J Wood Sci (2006) 52:33–38
DOI 10.1007/s10086-005-0716-9

ORIGINAL ARTICLE

**Eiichi Obataya · Sakae Shibutani · Kensuke Hanata
Shuichi Doi**

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

Received: October 13, 2004 / Accepted: February 21, 2005 / Published online: February 17, 2006

Abstract The effect of heating on the hygroscopicity of Japanese cedar wood was investigated as a simple evaluation of thermal degradation in large-dimension timber being kiln-dried at high temperatures (>100°C). Small wood pieces were heated at 120°C in the absence of moisture (dry heating) and steamed at 60°, 90°, and 120°C with saturated water vapor over 2 weeks, and their equilibrium moisture contents (M) at 20°C and 60% relative humidity (RH) were compared with those of unheated samples. No significant change was induced by steaming at 60°C, while heating above 90°C caused loss in weight (WL) and reduction in M of wood. The effects of steaming were greater than those of dry heating at the same heating temperature. After extraction in water, the steamed wood showed additional WL and slight increase in M because of the loss of water-soluble decomposition residue. The M of heated wood decreased with increasing WL, and such a correlation became clearer after the extraction in water. On the basis of experimental correlation, the WL of local parts in large-dimension kiln-dried timber was evaluated from their M values. The results indicated that the thermal degradation of inner parts was greater than that of outer parts.

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

Introduction

Despite many attempts, kiln drying of Japanese cedar (*Cryptomeria japonica* D. Don.) is still a problem facing the Japanese wood industry. The high moisture content of its heartwood requires long drying duration,[1] and the steep moisture gradient frequently causes serious surface cracks during drying. Among various methods so far proposed, high-temperature kiln drying is an effective means of preventing surface cracks of boxed-heart Japanese cedar timber.[2] When green Japanese cedar timbers are heated at high temperatures (>100°C) in the early stage of drying, the surface cracks are drastically reduced probably because of the thermal softening of the wood involves the effective relaxation of drying stress. Although internal cracks are often developed instead, such an invisible defect is not a serious problem for the commercial value of the timber. Therefore, high-temperature drying has recently become more popular in Japan as a method to improve the value of final products at low cost.

Because high-temperature heating possibly induces the thermal degradation of wood components, many researchers have examined the practical performance of kiln-dried timber. By kiln drying at high temperatures, no significant change is recognized in yellow poplar,[3] southern pine,[4,5] and also in some Japanese domestic species,[6–9] while some species show a slight reduction in their performance.[10–12] In most cases, however, only the mechanical properties have so far been tested. We have recently found that the antitermite resistance of wood, including Japanese cedar, was more or less degraded by high-temperature steaming.[13–15] Such a negative effect was explained by the production of termite feeding attractants as well as the decomposition of natural antitermite extractives. These findings suggest that more detailed investigation is needed on the thermal degradation due to kiln drying to avoid unpredictable problems in the future.

When kiln drying large-dimension timber, nonuniform hygrothermal effects should be taken into consideration. In a high-temperature kiln, the inner part of timber is "steamed" longer, while its outer part is rapidly dehydrated and "heated in dry." In this situation, the thermal degradation of the inner part must be greater than that in outer part because the hydrolysis of wood constituents is accelerated in the presence of moisture.[16,17] The localized degradation of inner parts might have little influence on the mechanical

E. Obataya (✉) · S. Doi
Graduate School of Life and Environmental Sciences, University of Tsukuba, 305-8572 Japan
Tel. +81-29-853-4649; Fax +81-29-855-2203
e-mail: obataya@sakura.cc.tsukuba.ac.jp

S. Shibutani · K. Hanata
Institute of Wood Technology, Akita Prefectural University, Kaieizaka, Noshiro 016-0876, Japan

properties such as bending strength, but it possibly reduces the durability of timber as a whole.

