Mechanical characteristics of aged Hinoki (Chamaecyparis obtusa Endl.) wood from Japanese historical buildings

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Mechanical characteristics of aged Hinoki (*Chamaecyparis obtusa* Endl.) wood from Japanese historical buildings Ⅱ

Comparison between naturally aged wood and thermally treated wood

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Abstract

This paper deals with the mechanical properties of naturally aged wood and thermally treated wood wood. Naturally aged wood samples delivered from Japanese historical buildings are precise dating with using both radioactive carbon dating ^{14}C and dendrochronology methods. And Hinoki (*Chamaecyparis obtusa* Endl.) specimens cut out from recently felled down and naturally dried were heated at 90-180 °C as accelerated aging treatment. The general trends in rigidity, Young's modulus and rupture energy might be similer, quantitative differences are likely to be observed between the various kinds of modifications induced by age.

1. INTRODUCTION

From the ancient times, wood has been used as construction materials, and some wooden buildings have been preserved for over a thousand years such as Horyu-ji Temple which is one of the oldest wooden buildings in the world. On the other hand, wood has also been used for various wooden artifacts like Buddhist statues, and aged ones are handled with highly care, because of their fragile qualities. It is well known that the properties of wood change over a long period in the environment after harvesting. Studies about the changes in physical and mechanical properties with elapsed time have been conducted due to the importance of safe long-term use and as basic studies of wood science. [1-4] In a previous paper the author examined he mechanical properties of naturally aged Hinoki (*Chamaecyparis obtusa* Endl.) from Japanese historical buildings. Although aged wood appeared more rigid and stronger than the recent wood, after density and humidity corrections no clear trend was anymore observed for L and R rigidity, as well as for L strength. The post-linear behavior, however, was drastically influenced by wood age. Aged wood was brittle, especially in R direction. [5] In another parallel study, lightness L* systematically decreased with time or temperature, variations of redness a* and yellowness b* exhibited complex patterns, indicating the combined action of several processes subject to different thermally activation. The extrapolation to the color of ancient wood was only possible by taking into account the accelerating effect of the ambient conditions, taken as equivalent to higher temperature levels. [6]

As for mechanical properties of thermally treated wood , Kohara considered that the aging was a long-term accumulation of heating at the atmospheric temperature, and showed that the hygroscopicity and the composition of components of thermally heated wood at 105℃ and 130 ℃ were analogous to those of naturally aged wood. [1] Kajita et.al indicated that the dynamic Young's modulus of heated at 70-170 ℃ once increased in the initial stage of heating times and then decreased. [7] And another common effect of aging and thermally treatment is the color change in the parallel study. [6] And in the previous and applied study, thermally treated wood were used in the conservation and restoration of Japanese wooden Buddhist statues. Fig. 1 shows the color changes of Hinoki samples with thermally treated and restored wooden statured using thermally treated wood.

Hence, comparing the mechanical properties of thermally treated wood with naturally aged wood is very important to investigate the mechanism and prediction of aging of wood. In this paper, the specimens were completely dried to avoid the effect of hydrolysis and then treated under the range of temperature from 90 to 180 °C, well below the thermal decomposition point of wood in dry condition. Therefore it was expected that just the effect of thermal oxidation on mechanical properties change was estimated and that it will be possible to predict mechanical properties change during natural aging where almost only thermal oxidation occurs.

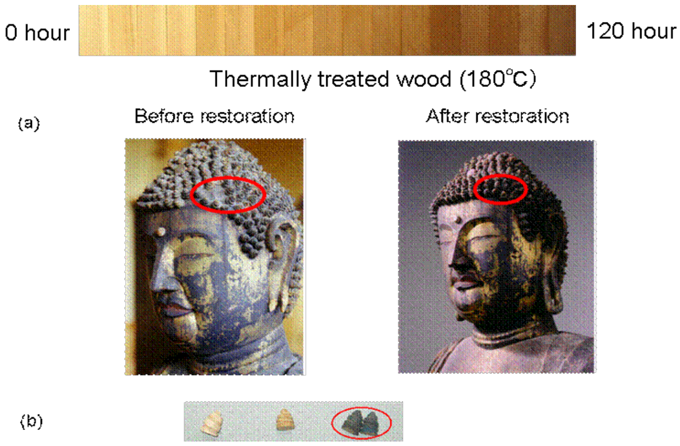

Fig.1 the color changes of Hinoki samples with thermally treated (a) and restored wooden statured using thermally treated wood (b).

2. Materials and method

Sample origins

The aged samples were Hinoki (*Chamaecyparis obtusa*) wood from Japanese historical buildings, mostly Horyu-ji temple in Nara. The specimens used in this study were cut from aged wooden members provided from the restoration sites, which were not reused. The appearance of the buildings and deliverd each aged wood samples are shown in Fig.2. The modern wood used for comparison was taken from 360-years-old Hinoki (*Chamaecyparis obtusa* Endl.) from Kiso, Japan was used. The tree was harvested in 1988 corresponding to annual rings from A.D. 1629 to 1988, and the wood had been dried for 18 years in ambient condition in shed.

