EFFECT OF HIGH TEMPERATURE AND HIGH HUMIDITY TREATMENT ON BENDING PROPERTIES OF WOOD

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Abstract. Japanese cedar (*Cryptomeria Japonica* D. Don) 110 × 110 × 1000-mm green boxed-heart timbers were dried under high temperature (110-140°C) and high humidity (0.01-0.24 MPa gauge pressure) conditions until the weight remained unchanged. Then strength properties were examined. Wood became brittle because of the high temperature and high humidity treatment. We hypothesize that the wood was seriously damaged by hydrolysis because of the long treatment time used in this study and that the large cross-sectional area and high set gauge pressure lengthened the time of water loss from the wood. We considered viscosity and plasticity, rather than elasticity, to be the main factors that contributed to the decrease of work for rupture.

Keywords: Cedar, high humidity, high temperature, impact bending, static bending, strength.

INTRODUCTION

In wood processing, it is important to lower drying costs by quickly drying without inducing damage, such as checks, splits, and honeycombs. Although high-temperature drying can decrease time and cost, traditional and conventional high-temperature drying methods cannot guarantee both speed and high-quality products.

Recently, a high-temperature (greater than 100°C) and high-humidity (greater than atmospheric pressure) treatment has been attracting attention as an improved drying method. In this method, wood is heated in nonsaturated (superheated) water vapor at controlled temperature and humidity. This hinders the formation of checks because the wood is softened while it is dried to some extent (Saito et al 1995; Kobayashi et al 1995, 1996, 1997; Hisada 1998).

To determine the appropriate drying conditions, we should understand not only the wood properties after drying but also those when water is being lost by heating. We measured temporal changes in MC and vibrational properties of

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green wood under a high temperature and atmospheric pressure condition and high temperature and high humidity (more than atmospheric pressure) one. Specific Young's modulus and loss tangent reached the minimum and maximum, respectively, early in the drying under both heating conditions. The minimum and maximum under the high temperature and high humidity condition were far greater and smaller than those under the high temperature and atmospheric pressure one, respectively. This showed that wood was remarkably softened by the high temperature and the moisture remaining in the wood (Kubojima et al 2002, 2003, 2004, 2005, 2009).

Hence, it was feared that heat treatment under the high temperature and high humidity condition decreased the wood strength more than that under the high temperature and atmospheric pressure condition (Kubojima et al 1998a, b, 2000; Ikeda et al 2009). Although many studies (Stamm et al 1946; Mitchell et al 1953; Inoue et al 1993; Mitchell 1988; Kim et al 1998; Tjeerdsma et al 1998; Poncsák et al 2006; Boonstra et al 2007; Esteves et al 2007; Shi et al 2007; Korkut et al 2008; Arnold 2010; Volkmer et al 2014) and several reviews (Esteves and Pereira 2009; Sandberg et al 2013; Xie et al 2013) on the mechanical properties of heat-treated wood exist, there are few studies on the mechanical properties of actual-size timbers heat-treated with monitoring temperature (more than 100°C), water vapor pressure (more than atmospheric pressure), and weight.

In this study, timbers were heat treated under high temperature and high humidity conditions until the weight remained unchanged for the purpose of obtaining basic data for drying under such conditions. We considered that the drying under each heating condition finished when the weight became stable. And then damages to wood were investigated from the aspect of strength.

MATERIALS AND METHODS

Specimens

Japanese cedar (*C. Japonica* D. Don) 110 × 110 × 1000-mm green boxed-heart timbers were used as the specimens. Two boxed-heart timbers were used for each heat treatment condition and controls. The boxed-heart timbers for controls were conditioned at 20°C and 65% RH according to Japanese Industrial Standard (2009) without heating until the weight was constant. The average and standard deviation of initial MC of all boxed-heart timbers were 61.6% and 10.4%, respectively. There was not any form of restraint applied to the wood during drying. After drying under each condition and weighing the oven-dried weight, five or six specimens for static bending tests were cut from a boxed-heart timber whereas five or six specimens for impact bending tests were cut from another boxed-heart timber. Specimens for static bending tests were 20 mm wide (R), 20 mm thick (T), and 320 mm long (L); those for impact bending tests were 20 mm wide (R), 20 mm thick (T), and 300 mm long (L). All bending tests were conducted at 20°C and 65% RH.

