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Vibrational properties of wetwood of todomatsu (*Abies sachalinensis*) at high temperature

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Abstract The object of this study was to understand precisely the drying characteristics of wetwood of todomatsu (*Abies sachalinensis* Mast.). For this purpose, the vibrational properties of wetwood of todomatsu at high temperature were compared with those of normal parts that had lower green moisture content than the wetwood. Specimens were cut respectively from the wetwood and normal parts, and matched in the radial direction. The specimens and the measuring systems were placed in an electric drying oven and free–free vibration tests were conducted in the oven under absolutely dry conditions. The wetwood and the normal parts were tested separately. The temperature was raised from room temperature to 200°C and then lowered to 50°C in steps of 25°C. The specific Young's modulus decreased with an increase in temperature during the heating process while it increased with the decreasing temperature during the cooling process. There was no significant difference in the specific Young's modulus between the wetwood and the normal part at all tested temperatures. The loss tangent took a minimum value at about 100°C in both the heating and cooling processes. There was no significant difference in the loss tangent between the wetwood and the normal part. Thus, the elastic and viscoelastic behaviors of the wetwood appear to be similar to those of the normal part in the temperature range of an actual kiln-drying process.

Key words Wetwood · Japanese fir · Vibrational properties · High-temperature drying

Introduction

Todomatsu (Todo fir, *Abies sachalinensis* Mast.), which is one of the main plantation-grown wood species in Hokkaido prefecture, as well as ezomatsu (Yeddo spruce, *Picea jezoensis* Carr.) and karamatsu (Japanese larch, *Larix leptolepis* Gord.),[1] often include wetwood. The wetwood is a heartwood part with much higher moisture content than normal heartwood and such trees sometimes account for as much as 40% of the trees in a plantation.[2] The wetwood causes serious troubles in drying because of its high moisture content, which leads to increased drying time and costs. Lumber that includes wetwood can easily generate cracks in the drying process, which decreases the lumber quality, and, consequently, the yield.

In order to develop an appropriate drying schedule for todomatsu with wetwood, not only are studies required on the emergence of the wetwood[3] and wood properties after drying,[4–6] but also on the changes in wood properties during the drying process. Moreover, to investigate its wetwood properties precisely, the wetwood should be tested separately from the normal part (in this study, the lumber that has ordinary moisture content is called the "normal part"). However, there are few studies that treat these two parts separately;[4–6] mechanical properties of todomatsu lumber have usually been measured using lumber for actual-size structures, which include both the wetwood and the normal part.

Thus, we investigated the influence of temperature on vibrational properties, comparing those of the wetwood and the normal part, as the first step to examine the behavior of the wetwood of todomatsu wood in the drying process. Vibrational properties are indices that are closely related to the strength of wood and can be measured even under high temperatures. Furthermore, the same specimen can be used

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throughout the drying process continuously because the vibration test is nondestructive.

Experimental

Specimens

Todomatsu (*Abies sachalinensis* Mast.) was used for the specimens. The dimensions of the test specimens were 180 (longitudinal direction, L) × 25 (radial direction, R) × 10mm (tangential direction, T). Specimens were cut separately from the wetwood and normal parts of the same lumber. The wetwood and normal parts were matched in the R-direction with each other. Matching in the L- or T-directions was impossible because of the distribution pattern of wetwood in the trunk. The wetwood occurred on the outer side of the normal part of the trunk in this study. All specimens were oven-dried at 105°C after air-drying in advance of the heating test.

Vibration test

In the same way as the previous study,[7] a free–free flexural vibration test was conducted to obtain resonance frequency and loss tangent. Three vibration test specimens were used for each case. To obtain the changes in dimensions, weight, and temperature of test specimens during the measuring process, two other specimens of the same size were employed.