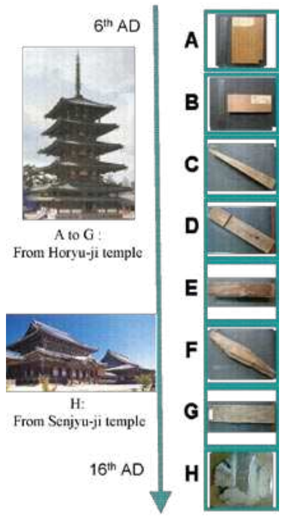

Fig.2 Aged wood samples from Japanese historical buildings.

Samples labeling, origin and basic structural information are given in Table 1. To avoid the effect of UV degradation and insects, the outer layer parts and the nails were removed, and the specimens for mechanical testing were taken from the central portion of the samples. No sapwood occurrence was detected, so that all the studied
materials were consisted of heartwood.

Age determination of naturally aged wood samples

To evaluate wood age, radioactive carbon dating ^{14}C and dendrochronology were used. For each sample the wood was processed as a board containing more than 60 tree rings. Tree ring dating was performed by comparing these ring patterns with a standard pattern available until back to 912 BC for Hinoki [8]. Distinct ring patterns of Hinoki enabled dating with yearly precision. For precision dating, ^{14}C wiggle-matching method was applied [9]. As shown in Table 1, the agreement between both methods was good: the difference between ^{14}C and dendro-date ranged from -40 to 29 years. These methods can only provide information about the wood age, defined as the time elapsed since wood formation in the tree. The analysis of colour variations in the same samples suggested that most of the aging occurred after wood processing [10], so that the period of time separating wood formation and tree felling should be subtracted from the wood age for the analysis of aging processes. However, in most cases this information is not available, and the time elapsed since tree felling (t_T) cannot be calculated. For the subsequent analysis, an upper bound of t_T will be considered, based on the newest visible ring on the sample. For the most recent historical sample H and the reference I, this gives a direct estimate as the bark was included in the sample. For the older samples the relative error is likely to be small. In the following, this estimate of t_T will be designated as the “age” of the sample. [5]

Table 1: Origin and dating of the samples

	Collection	Origin	Block dimensions (R x T x L, cm)	RW (mm)	Dendro chronology* (AD)	^{14}C interval dating* (AD)	t_W (yrs)	t_T (yrs)
A	KYOw2701, RISH	HYJ	11 x 3.4 x 10	0.8	343 / 434	367 / 458	1618	1583
B	KYOw2738, RISH	HYJ	7.0 x 4.2 x 10	0.5	458 / 612	418 / 572	1467	1405
C	private	HYJ (leg)	6.7x 11.5 x 47	0.9	400 /502	418 / 520	1548	1515
D	private	HYJ (leg)	7.5 x 11.5 x 55	0.8	431 /537	421 / 527	1530	1480
E	private	HYJ (leg)	9.5 x 13 x 42	0.7	584 / 792	587 / 795	1319	1225
F	private	HYJ (leg)	5 x 7.8 x 52	1.0	1029 / 1086	1000 /1059	899	931
G	private	HYJ (leg)	2.5 x 14 x 58	0.8	1106 / 1270	1098 /1262	822	747
H	(temple donation)	SJJ	1100 (∅) x 30 (L)	0.8	1069 / 1438	1071 / 1438	753	569
I	(workshop)	Kiso forest		1.0	1622 / 1988	1631 / 1973	200	19

HYJ = Horyuji temple, Nara ; (leg) = legendly ; SJJ = Senjyuji temple, Mie ; RW =average width of annual rings ; * dates (A.D.) of first/last measured growth ring ; t_W = mean time elapsed since wood formation in the measured portion ; t_T = time elapsed since tree felling (estimated upper bound for samples A to G) ; t_W and t_T are estimated from dendro dating.

An accelerated aging:Thermally treated wood

Aging is defined as a slow oxidation process caused by oxygen in the air. Therefore, based on the temperature-time conversion law an accelerated aging test was performed by thermally treated. Specimens were cut out with the dimensions of 120 mm (L) × 20 mm (R) × 4 mm (T) from near the outermost part of the heartwood. The specimens were dried at 60°C in an air-circulating oven for 12 hours and then at a room temperature in a desiccator with silica-gel and P_2O_5 until getting constant weight. Dried specimens were heated in an air-circulating oven at 4 temperatures levels from 90 to 180 °C for a duration ranging from 0.5 hour to approximately 2 years. Table 2 shows the treated time of the specimens at each treated temperature. They were planned by assuming that a 10 °C increase is equivalent to dividing the time by 2.

Table 2: Treated temperatures and time of accelerated aged wood samples.