Temperature and MC during Drying

The measuring system was in an airtight chamber (Takahashi Boiler Co., Ltd., Nagoya, Japan), and the thermocouple and load cells were connected to a data logger outside the chamber (Fig 1). This heating chamber comprised two cans; the inner can (chamber) and the outer can (jacket). The chamber was heated by water vapor introduced between the two cans, and superheated water vapor formed inside. Both temperature and pressure were controlled. Because the pressure changed according to the water from the wood and condensation in a pipe connected to the heating instrument, the pressure was controlled by leak and steam valves, respectively. The inner can was 500 mm in diameter and 1500 mm long, whereas the outer can, including the jacket, was 610 mm in diameter and 1600 mm long. The temperature control range was 100-170°C, maximum pressure was 0.98 MPa, and the pressure could be changed in 0.01-MPa increments. The motor for the inner fan was located outside the outer can, and a heat-resistant ground packing was tied around a shaft to prevent water vapor leakage.

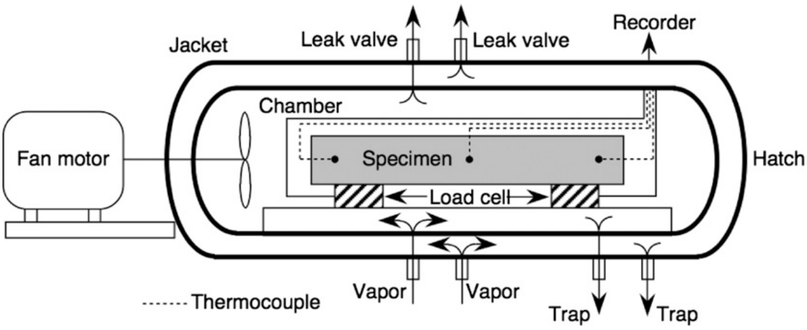

Figure 1. Apparatus for measuring MC during drying under high temperature conditions (Kubojima et al 2013).

As shown in our previous study (Kubojima et al 2009, 2013), to measure temperature in a specimen, a T-type thermocouple was inserted lengthwise at a depth of 50 mm from the central point of the radial-tangential (RT) and longitudinal-tangential (LT) planes. To measure the weight of a specimen, two beam-type load cells for high temperature conditions (LUB-10KBM96, Kyowa Electronic Instruments Co., Ltd., Tokyo, Japan) were used, which supported the specimen at two points.

Table 1 shows the set temperature, set gauge pressure, and set RH. Temperature and weight were measured at intervals of 1 min. When the weight remained unchanged for less than 24 h, the boxed-heart timbers were removed from the chamber and immediately weighed. And then, they were oven-dried at 105°C. MC was calculated based on the oven-dried weight. The Young's modulus of air-dried wood heat-treated at 120°C for 16 h did not decrease but slightly increased (Kubojima et al 1998a). Hence, we think that wood will not be seriously damaged by drying at 105°C.

Static Bending Test

The static bending test was performed using center-point loading across a 280-mm span with the load applied in the tangential direction. The cross-head rate was 5 mm/min. From the load-deflection relationship, the Young's modulus, bending strength, and work for rupture were obtained.

Impact Bending Test

A Charpy-type impact bending machine with a capacity of 29.4 J was used. The span was 240 mm. The absorbed energy in impact bending was obtained by the angle of the hammer when it was in the highest position.

Table 1. Set RH (%) under conditions of set temperature and set gauge pressure used for heat treatment (Kubojima et al 2009).