It is experimentally easy to evaluate the thermal degradation in a small piece of wood, because we have only to compare its weight, mechanical properties, and chemical characteristics before and after heating. However, such a manner is not simply applicable to a local part of large-dimension timber because we can hardly determine its characteristics in an unheated green state. The end-match method is sometimes employed to evaluate the effects of heating, but it always includes uncertainty due to the original variations in physical and chemical properties of wood.

These considerations led us to focus on the effects of heating on the hygroscopicity of wood, because the hygroscopicity of wood is generally less variable than the other wood properties, and it decreases as the degree of thermal degradation increases.[18–20] Recent investigations have suggested that dry heating and steaming gave almost the same reduction in hygroscopicity at the same loss in weight due to the thermal degradation, when spruce wood was heated above 120°C and the water-soluble decomposition residues were removed.[21] These facts imply the possibility of hygroscopicity measurement as an evaluation of localized thermal degradation in large-dimension kiln-dried timber. Thus the present article describes: (1) variation in the hygroscopicity of Japanese cedar wood; (2) changes in hygroscopicity due to controlled heating; and (3) evaluation of thermal degradation in the local part of large-dimension kiln-dried timber.

Materials and methods

Measurements of natural variation in the hygroscopicity of Japanese cedar wood

Japanese cedar wood (*Cryptomeria japonica* D. Don) was used for all following experiments. A green log was separated into sapwood and heartwood, and each part was cut into small pieces with dimensions of 0.5 × 2.5 × 2.5 cm (longitudinal, L × radial, R × tangential, T) at different longitudinal positions. Eight specimens were obtained from the sapwood and four from the heartwood at each position. On the other hand, green wood blocks of dimensions 1 (L) × 12 × 12 cm were obtained from the bottom part of 56 individual boxed-heart timbers (12 × 12-cm cross section). Each block was divided into 36 small pieces of dimensions 1 (L) × 2 × 2 cm. After 2 months of conditioning at 20°C and 60% relative humidity (RH), all those specimens were dried in vacuo at room temperature over P_2O_5 and weighed. The specimens were then conditioned at 20°C and 60% RH for about 2 months and weighed to determine their equilibrium moisture contents (M).

Hygroscopicity measurement of heat-treated wood

The sapwood and heartwood of a green log were cut into small pieces of dimensions 0.5 × 2.5 × 2.5 cm (L × R × T), and their absolutely dry weights were measured in the same manner described above. The specimens were then heat-treated by the following methods: completely dry specimens were heated at 120°C over 2 weeks in the absence of moisture by using a drying oven (dry heating); specimens were sufficiently moistened at 20°C and 100% RH for 1 month and then heated at 60°, 90°, and 120°C over 2 weeks in a steel autoclave (Taiatsu, TVS-N2-200) filled with saturated water vapor (steaming). To cancel the temporary effects of dry heating,[22] the dry-heated specimens were moistened once at 20°C and 100% RH for about 2 weeks prior to complete drying. The steamed specimens were cooled and roughly dried at 20°C and 60% RH for 1 week and then completely dried.

Eight specimens were used for each treating condition. Half of each sample set remained unextracted while the others were extracted in water in the following manner. The specimens were soaked in methanol for 1 week at room temperature with freshing solvent used each. The samples were then washed in running water for 1 week followed by boiling at 95°C for 1 hour, and then leached with distilled water at room temperature for 1 week. The water-extracted specimens were dried completely in vacuo at room temperature. All specimens were finally conditioned at 20°C and 60% RH for 2 months to determine their M values.