	90°C	120°C	150°C	180°C
Treatment time [hour]	256	32	4	0.5
	512	96	8	1
	1024		16	2
	1536	192	24	3
	2560	320	40	5
			56	7
	5000		80	10
	7296	768	96	12
	9216		144	18
	12288		192	24
	18432	2304	288	36
	(24576)	3072	384	48
	(30720)	3840	480	60
	(36864)	4608		72
	(43008)		672	84
	(49152)	6144	768	96
	(61440)	7680	960	120

The treated at 90°C is now in processing planed with treated time in parenthesis.

Bending test

Naturally aged wood Specimens of 60 mm (L) × 10 mm (R) × 2 mm (T) were cut for 3 points bending tests. The samples were initially dried at room temperature for 3 weeks in a desiccator with silica gel, then conditioned at 20°C and 60% relative humidity (R.H.). They were weighed before and after the tests performed in the air-dry condition, then oven dried at 60°C, 24 hours at atmospheric pressure and 24 hours in vacuum in presence of P_2O_5, and weighted again to calculate the moisture content during the test, as well as the oven-dry density and the air-dry density. The tests were performed on 5 to 10 specimens per sample and loading direction, with span length 50 mm and crosshead speed 5 mm/min. For comparison of naturally aged Hinoki wood, heat treated Hinoki wood was tested as same way. Thermally treated wood specimens of 120 mm (L) × 20 mm (R) × 4 mm were cut for 3 points bending tests.

Equivalent stress (σ) and strain (ε) were calculated from the load (F) and crosshead displacement (f) as follows:

(1) $$\sigma = 3.Fl / (2t^2 w)$$

(2) $$\varepsilon = 6tf / l^2$$

where t is the specimen thickness, w its width, l the span. These expressions correspond to the maximum value in the central part, assuming homogeneous mechanical response and linearity between stress and strain. The following parameters were used to describe each stress-strain curve: the Young's modulus or rigidity (E) defined as the initial slope; the elastic limit (ε^e) as the strain where the stress falls by 1% below the linear extrapolation from linear part; the strength (σ^m) as the peak stress; the breaking strain (ε^m) as the strain at peak stress; the rupture energy (W) as the area below the curve up to the complete rupture, divided by the cross-sectional area

$$W = \frac{1}{tw}\int F.df$$

where F is the applied force and f the displacement. From equations (1) and (2), W can be expressed as:

$$W = \frac{L}{9}\int \sigma.d\varepsilon \qquad (3)$$

3. Results and discussion

Fig.3 shows the changes of rigidity, young's modulus and rupture energy of dry thermally treated woods and aged woods with no correction as a function of temperature and time. Kohara observed that all these features are similar in thermally treated wood performed at 130℃ [11, 12].

The general trends might be analogous, quantitative differences are likely to be observed between the various kinds of modifications induced by age. The relation of the kinetics of identified phenomena with physical and chemical changes remains to be investigated. Analysis on the time-temperature dependency in each data set of both naturally aged wood and thermally treated wood is under progress concerning these mechanical properties. Master curve obtained by shifting individual stress-strain curves and the activation energy delivered shift factors for each must be investigated further.

(a) (b) (c)

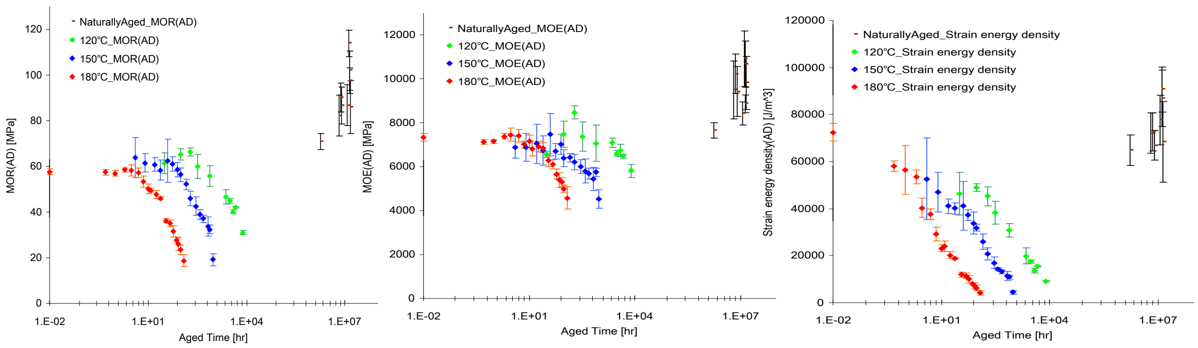

Fig.3 Changes of rigidity, Young's modulus and rupture energy with age in logarithm.
(a) Rigidity, (b) Young's modulus, (b) rapture energy

4. Conclusions

The trend of mechanical properties of aged Hinoki (*Chamaecyparis obtusa* Endl.) wood are similar to the effect of a thermally treatment at 90℃, 120℃, 150℃ and 180℃ were observed. But the mechanism should be discussed in aged woods and dry thermally treated wood in detail on the time-temperature equivalency.

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