	Temperature (°C)			
Gauge pressure (MPa)	110	120	130	140
0.01	77.7	—	41.2	30.8
0.02	—	61.1	—	—
0.03	91.6	—	48.6	—
0.04	98.6	71.2	—	39.1
0.05	—	—	—	—
0.06	—	81.3	59.7	—
0.07	—	—	—	—
0.08	—	91.3	—	50.2
0.09	—	96.4	70.8	—
0.10	—	—	—	—
0.11	—	—	78.2	—
0.12	—	—	—	61.2
0.13	—	—	—	—
0.14	—	—	89.3	—
0.15	—	—	—	69.5
0.16	—	—	96.7	—
0.17	—	—	—	—
0.18	—	—	—	—
0.19	—	—	—	80.6
0.20	—	—	—	—
0.21	—	—	—	—
0.22	—	—	—	88.9
0.23	—	—	—	—
0.24	—	—	—	94.4

RESULTS AND DISCUSSION

Figure 2 shows an example of temporal changes in temperature (eg RT plane), gauge pressure, and MC. Heating time and EMC depended on temperature and humidity conditions because heating was stopped when the weight remained unchanged (Kubojima et al 2009). The heating time in this study is the longest time taken for high temperature and high humidity treatment for actual wood drying.

Wood properties (average [standard deviation]) for the controls are shown in Table 2.

Figures 3-8 show changes in wood properties caused by high temperature and high humidity treatment. Changes in density, Young's modulus, bending strength, work for rupture, and absorbed energy in impact bending were compared with those in our previous studies (Kubojima et al 1998b; Kubojima and Shida 2001), in which Japanese cedar green wood, 25-mm wide (R), 25-mm thick (T), and 350-mm long (L), was dried at 120°C and 160°C under atmospheric pressure.

As shown in Fig 3, density decreased, although it did not show a clear trend. It decreased more compared with our previous study because the density ratio of the heat-treated specimens to the control was 0.97 in our previous study (Kubojima et al 1998b).

Table 2. Wood properties for the controls.[a]

Density (kg/m^3)	386 (19.7)
Young's modulus (GPa)	6.82 (0.90)
Bending strength (MPa)	67.5 (6.43)
Work for rupture (kJ/m^2)	20.6 (4.10)
Absorbed energy in impact bending (kJ/m^2)	32.4 (3.7)

[a] Average (standard deviation). The green boxed-heart timbers were conditioned under 20°C and 65% RH without heating. Six specimens were used for the static and impact bending tests, respectively.

As shown in Fig 4, Young's modulus decreased, although it did not show a clear trend. It decreased significantly more compared with our previous study because the Young's modulus ratio of the heat-treated specimens to the control was 1.03 in our previous study (Kubojima et al 1998b).

As shown in Fig 5, bending strength decreased with an increase in the set gauge pressure. It decreased significantly more compared with our previous study because the bending strength ratio of the heat-treated specimens to the control was 1.08 in our previous study (Kubojima et al 1998b). There was not a clear tendency derived from the heating temperature.

As shown in Fig 6, work for rupture decreased with an increase in the set gauge pressure. It decreased significantly more compared with our previous study because the work for rupture ratio of the heat-treated specimens to the control was 1.06 in our previous study (Kubojima et al

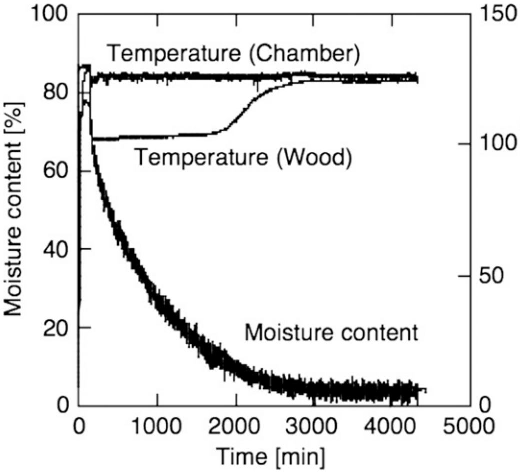

Figure 2. An example of temporal changes in temperature, gauge pressure, and MC (130°C and 0.01 MPa).

