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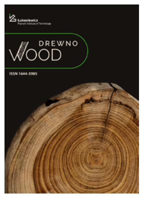

Moisture state and bending properties of Japanese larch (*Larix kaempferi*) boxed-heart timbers subjected to high-temperature kiln drying and stored under different conditions

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The high-temperature setting (HTS) method is a kiln drying method in which boxed-heart (BH) timbers are rapidly dried at high temperatures and low relative humidity. We investigated the moisture state and mechanical properties of Japanese larch (Larix kaempferi) BH timbers dried using this method and the effects of storage conditions on these properties. The timbers were dried under four different conditions: 18 h HTS kiln drying, 48 h HTS kiln drying, medium-temperature kiln drying, and air seasoning. They were then stored for one year under three different conditions, namely outdoor storage exposed to the weather, outdoor roofed storage, and indoor storage. After any of the storage treatments, the moisture gradient from the surface to the middle in the HTS-dried timbers was larger than that in the air-seasoned timbers and similar to or larger than that in the medium-temperature-dried timbers. The gradient in the HTS-dried timbers after outdoor roofed storage or indoor storage was smaller than that after outdoor storage exposed to the weather. The mechanical properties did not differ significantly among the timbers after different storage conditions for all drying conditions. The modulus of elasticity of the HTS-dried timbers was comparable to that of the medium-temperature-dried and air-seasoned timbers. The bending strength of the timbers dried by 18 h HTS drying was lower than that of the timbers dried by air seasoning, but comparable to or higher than that of the timbers dried by medium-temperature drying. The strength of the timbers dried by 48 h HTS drying was comparable to or lower than that of the timbers subjected to medium-temperature drying.

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Introduction

More than 300,000 wooden houses are built annually in Japan using the traditional framework construction method (Kurokawa, 1990; Matsudome, 1990). In these houses, boxed-heart (BH) timbers, which contain pith enclosed within the four surfaces of the timber, are used as structural members. The demand for properly dried timber for the construction of wooden houses in Japan has increased, because the use of such timber can shorten the construction period and prevent the distortion of members after construction. Drying of the BH timber is challenging because it consists mostly of heartwood, which dries slowly and is prone to develop drying checks on the timber surface due to its anisotropic shrinkage. To solve this problem, the

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high-temperature setting (HTS) method, which is a kiln drying method, has been developed. In this method, BH timbers are softened by steaming and then rapidly dried under high temperature and low relative humidity (Yoshida et al., 2000; 2004). Since a large tension set is formed on the surface layer of the timber during the initial drying stage, the occurrence of surface checks is prevented (Tokumoto et al., 2004; 2005). The HTS method is currently widely used throughout Japan as an important technique for BH timber drying.

Japanese larch (*Larix kaempferi*) is a major silvicultural species in northern and central Japan because of its rapid growth and high cold tolerance (Matyssek and Schulze, 1987; Takei, 1992; Kurinobu, 2005; Ryu et al., 2009). It has been planted not only in Japan, but also in northern Europe, northern China, and North America (Park and Fowler, 1983; Takei, 1992). The value of Japanese larch timber as a structural material has increased recently because its disadvantages, such as abundant resin exudation and severe checking and twisting due to drying, can now be ameliorated by the improvement of drying techniques, including the development of the HTS method. Japanese larch BH timber dried using the HTS method has also been used in wooden construction.

Although the application of the HTS method to the drying of BH timber has various advantages, kiln drying at high temperatures can cause a reduction in wood strength (Kuroda, 2007). The effects of high-temperature drying on the mechanical properties of wood have been investigated using small specimens and solid boards (Campean et al., 2007; Frühwald, 2007; Oltean et al., 2007; Sik et al., 2009; Borrega and Kärenlampi, 2010; 2011; Herrera-Díaz et al., 2017; Kumar et al., 2022; Sargent and Lenth, 2022). However, limited information is currently available regarding the effects of HTS drying on the mechanical properties of Japanese larch BH timbers. Studies comparing the mechanical properties of Japanese larch BH timbers dried using the HTS method with those of timbers dried using other methods are also scarce. Greater insight into the mechanical properties of HTS-dried Japanese larch BH timbers is important for more effective use of these timbers.

The environmental conditions under which structural wood materials are stored until use and those under which they are used are important factors that affect the construction and performance of wooden buildings. When structural wood materials are placed outdoors, the environmental conditions can affect certain of their properties, such as moisture state, dimensional stability, and strength, for example due to the effects of wet–dry cycles and ultraviolet exposure. Previous studies have investigated the effects of outdoor exposure on the physical and mechanical properties of wood-based materials (Biblis, 2000; Hayashi et al., 2000; 2002, 2005; Kojima et al., 2011, 2012, 2017; Korai, 2012; Sekino et al., 2014; Korai et al., 2015). However, the effects of storage conditions, including outdoor storage, on the properties of Japanese larch BH timbers dried using the HTS method remain unclear.