Hygroscopic measurements on kiln-dried large-dimension Japanese cedar timber

Fifty-six boxed-heart green timbers (longer than 4.0 m with 12 × 12-cm cross section) were separated into longer (3.6 m) and shorter (>0.4 m) parts. The longer parts were kiln-dried at high temperatures up to 120°C with a conventional method, while the shorter ones were dried at room temperature. After kiln drying, the average moisture content of timber varied from 6.1% to 30.0% (12.9% as a mean). After 1 month of conditioning at room temperature, the center parts of the timbers were cut into blocks of dimensions 1 (L) × 12 × 12 cm. Each block was then separated into 36 small pieces of dimensions 1 (L) × 2 × 2 cm, and 6 pieces on a diagonal line of the cross section were milled to give wood meal of fineness 0.5–1.0 mm. The wood meal samples were extracted in methanol and water in the same manner as described above. The water-extracted wood meals were absolutely dried at room temperature, and then their M values were determined at 20°C and 60% RH after 2 months of conditioning.

Results and discussion

Variation in the original hygroscopicity of Japanese cedar wood

Figure 1 shows two typical variations of equilibrium moisture content (M) at 20°C and 60% RH in the transverse cross section of boxed-heart Japanese cedar timber. In the type I specimen, the M of heartwood was lower than that of

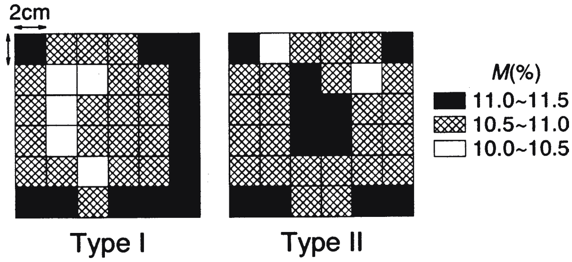

Fig. 1. Typical variations of equilibrium moisture contents (*M*) at 20°C and 60% relative humidity (RH) in the cross section of boxed-heart square timber of Japanese cedar wood

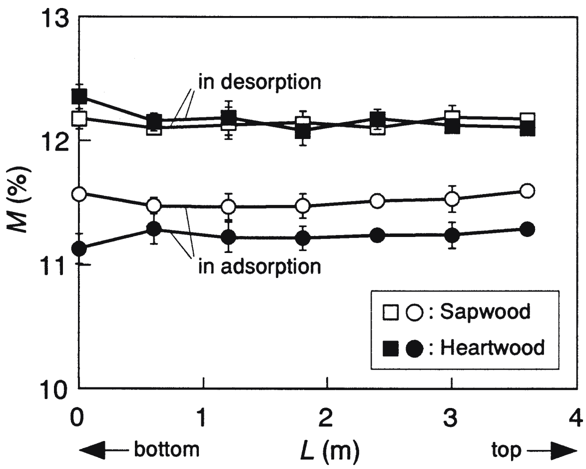

Fig. 2. Effects of longitudinal position (*L*) on the equilibrium moisture contents (*M*) at 20°C and 60% RH of a Japanese cedar log. *Bars* indicate standard deviations

sapwood. In the type II specimen, the *M* of pith and sapwood were almost the same while a ring-like middle part gave a lower *M*. These different variations were attributable to the localization of some hydrophobic extractives: the homogeneous dispersion of extractives gave the type I distribution, whereas the type II distribution resulted from the localization of extractives at the border between the heartwood and sapwood. In any case, however, the variation in *M* was very small. Figure 2 shows the longitudinal variation of *M* in a Japanese cedar wood log. Although the desorption and adsorption processes gave different *M* because of a hysteresis effect, the *M* values were independent of longitudinal position. Table 1 lists the minimum, mean, and maximum *M* values of all unheated specimens tested. Although the specimens included both the sapwood and heartwood from 56 timbers, their *M* values varied only slightly. Thus, the natural variation in the hygroscopicity of Japanese cedar wood is small enough to assume its homogeneity.