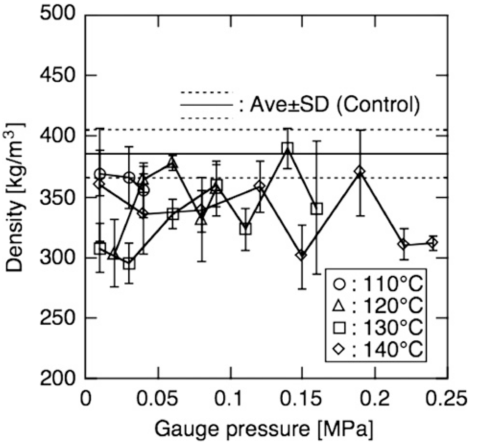

Figure 3. Changes in density caused by high temperature and high humidity treatment.

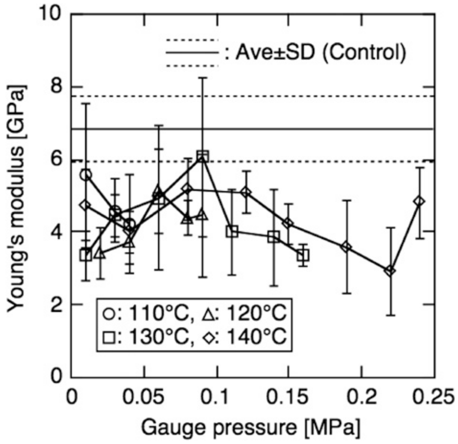

Figure 4. Changes in Young's modulus caused by high temperature and high humidity treatment.

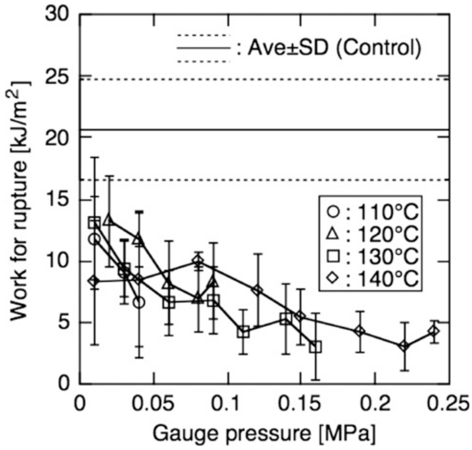

Figure 6. Changes in work for rupture caused by high temperature and high humidity treatment.

1998b). There was not a clear tendency derived from the heating temperature.

Figure 7 shows the changes in each work part of the work for rupture caused by the heat treatment. The work for rupture is the sum of the work in the linear region until the proportional limit (W_p) and work in the curved region from the proportional limit to rupture (W_{pr}). In this study, the boundary point between the linear region and the curved region could be clearly fixed. The value of W_{pr} was larger than that of W_p. The change in W_{pr} was much greater than that in W_p and decreased as the set gauge pressure increased, whereas W_p did not markedly change. Hence, it was thought that heat-treated wood was more brittle in the static bending test than untreated wood because W_{pr} decreased because of the heat treatment. In addition, the Young's modulus did not decrease with an increase in the set gauge pressure as previously mentioned. Therefore, we considered viscosity and plasticity to be the main factors that contributed to the decrease of work for rupture, rather than elasticity. This was similar to the trend observed in our previous study (Kubojima et al 2000).

As shown in Fig 8, absorbed energy in impact bending decreased with an increase in the set gauge pressure. It decreased significantly more

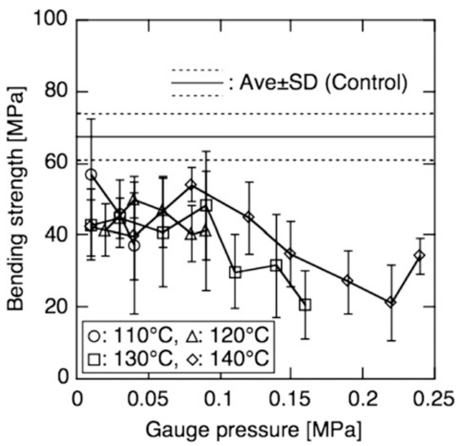

Figure 5. Changes in bending strength caused by high temperature and high humidity treatment.