In this study, Japanese larch BH timbers were divided into four groups and dried under different conditions, including two HTS conditions. The timbers of each group were further divided into three groups and stored under different conditions for one year. The moisture state and mechanical properties of the timbers were investigated and compared under different drying and storage conditions. Based on these results, the moisture state and mechanical properties of Japanese larch BH timbers dried using the HTS method and the effects of storage conditions on these properties are discussed.

Materials and methods

1. Timber specimens

Approximately 40-year-old Japanese larch green logs with top-end diameters ranging from 16 to 22 cm were sawn into BH timbers with a cross-section of 135 × 135 mm^2 and a length of 3,000 mm. A total of 72 sawn timbers were collected. These timbers were used for the subsequent experiments.

2. Drying and storage conditions

The 72 BH timbers were divided into four groups, consisting of 18 timbers each and denoted as HS, HL, M, and AS. This grouping achieved a nearly equal mean dynamic modulus of elasticity (E_{fr}) for each group, measured as described below. The timbers of each group were stacked and then either kiln-dried or air-seasoned.

The HS, HL, and M timbers were placed in a kiln drying machine (SK-IF10LHP, Shinshiba Industries, Asahikawa, Japan). The HS and HL timbers were dried using the HTS method, and the M timbers were dried using medium-temperature drying. The HS and HL timbers were steamed at 95 °C for 7 h and then HTS-treated at a dry-bulb temperature of 120 °C and a wet-bulb temperature of 90 °C. The HTS treatment time for the HS timbers was 18 h, and that for the HL timbers was 48 h. The M timbers were dried at a dry-bulb temperature of 90 °C and wet-bulb temperatures of 60–85 °C after steaming at 95 °C for 7 h. The total drying time for these timbers was 312 h. The AS timbers were air-seasoned in parallel with the kiln drying of the other timbers. During the kiln drying and air seasoning processes, weights of 3.5 tons in total were loaded onto each timber stack to prevent warping and twisting.

After being dried, each timber group was further divided into three sub-groups, each comprising six timber units. These timber sub-groups were formed such that no significant differences in E_{fr} existed among them, and they were stored under different conditions and labeled OUT-E, OUT-R, or IN accordingly. The timbers for OUT-E and OUT-R storage were stored outdoors on stickers placed on the foundation of concrete blocks to keep the bottom of the timbers above the ground. Under the OUT-E conditions, the timbers were directly exposed to the weather. Under the OUT-R conditions, the timbers were covered with corrugated roof sheets to protect them from sunlight and precipitation. Under IN conditions, the timbers were stacked and stored indoors. All timbers were stored for one year at the Nagano Prefecture Forestry Research Center, Shiojiri, Japan (36°8'27"N, 138°0'0"E, altitude 850 m above sea level). The average annual temperature, annual precipitation, and average hours of sunlight per day during the storage treatments in the Shiojiri region were 11.7 °C, 1333.5 mm, and 5.9 h, respectively.

After each storage treatment, the timbers were processed into cross-sections of 120 × 120 mm^2. From each processed timber, a specimen for static bending tests with a cross-section of 120 × 120 mm^2 and a length of 2,400 mm was taken, and two 15 mm thick transverse disks were prepared for the investigation of moisture content and its gradient (Fig. 1).

3. Dynamic modulus of elasticity

Prior to drying, the E_{fr} value of the timbers was determined using the longitudinal vibration method (Sobue, 1986; Haines et al., 1996; Ilic, 2003; Yang et al., 2003). E_{fr} was also determined for the dry-treated timbers before and after the storage treatments. One cross-section of the test timber was tapped using a hammer to induce vibrations in the longitudinal direction of the timber. The longitudinal vibration transmitted within the timber was detected using a microphone placed near the other cross-section of the timber. The detected vibration was processed using a fast Fourier transform analyzer (SA-77, RION, Tokyo, Japan), and the first natural frequency of the vibration was determined. The weight and dimensions of the timber were measured to calculate its density. E_{fr} was calculated according to:

$$E_{fr} = (2Lf)^2\rho \quad (1)$$

where L is the length of the timber, f is the first natural frequency, and ρ is the density of the timber.

4. Moisture content and gradient

The moisture content of the timber samples before drying was measured using a high-frequency moisture meter (HM-520; Kett Electric Laboratory, Tokyo, Japan). The moisture content measured using this meter was denoted as MC_{mm} in this study. The MC_{mm} of the dry-treated timbers was measured before and after storage.