Loss in weight due to heat treatments and subsequent water extraction

In general, the loss in weight (*WL*) due to heating is an indication of thermal degradation, because it reflects the amount of wood components depolymerized and lost at high temperatures. When such degradation occurs in the framework of the wood cell wall, it directly degrades the practical performance of wood. Actually, the mechanical properties of heat-treated wood often depend on *WL*.[16,20,23–25]

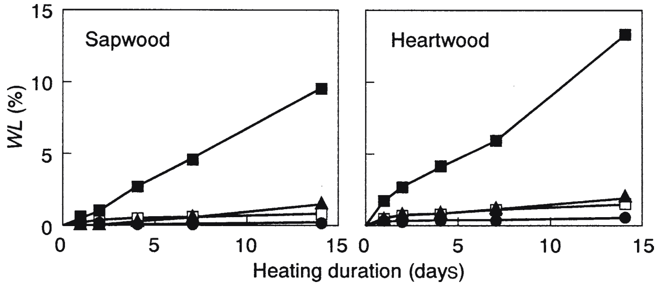

Fig. 3. Loss in weight (*WL*) of sapwood and heartwood specimens due to heat treatments as functions of heating duration. *Circles*, steamed at 60°C; *triangles*, steamed at 90°C; *filled squares*, steamed at 120°C; *open squares*, heated in dry at 120°C

Table 1. Equilibrium moisture content (*M*) of unheated Japanese cedar at 20°C and 60% relative humidity (RH)

n	Min (%)	Mean (%)	Max (%)	SD (%)
2016[a]	10.2	10.9	11.8	0.3

[a] Thirty-six specimens were obtained from 56 boxed-heart timbers

Figure 3 shows the *WL* of wood specimens as a function of heating duration. The *WL* of heartwood was slightly larger than that of sapwood because of greater contents of resin or other volatile substances that are removable on heating. At the same heating temperature (120°C), the *WL* due to steaming was much greater than that due to dry heating. As suggested by many researchers, the hydrolysis of wood components, especially that of hemicelluloses, is drastically accelerated in the presence of moisture.[16,17,26,27] On the other hand, the *WL* due to steaming at 60°C and 90°C were very small (<2%), and did not strongly depend on the heating duration. This fact did not indicate that the treatment caused little thermal degradation but that part of the depolymerized substances still remained in the wood specimens. These decomposition products are no longer major components, but they affect the hygroscopicity of wood.[21] Therefore, such minor residues should be removed when evaluating the changes in major wood polymers responsible for various practical performances of wood. Figure 4 shows the total weight losses due to heating and subsequent extraction in water (WL_e) plotted against the heating duration. Although the WL_e due to steaming at 60°C was still independent of heating duration, that due to steaming at 90°C increased monotonously with an increase in the steaming duration. Furthermore, the WL_e steeply increased in a few days of steaming at 120°C. These results suggest that the thermal degradation due to steaming is drastically accelerated by increasing the temperature above 90°C, whereas little degradation occurs at 60°C.

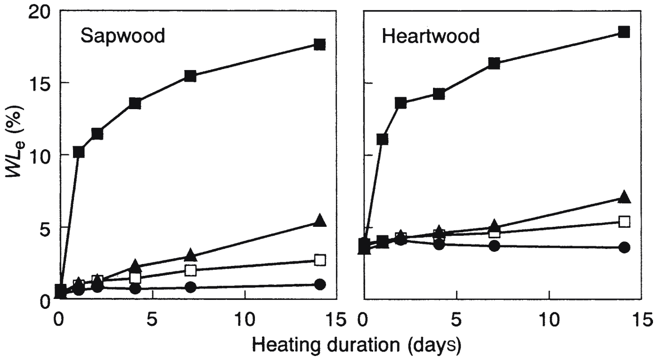

Fig. 4. Loss in weight of sapwood and heartwood specimens due to heat treatments and subsequent water extraction (WL_e) plotted against the heating duration. Symbols are the same as in Fig. 3