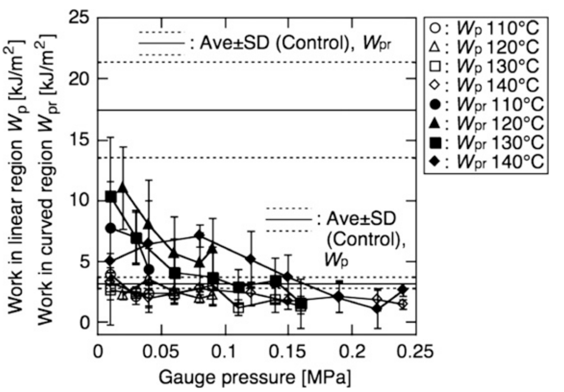

Figure 7. Changes in each work part caused by high temperature and high humidity treatment.

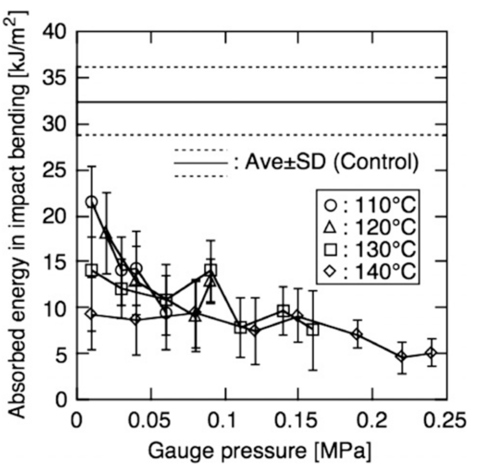

Figure 8. Changes in absorbed energy in impact bending caused by high temperature and high humidity treatment.

compared with our previous study because the ratio of absorbed energy in impact bending for the heat-treated specimens to the control was 0.83 in our previous work (Kubojima and Shida 2001). There was not a clear tendency derived from the heating temperature. Although load-deflection relationships for impact bending tests were not measured, it is reasonable that viscosity and plasticity were the main factors that contributed to the decrease of work for rupture, rather than elasticity (Kubojima et al 2000), as the static bending test as previously mentioned.

It is hypothesized that the significant decreases in the previously mentioned wood properties can be attributed to the much longer heating time used in this study compared with the previous studies; heating times in this study and the previous studies (Kubojima et al 1998b; Kubojima and Shida 2001) were about 2800-33,000 min and 300-750 min, respectively. We think that the wood was seriously damaged by hydrolysis because of the longer time used in this study and that the larger cross-sectional area ($110^2/25^2 = 19.36$ times) and higher set gauge pressure lengthened the time for water loss from the wood.

The MC of the boxed-heart timber at the time when its weight remained unchanged, ie the EMC, varied based on each heating condition (2.1-28.7%) (Kubojima et al 2009). Hence, the MC in performing the static and impact bending tests depended on each heating condition, and it ranged from 6.4% to 8.4%. The changes in Young's modulus, bending strength, and absorbed energy in impact bending of this study previously mentioned were much larger than those of previous studies in the MC range of 6.4-8.4% (Matsumoto 1962; Küch 1943; Miyajima 1979; Ebihara et al 1985; Urakami and Fukuyama 1985; Sumi et al 1986). Hence, we think that the variation of EMC was not a serious problem in this study.

Because specimens became brittle, the heat treatment under high temperature and high humidity conditions for too long was not adequate for maintaining or improving the bending properties of wood. However, using the high temperature and high humidity treatment at the initial stage of wood drying would be effective (Hisada 1998). Hence, the effect of heating time should be investigated, eg determining if wood properties decrease immediately after heating.

CONCLUSIONS

Japanese cedar green boxed-heart timbers were heat treated under high temperature and high humidity conditions, and then the bending properties of the treated wood were investigated. The results obtained were as follows:

1. Wood became brittle because of the high temperature and high humidity treatment for a long time.
2. We hypothesize that wood was seriously damaged by hydrolysis because of the longer time used in this study and that the larger cross-sectional area and higher set gauge pressure lengthened the time for water loss from wood.
3. We considered viscosity and plasticity, rather than elasticity, to be the main factors that contributed to the decrease of work for rupture.

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