Of the two transverse disks cut from each timber sample after each storage treatment (Fig. 1), one disk was subjected to moisture content measurements using the oven drying method without further division. The moisture content measured using this method was denoted as MC_{od} in this study. From the other disk, a 40 mm wide central strip running from the top to the bottom when viewed in the cross-section of the disk was taken, and the strip was further cut into seven rectangular pieces (Fig. 1). The MC_{od} values of these pieces were measured, and the moisture gradient from the surface to the middle portions of the timber was examined.

5. Static bending properties

Static bending tests were conducted on the timber specimens prepared from each timber sample after each storage treatment (Fig. 1) according to the standard method of the International Organization for Standardization (2005). The specimens were tested under four-point loading using a material testing machine (UH-1000kNA, Shimadzu, Kyoto, Japan). The support span was 2,160 mm, which was 18 times the height of the specimen, and two loading points were set to divide the span into three equal parts of 720 mm each. The load was applied with stroke control at a constant

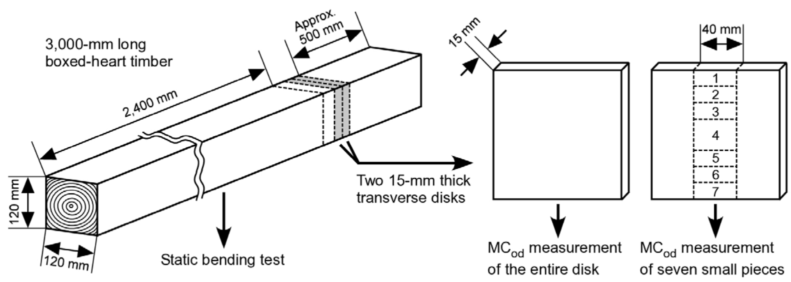

Fig. 1. Preparation of specimens for static bending tests and for measurement of moisture contents (MCod) using the oven-drying method

speed of 10 mm/min. The deflection at the midspan was measured using displacement gauges, and the load–deflection curve was recorded. The modulus of elasticity (MOE), modulus of rupture (MOR), and stress at the proportional limit (σ_{bp}) of the specimens were calculated using the following equations:

$$\mathrm{MOE} = \frac{\Delta Pa(3l^2 - 4a^2)}{4\Delta Ybh^3} \quad (2)$$

$$\mathrm{MOR} = \frac{3P_m a}{bh^2} \quad (3)$$

$$\sigma_{bp} = \frac{3P_p a}{bh^2} \quad (4)$$

where ΔP is the increment of the load in the linear region of the load-deflection curve, ΔY is the increment of deflection corresponding to ΔP, l is the support span, a is the distance between a loading point and the nearest support, b is the width of the specimen, h is the height of the specimen, P_m is the maximum load, and P_p is the load at the proportional limit. The work of bending (W_b), which is defined as the energy absorbed up to the maximum load of the specimen, was also determined. W_b was calculated as the area under the load–deflection curve from the origin to the maximum load point. The MOE value was adjusted to 15% moisture content using the equation given by the Japan Housing and Wood Technology Center (2011):

$$S_2 = S_1\ (1.857 - 0.0237 \times 15)/(1.857 - 0.0237M_1) \quad (5)$$

where S_2 is the MOE value at a moisture content of 15%, S_1 is the MOE value at testing, and M_1 is the MC_{od} value of the transverse disk. The MOR value was adjusted to 15% moisture content using the following equation (Japan Housing and Wood Technology Center, 2011):

$$S_2 = S_1 + (S_1 - 16.6)/(40 - M_1)\ \times (M_1 - 15) \quad (6)$$

where S_2 is the MOR value at a moisture content of 15%, S_1 is the MOR value at testing, and M_1 is the MC_{od} value of the transverse disk.

Results and discussion

1. Moisture content

The measured MC_{mm} values of the timbers and MC_{od} values of the transverse disks cut from each timber are listed in Table 1. The initial MC_{mm} before drying was approximately 40% and there were no significant differences in the MC_{mm} values between the groups. The MC_{mm} values of HS, HL, and M timbers were considerably reduced by kiln drying under each condition. Prior to the storage treatments, the MC_{mm} of the kiln-dried timbers was significantly lower than that of the AS timbers. Among the kiln-dried timbers, the HS timbers had the highest MC_{mm} values, followed by the HL timbers, and the M timbers had the lowest MC_{mm} values. The MC_{mm} of the kiln-dried timbers increased, whereas that of the AS timbers decreased under all storage conditions. After all storage treatments, although the differences in MC_{mm} between the drying conditions became smaller compared with those before storage, the MC_{mm} values of the HL and M timbers were lower than those of the HS and AS timbers. Under all storage conditions, the MC_{od} of the HL timbers was lower than that of the HS timbers, and the MC_{od} of the M timbers was significantly lower than that of the HS and AS timbers. These results indicate that excessive HTS drying and medium-temperature drying reduce the equilibrium moisture content of Japanese larch BH timber.

