In this case, the increase in stiffness due to steaming is attributed to the reduction in hygroscopicity. The remarkable decrease in *E* for *M* values below 9% is explained by the negative effect of the thermal degradation that exceeds the positive effect of hygroscopicity reduction. On the other hand, the *E* of the steamed heartwood sample was greater than that of the unheated sample in the range of *M* from 8% to 10%. It was speculated that certain heartwood extractives modified by mild steaming could enhance the *E* of wood, although further experiments are needed for more convincing explanation. For *M* values below 8%, the *E* of heartwood dropped with a decrease in the values of *M*; this trend is similar to that observed in sapwood.

The results shown in Fig. 4 suggest that the *M* of wood can be used to evaluate the thermal degradation of wood caused by kiln-drying. If the *M* of kiln-dried wood is lower than 8% at 20°C and 60% RH, then the wood was subjected to severe hygrothermal conditions that involve serious reduction in the stiffness. On the other hand, *M* values greater than 8% guarantee a slight reduction in stiffness caused by kiln-drying.

When the *M* of the wood is below 8%, however, it is not suitable for the qualitative evaluation of thermal degradation. As shown in Figs. 1 and 3, the *M* of the wood was leveled off by steaming at 120°C for more than 4 days during which *E* continued to decrease with the steaming duration. Accordingly, *E* of the wood dropped with a slight change in *M* below 8%, as shown in Fig. 4. By severe steaming, parts of the wood components, such as hemicelluloses, are depolymerized into water-soluble, low molecular weight substances.[5,6] A large amount of decomposition residue remains in the wood cell wall unless the wood is sufficiently leached with water. Although this remaining decomposition residue is no longer a "major" component responsible for the mechanical performances, it contributes to the hygroscopicity of wood. Consequently, the changes in *E* were greater than those in *M* under severe steaming conditions. In order to evaluate the effects of severe steaming by hygroscopicity measurement, the *M* of the wood should be measured after the removal of the decomposition residue, as suggested in the previous article.[1] However, in the present study, the length of wood specimens (150mm) hindered sufficient extraction.

Figure 5 shows the stress–strain (σ–ε) curves of unheated and steamed sapwood specimens. The maximum values of σ and ε were reduced by steaming, while the initial slope of the σ–ε curves remained almost constant for steaming at 100°C or below. This indicates that the toughness of wood is degraded even by mild steaming that involves a slight reduction in stiffness.

In order to evaluate the effects of steaming on the strength (σ_{max}) of wood, we used the relative strength (σ_{max}/E_u) to minimize the influence of the original variation in σ_{max}. Figure 6 shows the σ_{max}/E_u values of unheated and steamed sapwood specimens plotted against their *M* values.

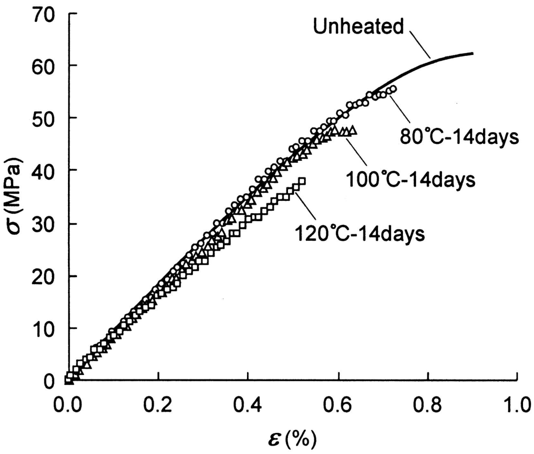

Fig. 5. Stress (σ)–strain (ε) curves for unheated and steamed sapwood specimens

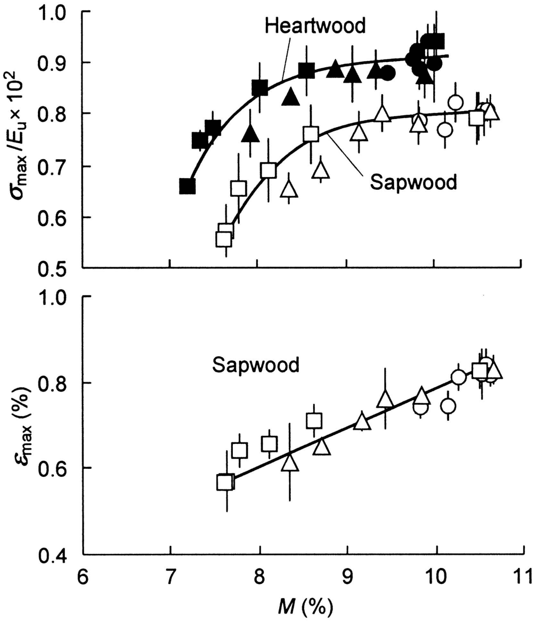

Fig. 6. Relative stiffness (σ_{max}/E_u) and breaking strain (ε_{max}) of unheated and steamed wood specimens plotted against M

The trends in σ_{max}/E_u were entirely similar to those observed for E (Fig. 4). However, σ_{max}/E_u did not exhibit an increase with a decrease in the values of M, whereas E was slightly enhanced by steaming. It was considered that steaming weakens the cohesion of major wood components and results in fragility, while such an effect causes a slight change in the stiffness determined at low strain levels. Again, 8% M is regarded as a threshold for judging the marked reduction of mechanical performances.

The ε_{max} of sapwood specimens is plotted against M values in Fig. 6. In contrast with the trends observed in E and σ_{max}, the ε_{max} was observed to decrease linearly with decreasing values of M, irrespective of the steaming temperature. The ε_{max} is reduced by the decrease in M as well as by the thermal degradation of wood components; therefore, it monotonously decreased with a decrease in M.

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