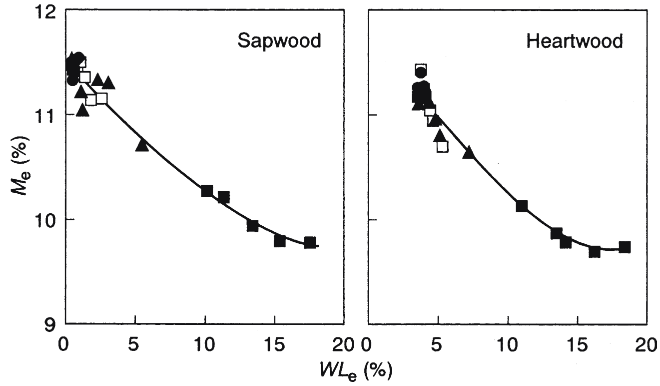

Fig. 6. Equilibrium moisture contents of water-extracted sapwood and heartwood specimens at 20°C and 60% RH (M_e) plotted against the WL_e. Symbols are the same as in Fig. 3

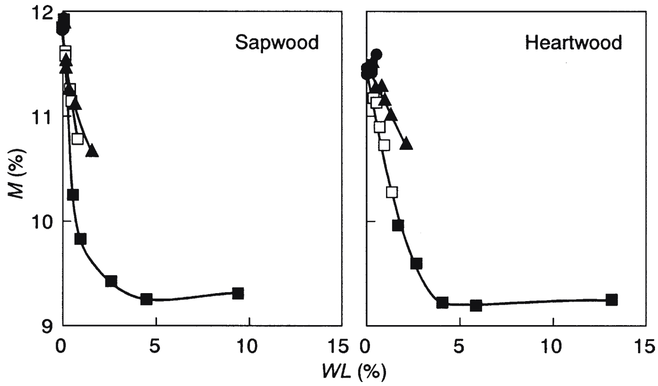

Fig. 5. Equilibrium moisture contents of unheated and heat-treated sapwood and heartwood specimens at 20°C and 60% RH as a function of *WL*. Symbols are the same as in Fig. 3

In Fig. 4, the heartwood shows a definite WL_e even in the unheated specimens. That loss was attributed to the removal of extractives originally present in heartwood. Such a loss should be taken into account when the WL_e is used as an indication of thermal degradation.

Effects of heating on the hygroscopicity of Japanese cedar wood

The *M* values of unheated and heat-treated specimens are plotted against the *WL* in Fig. 5. The sapwood and heartwood showed similar trends in which the *M* decreased with increasing *WL* up to 4%, after which it leveled off and tended to increase slightly. Remarkable reduction of *M* was induced by heating above 90°C, whereas no significant change was induced by the steaming at 60°C. At the same *WL*, higher treating temperature resulted in greater reduction of *M*.

The aim of this study was originally to evaluate the degradation of wood performances on the basis of hygroscopicity measurements. In this sense, the *M* of heated wood had been expected to depend on the *WL*, especially at high *WL* levels, irrespective of heating temperature. However, the experimental results failed to meet this expectation, that is, the *M* did not depend on *WL* above 4%, and different heating temperature gave different trends on the plots of *M* vs *WL*.

Here we reconsider the changes in *M* due to heating. Lower hygroscopicity of heat-treated wood is usually attributed to the irreversible structural changes of wood constituents, such as the loss and chemical changes of hygroscopic hemicelluloses[19,20] and the recrystallization of cellulose.[28] However, it should be recalled that the water-soluble decomposition residue also affects the hygroscopicity of wood, and, therefore, the effects of such minor components should be excluded for the evaluation of thermal degradation in major components. Figure 6 exhibits the equilibrium moisture content of extracted specimens (M_e) plotted against WL_e. After the removal of extractives, the hygroscopicity of steamed wood slightly increased with large loss in weight. Consequently, the M_e showed a monotonous decrease with an increase of WL_e up to 18%. Although the correlation between M_e and WL_e was obscure at low WL_e levels (<5%), the M_e depended strongly on WL_e above 5% irrespective of heating temperatures (90°–120°C). These trends seem suitable for the current trial.