The MC_{od} values of the M and AS timbers after IN storage were significantly lower than those after OUT-E or OUT-R storage. Although significant differences between the storage conditions were not observed for the MC_{od} values of the HS and HL timbers, similar results were obtained for the MC_{od} values of these timbers. These results suggest that one-year storage conditions have similar effects on the moisture contents of Japanese larch BH timbers dried by the HTS method and the timbers dried by medium-temperature drying and air seasoning, and that indoor storage maintains the moisture content of these timbers at lower values than outdoor storage. After each storage treatment, the mean MC_{mm} and MC_{od} values were below 20% for all groups. It is likely that the moisture content of the HTS-dried timbers does not increase considerably, even if these timbers are stored outdoors for one year, similarly as with the medium-temperature-dried and air-seasoned timbers.

Under all drying conditions, the differences between the storage conditions were larger for the MC_{od} values than for the MC_{mm} values. MC_{od} represents the average moisture content of the entire disk, whereas MC_{mm} represents the moisture content of the surface region of the timber. The observed larger differences in MC_{od} appear likely to be mainly due to the differences in the moisture gradients in the timbers under different storage conditions.

2. Moisture gradient

The MC_{od} values of the small pieces prepared from each position of the transverse disks are shown in Fig. 2. The MC_{od} values of the surface region (positions 1 and 7 in Fig. 2) were lower than those of the interior region

Table 1. Moisture contents (MC_{mm} and MC_{od}) of Japanese larch boxed-heart (BH) timbers dried by different methods and stored under different conditions for one year

Drying condition	Storage condition	MC_{mm} (%)			MC_{od} (%)
		Initial	Before storage	After storage	
HS	OUT-E	44.4 ± 10.0	13.6 ± 5.6^{B}	17.8 ± 3.8	18.40 ± 1.18^{A}
	OUT-R	38.8 ± 11.1	13.8 ± 3.6^{B}	16.4 ± 2.3	18.20 ± 1.22^{A}
	IN	41.5 ± 5.1	15.0 ± 1.7^{B}	15.6 ± 1.7	15.83 ± 2.01^{A}
HL	OUT-E	36.3 ± 5.0	10.1 ± 1.6^{B}	14.1 ± 1.4	17.54 ± 2.63^{AB}
	OUT-R	43.2 ± 5.7	11.3 ± 2.4^{B}	14.1 ± 1.6	15.31 ± 1.08^{BC}
	IN	39.4 ± 4.5	10.3 ± 2.7^{BC}	13.1 ± 1.7	14.47 ± 1.56^{AB}
M	OUT-E	37.1 ± 6.0	7.0 ± 2.0^{B}	13.9 ± 2.2	15.36 ± 0.96$^{B, a}$
	OUT-R	44.0 ± 4.9	8.4 ± 1.6^{B}	14.9 ± 2.2	14.35 ± 1.04$^{C, a}$
	IN	42.9 ± 4.9	7.6 ± 2.0^{C}	13.7 ± 1.7	11.56 ± 0.91$^{B, b}$
AS	OUT-E	41.3 ± 5.1	24.2 ± 3.1^{A}	17.9 ± 2.8	19.97 ± 1.79$^{A, a}$
	OUT-R	40.5 ± 9.2	30.3 ± 6.9^{A}	16.5 ± 1.4	16.41 ± 0.40$^{AB, b}$
	IN	43.7 ± 3.9	29.8 ± 3.2^{A}	16.6 ± 2.0	14.12 ± 0.27$^{A, c}$

MC_{mm}, moisture content measured before the drying treatments (initial), before the storage treatments following the drying treatments (before storage), and after the storage treatments (after storage) using a high-frequency moisture meter; MC_{od}, moisture content of the transverse disks. HS, drying using 18-h high-temperature setting (HTS) treatment; HL, drying using 48-h HTS treatment; M, medium-temperature drying; AS, air-seasoning; OUT-E, outdoor storage exposed to the weather; OUT-R, outdoor roofed storage; IN, indoor storage. Values are presented as mean ± standard deviation (n = 6). Different uppercase letters in the same column indicate significant differences between the drying conditions in the same storage treatment groups, and different lowercase letters in the same column indicate significant differences between the storage conditions under the same drying conditions (Steel-Dwass test, P < 0.05).