Figure 1 shows the apparatus for the vibration test. The test beam was suspended by two wires of 0.12mm in diameter at the nodal positions of the free–free flexural vibration corresponding to its first resonance mode. It was excited in the T-direction at one end by a magnetic driver (Electro, high temperature speed sensor 3030 HTB, temperature range: −73° to +273°C). The motion of the beam was detected by a displacement sensor (Keyence, high accuracy positioning sensor SH-816, temperature range: −10° to +200°C, linear range 1–2V) at the other end. The signal was processed through a fast Fourier transform (FFT) digital signal analyzer (Ono Sokki, multipurpose FFT analyzer CF-5220).

The loss tangent was calculated from the width at −6dB from the peak of the resonance curve. The resonance frequency range of the specimens was about 1400–1540Hz. In this frequency range, the loss tangent is not subject to frequency.[8–11] It took 100s to draw one resonance curve.

Temperature control

The specimens for the vibration test, those for the temperature measurements of specimens, and those for the dimensions and weight tests were heated in an electric oven (Isuzu Seisakusho, drying oven kosumosu). In the vibration tests, a specimen and apparatuses, such as the magnetic driver and displacement sensor, were arranged in the oven as shown in Fig. 1. After the vibration test at room temperature (about 24°C), the temperature of the oven was increased to 200°C in 25°C intervals and then decreased from 200° to 50°C by the same intervals. Throughout this article, these processes are called the heating process and cooling process, respectively. In the cooling process, it was difficult to keep the temperature below 50°C, so the second vibration tests at room temperature were not conducted.

Each vibration test was conducted after the oven temperature was held at each set value for 25–30min except for the last two steps (held for 40–60min). The specimens for dimensions and weight measurements were taken out of the oven at each set temperature. Thermocouples were attached to the specimens for the temperature test. They were placed on the LR-plane and inserted in the R-direction at a depth of 12mm from the central point of the LT-plane and in the L-direction at a depth of 30mm from the central point of the RT-plane as shown in Fig. 2. The rate of temperature change was about 5°C/min.

Results and discussion

Figure 3 shows the temperatures of a specimen. The temperatures of both the wetwood and normal part were similar to the temperature in the oven. Figure 4 shows the change in weight of the specimens. These changes were expressed using the ratio based on the values measured after oven-drying before the heating process. The weight decreased with increasing temperature during the heating

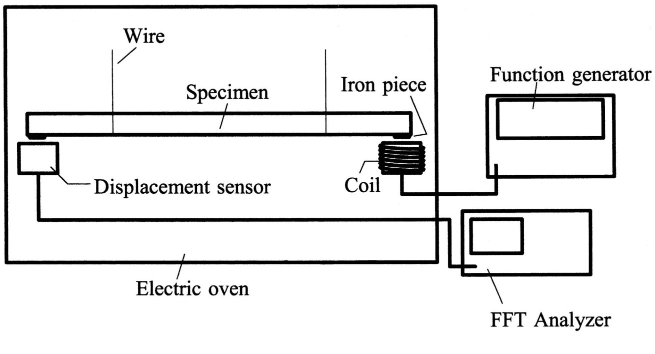


Fig. 1. Apparatus for vibration test

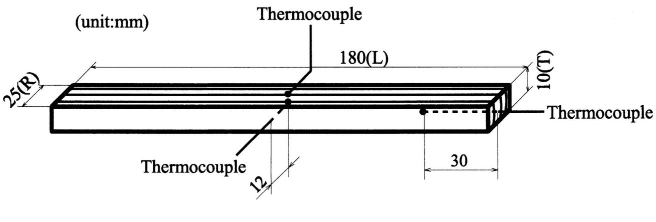


Fig. 2. Thermocouples for measuring surface and interior temperatures of the specimens. Thermocouples were placed on the LR-plane and inserted in the R-direction at a depth of 12mm from the central point of the LT-plane and in the L-direction at a depth of 30mm at the central point of the RT-plane