As shown in Fig. 6, the heartwood gave greater WL_e on the whole because it had contained about 4% natural extractives. To cancel the effects of such extractives, the following factors were defined:

$$HM_e = M_e(\text{heated}) - M_e(\text{unheated}) \quad (1)$$

$$HWL_e = WL_e(\text{heated}) - WL_e(\text{unheated}) \quad (2)$$

These reflect only the thermal effects under the assumptions that the original heartwood extractives remain soluble in water and their disappearance results in no significant changes in the hygroscopicity of major wood components. Figure 7 shows the plots of HM_e vs HWL_e for the wood specimens heated at 90°C and 120°C. The plots lay around a curve regardless of sapwood and heartwood so that we do not have to distinguish the sapwood and heartwood when the HWL_e of local parts are evaluated from their HM_e. In Fig. 7, the plots for dry-heated sapwood also locate around the regression curve for steamed wood. This fact suggests

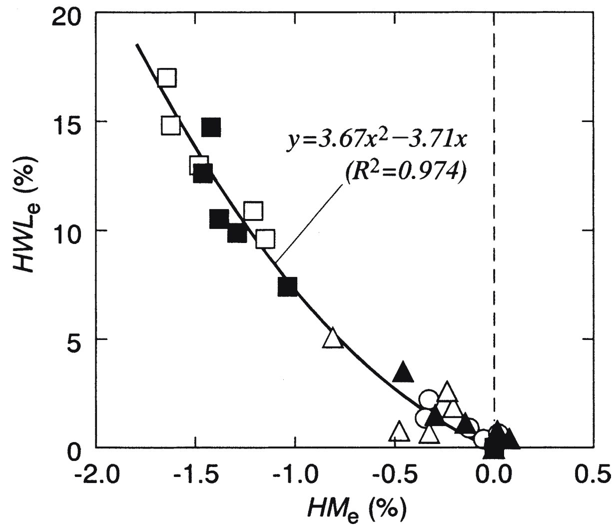

Fig. 7. Relationship between the changes in WL_e (HWL_e) and that in M_e (HM_e) of wood specimens due to heating above 90°C. *Triangles*, steamed at 90°C; *squares*, steamed at 120°C; *circles*, heated in dry at 120°C; *open symbols*, sapwood; *filled symbols*, heartwood

that the regression curve is applicable to the surface of large-dimension timber where the sapwood is possibly "heated in dry."

Evaluation of thermal degradation in the local parts of large-dimension kiln-dried timber

Figure 8 demonstrates typical variations of HM_e and HWL_e in the transverse cross section of boxed-heart Japanese cedar timber that had been kiln-dried at high temperatures up to 120°C. The HWL_e values were evaluated from the experimental values of HM_e according to the formula shown in Fig. 7. Although detailed hygrothermal history was unknown, the greater HWL_e corresponding to smaller HM_e values of inner parts suggested more remarkable thermal degradation. It was supposed that the inner part was kept humid for longer and as such the prolonged "steaming" resulted in greater decomposition of wood. On the contrary, the outer part could be dried faster and heated with less moisture. Furthermore, the temperature of the outer part must be more or less reduced by the dehydration at the surface. These may be reasons for less degradation in the outer parts of large-dimension timber.

As described earlier, the natural variation of hygroscopicity is very small in Japanese cedar wood. In addition, no complicated equipment is needed for measuring the equilibrium moisture content. These are advantages of hygroscopicity measurement as a method for rough evaluation of nonuniform thermal degradation in large-dimension kiln-dried timber. The mechanical properties of heat-treated Japanese cedar will appear in a following article.