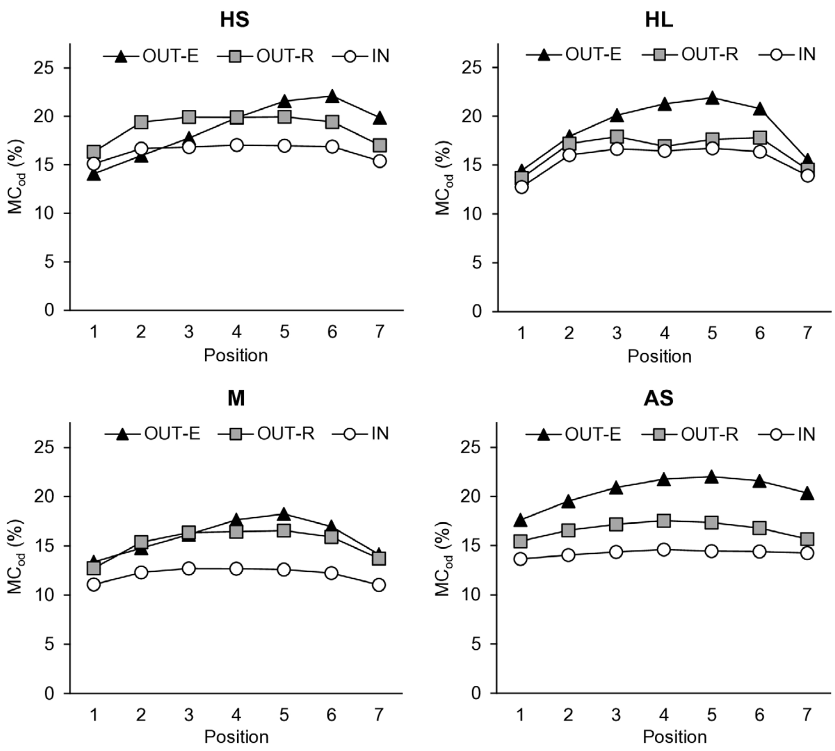

Fig. 2. Variation of moisture content (MCod) from the surface to middle region in Japanese larch BH timbers dried by different methods and stored under different conditions for one year. Sample position numbers correspond to those shown in Fig 1. Each point on the graphs represents the mean of the measurements on six different samples

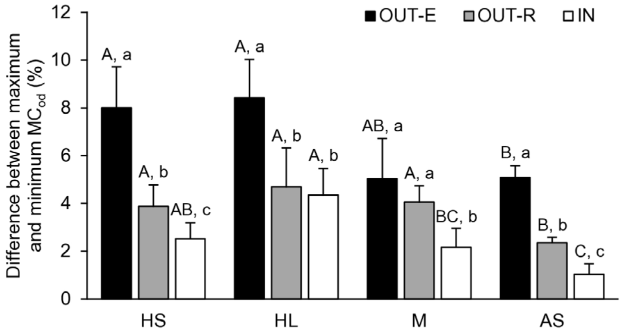

Fig. 3. Difference between the maximum and minimum moisture contents (MCod) within the same Japanese larch BH timbers dried by different methods and stored under different conditions for one year. The error bars represent the standard deviation of the mean (n = 6). Different uppercase letters show significant differences between the drying conditions in the same storage conditions, and different lowercase letters show significant differences between the storage conditions in the same drying conditions (Steel-Dwass test, P < 0.05)

(positions 2–6 in Fig. 2) for all investigated disks. Under all storage conditions, the moisture gradient in the cross-sectional direction, i.e., the MC_{od} difference between the surface and interior regions, in the HL timbers was the largest among the four dry-treated groups. The moisture gradient in the HS timbers was larger than that in the AS timbers and was similar to or larger than that in the M timbers. The difference between the maximum and minimum MC_{od} values within the same timber was significantly larger for the HL and HS timbers than for the AS timbers (Fig. 3). These results indicate that the moisture gradient in Japanese larch BH timbers dried by the HTS method, particularly when using a long HTS treatment time, is larger than that of the timbers dried by air seasoning when stored for one year under the same conditions.