Fig. 3. Temperatures of wetwood and normal specimens during heating and cooling

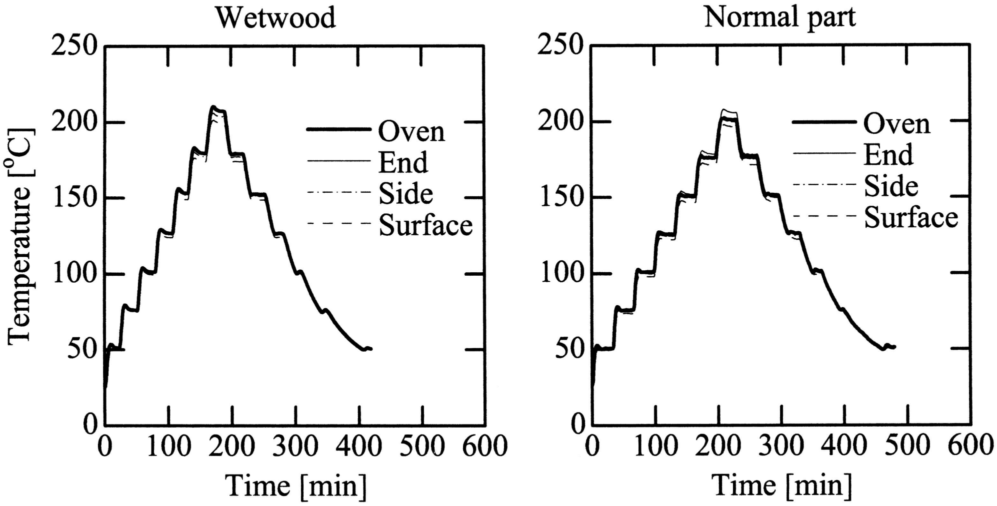
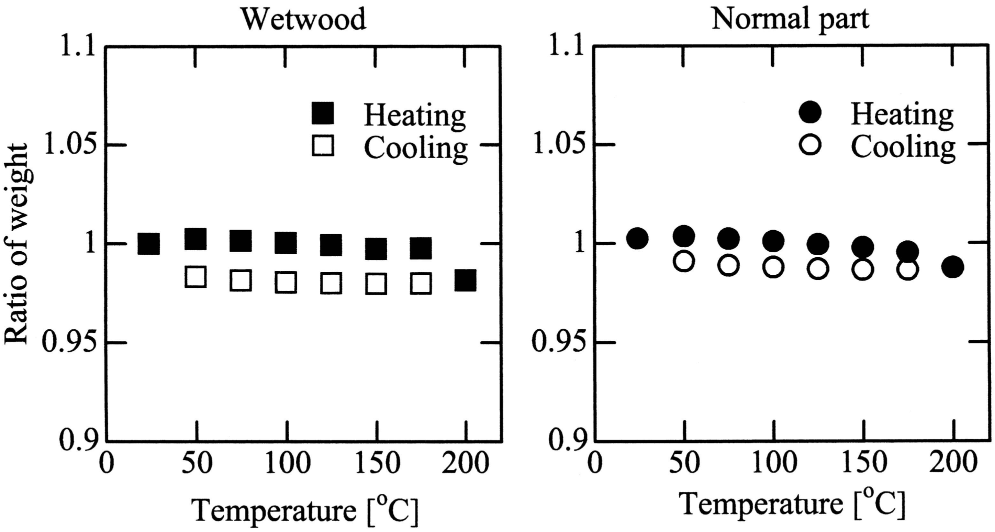


Fig. 4. Changes in weight of wetwood and normal wood during heating and cooling. The ratios were calculated based on the value measured after oven drying at 105°C before the heating process



process, and slightly increased with a decrease in temperature during the cooling process. The weight decreased most in the temperature range of 175°–200°C. The increment in the weight was likely due to the absorption of humidity during the measuring process and the decrement to the thermal degradation and the loss of volatile constituents.[7] The tendencies of the changes in the weight of the wetwood were similar to those of the normal part.