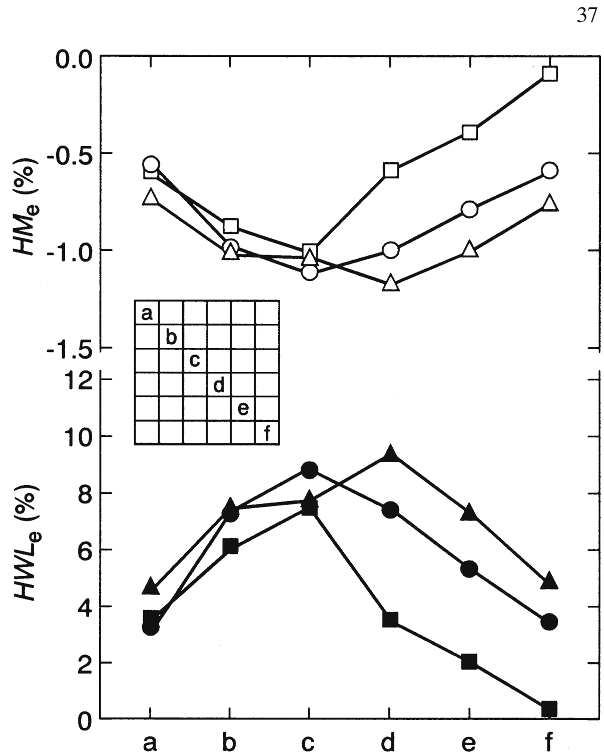

Fig. 8. Experimental values of HM_e and calculated values of HWL_e for the cross section of three boxed-heart Japanese cedar timbers kiln-dried at high temperatures up to 120°C. Symbols indicate different three timbers

Conclusions

Significant loss in weight (WL) and reduction in equilibrium moisture content (M) were recognized in Japanese cedar wood specimens after heating at 90° and 120°C, whereas no change was induced by steaming at 60°C. The M of heated wood was reduced with an increase of WL, and such a correlation became clearer after water extraction. Hygroscopicity variations in large-dimension timbers suggested that the thermal degradation of inner parts was greater than that of outer parts when a large-dimension timber is kiln-dried at high temperatures.

Acknowledgments Part of this work was performed as part of the Cooperation of Innovative Technology and Advanced Research in Evolutional Area (Yoneshiro Basin Area), which is supported by the Ministry of Education, Culture, Sports, Science, and Technology and the Akita Wood Technology Transfer Foundation.

References

1. Nakada R, Fujisawa Y, Hirakawa Y, Yamashita K (1998) Longitudinal change of the green moisture content in the stem of *Cryptomeria japonica* D.Don (in Japanese). Mokuzai Gakkaishi 44:395–402
2. Yoshida Y, Hashizume T, Fujimoto N (2000) High-temperature drying characteristics on box-heart square timber of karamatsu and sugi: influences of high temperature conditions with low humidity on drying properties (in Japanese). Wood Ind 55:357–362
3. Gerhards CC (1983) Effect of high-temperature drying on bending strength of yellow-poplar 2 by 4's. Forest Prod J 33:61–67