Under all drying conditions, the moisture gradient after OUT-E storage was the largest, followed by those after OUT-R and IN storage (Fig. 2). The difference between the maximum and minimum MC_{od} values within the same disk was significantly larger after OUT-E storage than after IN storage (Fig. 3). These results indicate that the moisture gradient in the HTS-dried timbers was larger after one year of weather exposure in outdoor storage than after one year of indoor storage, and similar results were obtained for the moisture gradient in the medium-temperature-dried and air-seasoned timbers. Furthermore, it is likely that outdoor storage with protection from direct sunlight and precipitation can suppress the moisture gradient in HTS-dried timbers more than outdoor storage with direct exposure to the weather. The moisture gradient in structural timber affects its dimensional stability (Yoshida et al., 1999). Nakajima and Tutihashi (2003) suggested that large-dimension Japanese larch timbers kiln-dried at high temperatures might be supplied as structural timbers with stable shape and quality when their moisture gradients are suppressed as much as possible and the moisture content of their interior regions is reduced to 20% or less. In this study, the mean MC_{od} at each position was lower than 20% under all drying conditions after OUT-R or IN storage (Fig. 2). The present results suggest that HTS-dried timbers stored without direct exposure to sunlight and precipitation may be more favorable in terms of dimensional stability than timbers stored with exposure to the weather.

3. Density and dynamic modulus of elasticity

The density measurement results are listed in Table 2. Before the drying treatments, the density did not differ significantly between the groups. Prior to storage, the densities of the dry-treated M and HL timbers were lower than those of the dry-treated HS and AS timbers. The observed density differences may be mainly due to the lower moisture content of the dry-treated M and HL timbers compared with those of the dry-treated HS and AS timbers (Table 1). The densities of the dry-treated HS and HL timbers did not decrease significantly after each storage treatment. This indicates that, similar to one-year indoor storage, one-year outdoor storage does not negatively influence the density of Japanese larch BH timbers dried using the HTS method. After the storage treatments, the density differences between the drying conditions were smaller than those recorded before the storage treatments. The density did not significantly differ between the drying conditions under all storage conditions and did not significantly differ between the storage conditions under all drying conditions. After one-year storage, the density of the HTS-dried timbers is likely to be comparable to that of the medium-temperature-dried and air-seasoned timbers. Furthermore, it is likely that the density of the HTS-dried timbers stored outdoors for one year is not lower than that of the timbers stored indoors for one

Table 2. Density of Japanese larch BH timbers dried by different methods and stored under different conditions for one year

Drying condition	Storage condition	Density (Kg/m^3)		
		Initial	Before storage	After storage
HS	OUT-E	672 ± 82	578 ± 77^AB^	550 ± 68
	OUT-R	667 ± 65	593 ± 37	569 ± 33
	IN	669 ± 72	584 ± 61	558 ± 59
HL	OUT-E	655 ± 36	506 ± 38^B^	520 ± 32
	OUT-R	692 ± 48	567 ± 42	565 ± 44
	IN	673 ± 65	545 ± 65	545 ± 53
M	OUT-E	649 ± 63	511 ± 41^B^	517 ± 38
	OUT-R	722 ± 32	554 ± 35	561 ± 30
	IN	674 ± 54	514 ± 51	532 ± 48
AS	OUT-E	663 ± 38	600 ± 33^A^	540 ± 32
	OUT-R	675 ± 58	597 ± 37	543 ± 37
	IN	690 ± 40	627 ± 41	578 ± 30

Values are presented as mean ± standard deviation (n = 6). Different uppercase letters in the same column indicate a significant difference between the drying conditions after the OUT-E storage (Steel-Dwass test, P < 0.05).

Table 3. Dynamic modulus of elasticity (E_{fr}) of Japanese larch BH timbers dried by different methods and stored under different conditions for one year

Drying condition	Storage condition	E_{fr} (GPa)		
		Initial	Before storage	After storage
HS	OUT-E	11.02 ± 1.76	10.96 ± 1.72	10.58 ± 1.59
	OUT-R	11.02 ± 1.56	13.40 ± 5.20	11.32 ± 1.57
	IN	11.07 ± 1.44	11.17 ± 1.46	11.07 ± 1.43
HL	OUT-E	10.95 ± 1.76	11.34 ± 1.63	10.68 ± 1.68
	OUT-R	10.97 ± 1.56	11.41 ± 1.50	11.31 ± 1.06
	IN	11.04 ± 1.44	10.89 ± 1.26	11.28 ± 1.42
M	OUT-E	11.08 ± 1.70	11.76 ± 1.61	11.14 ± 1.41
	OUT-R	11.07 ± 1.55	11.64 ± 1.47	11.16 ± 1.46
	IN	11.11 ± 1.45	11.95 ± 1.52	11.89 ± 1.58
AS	OUT-E	11.13 ± 1.72	11.04 ± 1.80	10.69 ± 1.67
	OUT-R	11.12 ± 1.52	11.04 ± 1.21	11.21 ± 1.56
	IN	11.15 ± 1.46	11.21 ± 1.35	11.63 ± 1.42

Values are presented as mean ± standard deviation (n = 6).

year, similarly as in the case of the medium-temperature-dried and air-seasoned timbers.