We now examine the dependence of the specific Young's modulus on temperature. Because the dimensions and weight of the test pieces for vibration tests were not measured directly, the resonance frequency (f_r) was used in its place. The changes in the dimensions during the experiment were less than 1%, so the resonance frequency would represent the behavior of the specific Young's modulus. In Figs. 5–8, the results for the wetwood and the normal part were plotted by shifting the temperature axis by –5°C and +5°C, respectively, to avoid their overlap.

The resonance frequencies of the wetwood and normal part decreased with an increase in temperature during the heating process, while they increased with the decrease in temperature during the cooling process (Fig. 5). The decrease in the resonance frequency seems to have been caused by the thermal softening of the wood. The resonance frequency decreased most in the temperature range of 175°–200°C in the heating process. This finding corresponds to the decrease in the weight from 175° to 200°C mentioned above.

Figure 6 shows the change in the loss tangent. The loss tangent had a minimum value at about 100°C during both the heating and cooling processes, and the change in the loss tangent was larger in the temperature range of 150°–200°C than in the range from room temperature to 150°C. These tendencies were similar to those in previous works.[7,12–16]

The wetwood had a larger resonance frequency and a smaller loss tangent than the normal part (Figs. 5, 6). In many cases, *t*-test showed significant differences between the wetwood and the normal part. These results could have been caused by the matching method in the R-direction employed here, in other words, an influence of annual ring width (wetwood: 3 mm, normal part: 5 mm),[17] or they could have been caused by the difference of wood properties

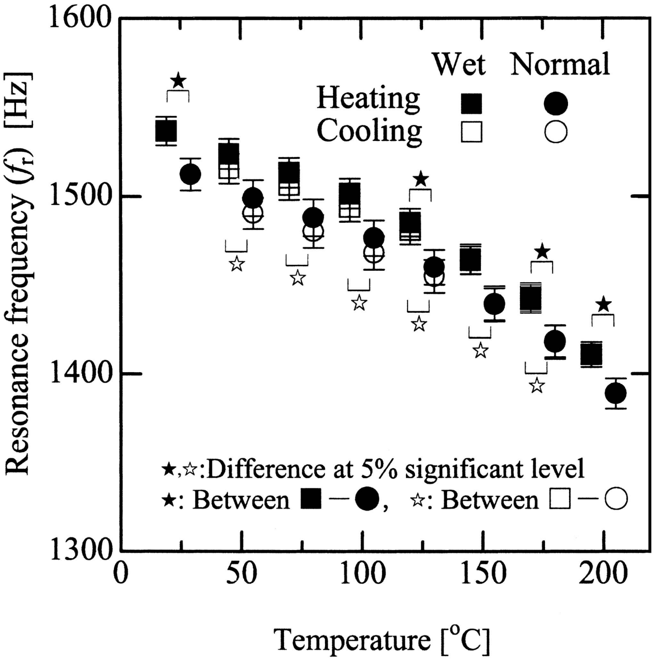


Fig. 5. Changes in the resonance frequency of wetwood and normal wood during heating and cooling. The results for the wetwood and the normal part were offset by −5°C and +5°C, respectively, to avoid overlapping of the plots. *Error bars* show standard deviations