4. Yao J, Taylor F (1979) Effect of high temperature drying on the strength of southern pine dimension timber. Forest Prod J 29:49–51
5. Price EW, Koch P (1980) Kiln time and temperature affect shrinkage, warp, and mechanical properties of southern pine timber. Forest Prod J 30:41–47
6. Kubojima Y, Shida S, Okano T (1998) Mechanical and chromatic properties of high-temperature-dried sugi wood (in Japanese). Wood Ind 53:115–119
7. Yoshida T, Hashizume T, Nakajima Y, Takeda T (1999) Effects of high temperature kiln drying on mechanical properties on square-sawn Japanese larch timbers I: bending strength (in Japanese). Wood Ind 54:122–125
8. Nakajima Y, Takeda T, Yoshida T, Hashizume T (1999) Effects of high-temperature kiln drying on mechanical properties on square-sawn Japanese larch timbers II: compressive strength (in Japanese). Wood Ind 54:265–268
9. Kubojima Y, Shida S (2001) Impact bending and shear properties of high-temperature-dried sugi (*Cryptomeria japonica* D.Don) wood (in Japanese). Wood Ind 56:64–68
10. Thompson WS (1969) Effects of steaming and kiln drying on the properties of southern pine poles. Part II: chemical properties. Forest Prod J 19:37–42
11. Kozlik CJ (1976) Effect of high temperature drying on tensile strength of Douglas-fir and western hemlock timber. Forest Prod J 26:30–34
12. Gerhards CC (1979) Effect of high temperature drying on tensile strength of Douglas-fir 2 by 4's. Forest Prod J 29:39–46
13. Doi S, Takahashi M, Yoshimura T, Kubota M, Adachi A (1998) Attraction of steamed Japanese larch (*Larix leptolepis* (Sieb. et Zucc.) Gord.) heartwood to the subterranean termite *Coptotermes formosanus* Shiraki (Isoptera: Rhinotermitidae). Holzforschung 52:7–12
14. Doi S, Kurimoto Y, Ohmura W, Ohara S, Aoyama M, Yoshimura T (1999) Effects of heat treatments of wood on the feeding behavior of two subterranean termites. Holzforschung 53:225–229
15. Kano H, Shibutani S, Hayashi K, Iijima Y, Doi S (2004) Effect of high-temperature drying processes on termite resistance of sugi (*Cryptomeria japonica*) heartwood (in Japanese). Mokuzai Gakkaishi 50:91–98
16. Stamm AJ (1956) Thermal degradation of wood and cellulose. Ind Eng Chem 48:413–417
17. Hillis WE (1984) High temperature and chemical effects on wood stability part 1: general considerations. Wood Sci Technol 18:281–293
18. Seborg RM, Tarkow H, Stamm AJ (1953) Effect of heat upon the dimensional stabilization of wood. J Forest Prod Res Soc 3:59–67
19. Mitchell RL, Seborg RM, Millett MA (1953) Effect of heat on the properties and chemical composition of Douglas-fir wood and its major components. J Forest Prod Res Soc 3:38–73
20. Stamm AJ (1964) Wood and cellulose science. Ronald, New York, pp 317–320
21. Obataya E, Higashihara T, Tomita B (2002) Hygroscopicity of heat-treated wood III: effect of steaming on the hygroscopicity of wood (in Japanese). Mokuzai Gakkaishi 48:348–355
22. Obataya E, Tomita B (2002) Hygroscopicity of heat-treated wood II: reversible and irreversible reductions in the hygroscopicity of wood due to heating (in Japanese). Mokuzai Gakkaishi 48:288–295
23. Millett MA, Gerhards CC (1972) Accelerated aging: residual weight and flexural properties of wood heated in air at 115°C to 175°C. Wood Sci 4:193–201
24. Dwianto W, Norimoto M, Morooka T, Tanaka F, Inoue M, Liu Y (1998) Radial compression of sugi wood (*Cryptomeria japonica* D.Don). Holz Roh Werkst 56:403–411
25. Saito Y, Takahashi S, Shida S, Arima T (2004) Changes of hygroscopicity and dynamic Young's modulus of wood by high temperature heat treatment (in Japanese). Mokuzai Gakkaishi 50:139–145
26. Hsu WE, Schwald W, Schwald J, Shields JA (1988) Chemical and physical changes required for producing dimensionally stable wood-based composites part 1: steam pretreatment. Wood Sci Technol 22:281–289
27. Higashihara T, Morooka T, Hirosawa S, Norimoto M (2004) Relationship between changes in chemical components and permanent fixation of compressed wood by steaming or heating (in Japanese). Mokuzai Gakkaishi 50:159–167
28. Hirai N, Sobue N, Asano I (1972) Studies on piezoelectric effect of wood IV: effects of heat treatment on cellulose crystallites and piezoelectric effect of wood. Mokuzai Gakkaishi 18:535–542