The measurement results for E_{fr} are listed in Table 3. Prior to the drying treatments, the E_{fr} values did not differ significantly between the groups. After the drying treatments, the E_{fr} values did not significantly differ among all drying conditions before and after each storage treatment. This indicates that the E_{fr} of the HTS-dried timbers is comparable to that of the medium-temperature-dried and air-seasoned timbers. Under all drying conditions, the E_{fr} of the dry-treated timber did not decrease considerably after each storage treatment. After the storage treatments, no significant differences in E_{fr} were observed among all storage conditions under any of the drying conditions. These results indicate that the E_{fr} of the HTS-dried timbers was not negatively influenced by either one-year outdoor storage or indoor storage, and the E_{fr} of the HTS-dried timbers after one-year outdoor storage was not inferior to that after one-year indoor storage, with similar results obtained for the medium-temperature-dried and air-seasoned timbers.

4. Static bending properties

The results of the static bending tests are shown in Fig. 4. Under all storage conditions, MOE values did not significantly differ between all drying conditions (Fig. 4a). This suggests that the MOE of Japanese larch BH timbers dried using the HTS method compares favorably with that of the timbers dried using medium-temperature drying and air seasoning. Takeda et al. (2004) showed that there was no significant difference in the MOE between sugi (*Cryptomeria japonica*) BH timbers dried using the HTS method and those dried using medium-temperature drying. For some other softwood and hardwood species, the MOE values of rectangular timbers dried at high temperatures (100–170 °C) have been shown not to differ appreciably from those of timbers dried by medium-temperature drying (Gerhards, 1983; Layton et al., 1986; Terziev and Daniel, 2002; Thiam et al., 2002; Frühwald, 2007; Sik et al., 2009; Borrega and Kärenlampi, 2010). The results of the present study are consistent with these previous results.

The MOR and σ_{bp} values of the kiln-dried timbers were lower than those of the AS timbers in all storage conditions (Fig. 4b, c). The MOR of the HL timbers was significantly lower than that of the AS timbers under OUT-E conditions. These results indicate that drying using the HTS method reduces the bending strength of Japanese larch BH timber. The MOR and σ_{bp} values of the HS timbers were higher than or comparable to those of the M timbers (Fig. 4b, c). This suggests that the bending strength of Japanese larch BH timbers dried using an appropriate HTS treatment time is not inferior to that of the timbers dried by medium-temperature drying, although it is lower than that of the timbers dried by air seasoning. In several softwood species, the bending strength of small specimens, planks, and boards that were kiln-dried at high temperatures (100–180 °C) has been shown to be lower than that of similar pieces dried by medium-temperature drying (Terziev and Daniel, 2002; Thiam et al., 2002; Frühwald, 2007;

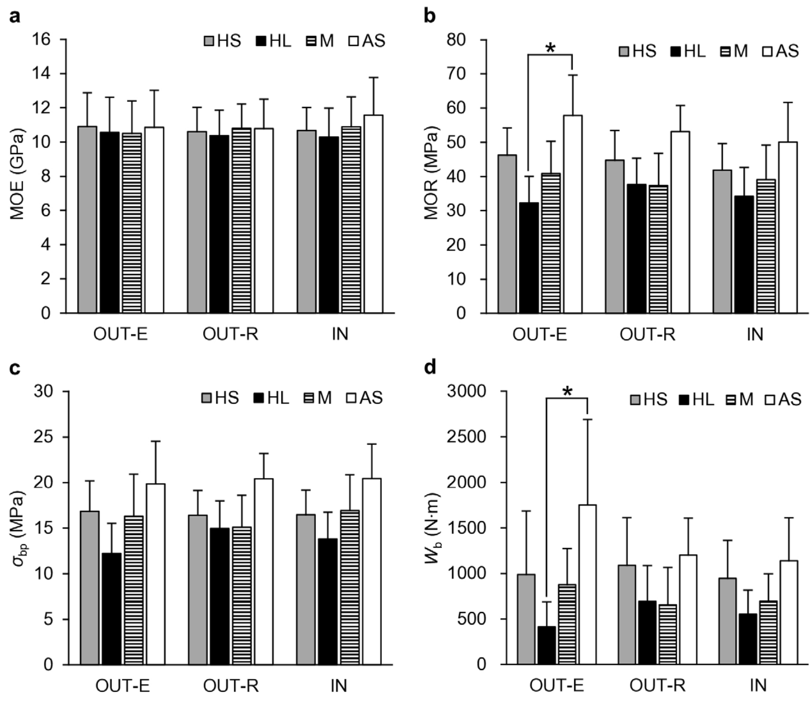

Fig. 4. Static bending properties of Japanese larch BH timbers dried by different methods and then stored under different conditions for one year. a, Modulus of elasticity (MOE); b, Modulus of rupture (MOR); c, Stress at the proportional limit (σbp); d, Work of bending (Wb). The error bars represent the standard deviation of the mean (n = 6). Asterisks indicate a significant difference between the HL and AS timbers after the OUT-E storage (Steel-Dwass test, P < 0.05)

Herrera-Díaz et al., 2017). In this study, the MOR and σ_{bp} values of the HL timbers were comparable to or lower than those of the M timbers (Fig. 4b, c). It is likely that the bending strength of Japanese larch BH timbers is significantly and negatively influenced by drying using an excessive HTS treatment time; the bending strength in that case is lower than that of the timbers dried by medium-temperature drying.

W_b was the largest in the AS-treated timbers, and the next largest in the HS timbers, followed by the HL and M timbers, under all storage conditions (Fig. 4d). It appears likely that the toughness of Japanese larch BH timbers dried using an appropriate HTS treatment time is higher than that of the timbers dried by medium-temperature drying, although lower than that of the timbers dried by air seasoning. The W_b value of the HL timbers was equivalent to or smaller than that of the M timbers under all storage conditions and was significantly lower than that of the AS timbers in the OUT-E conditions (Fig. 4d). This indicates that an increase in the HTS treatment time reduces the toughness of Japanese larch BH timber. Katagiri et al. (2005) suggested that sugi BH timber dried using a prolonged HTS treatment is more brittle than that dried using a short HTS treatment. It is likely that Japanese larch BH timbers dried using excessive HTS treatment time have lower toughness and are more brittle than those dried by medium-temperature drying or air seasoning.

Hemicelluloses of wood in green condition begin to be thermally softened and degraded at 80–90 °C (Tejada et al., 1998; Placet et al., 2008). Doi et al. (2005) demonstrated that high-temperature drying at 120–130 °C reduces the durability of Japanese larch BH timbers against the decaying fungus *Fomitopsis palustris* and attacks from the termites *Coptotermes formosanus* and *Reticulitermes speratus*. They hypothesized that the durability reduction occurred because the hemicelluloses in these timbers were hydrothermally degraded to low-molecular-weight sugar fragments during high-temperature drying. Sweet and Winandy (1999) suggested that hemicelluloses played an important role in determining the MOR and toughness of southern pine wood. It is possible that the hemicellulose in Japanese larch BH timbers is degraded during HTS drying, negatively influencing the strength and toughness of these timbers.

Under all drying conditions, no significant differences in the MOE, MOR, and σ_{bp} values were observed between storage conditions (Fig. 4). This suggests that the static bending properties of HTS-dried Japanese larch BH timber stored outdoors for one year are comparable to those of timber stored indoors as well as to those of medium-temperature-dried and air-seasoned timbers. Hayashi et al. (2002, 2005) demonstrated that laminated veneer lumber (LVL) exhibits reduced MOE and MOR values following year-long or long-term outdoor exposure. Additionally, other studies have demonstrated that oriented strand board (OSB), particleboard (PB), plywood (PW), and medium-density fiberboard (MDF) have reduced MOE and MOR values following year-long outdoor exposure (Hayashi et al., 2000; Kojima et al., 2011; 2012; 2017; Korai, 2012; Sekino et al., 2014). Overall, the mechanical properties of HTS-dried Japanese larch BH timber appear to be less influenced by the outdoor exposure of the timber for one year than the properties of wood-based materials such as LVL, OSB, PB, PW, and MDF.

Conclusions

This study indicates that the moisture state of Japanese larch BH timbers dried using the HTS method is affected by one-year storage conditions, whereas the mechanical properties of such timbers are not significantly affected by these conditions. Storage without direct exposure to sunlight and precipitation is likely to suppress the moisture gradient in the cross-sectional direction of the HTS-dried timbers compared with storage with direct exposure to the weather. The results also indicate that the modulus of elasticity of the HTS-dried timbers is comparable to that of the medium-temperature-dried and air-seasoned timbers. The bending strength and toughness of HTS-dried timbers dried using an appropriate HTS treatment, such as the HS timbers, were not inferior to those of the medium-temperature-dried timbers, although they were lower than those of the air-seasoned timbers. It is likely that these properties are significantly and negatively influenced by drying using a longer HTS treatment, for example under the HL conditions. The information obtained in this study is expected to contribute to the further understanding and effective use of HTS-dried timbers.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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