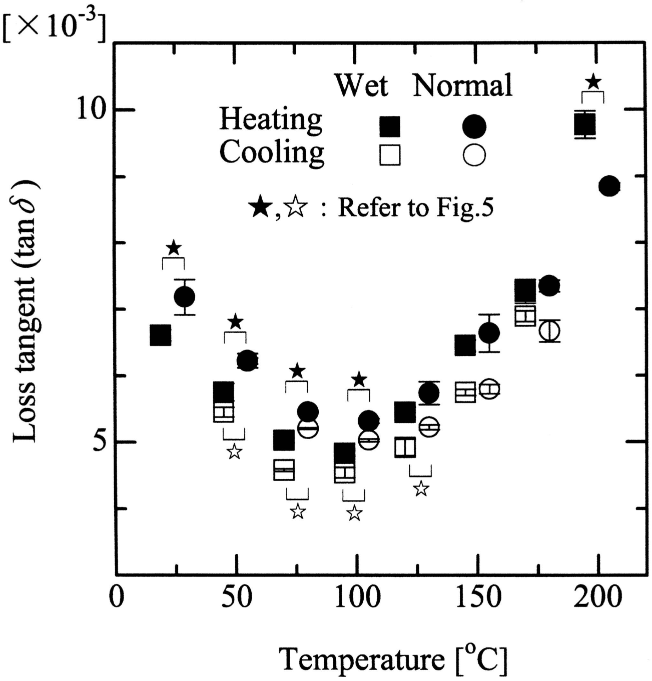


Fig. 6. Changes in the loss tangent of wetwood and normal wood during heating and cooling

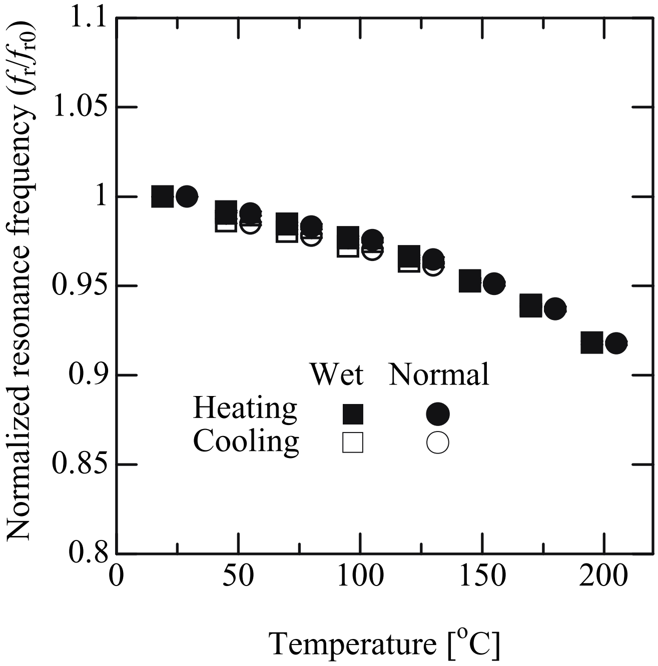


Fig. 7. Changes in the normalized resonance frequency (f_r/f_{r0}) of wetwood and normal wood during heating and cooling. The values were calculated based on the values measured after oven drying at 105°C before the heating test

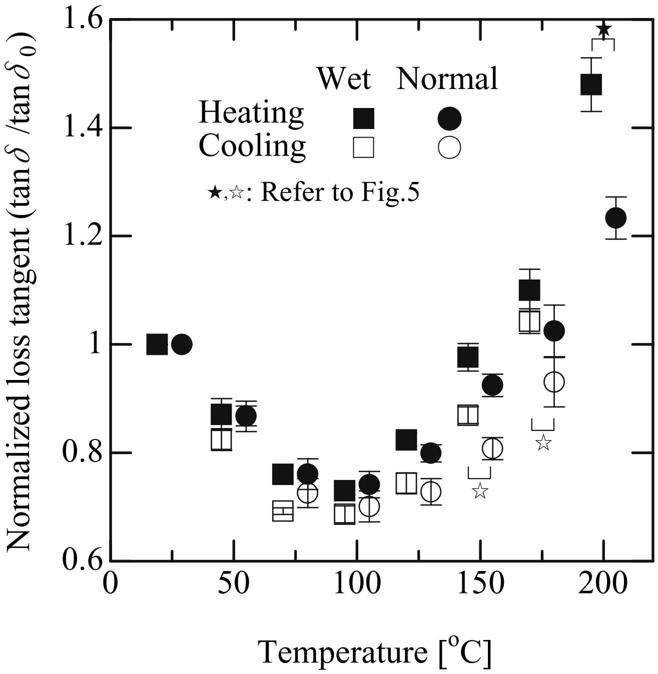


Fig. 8. Changes in the normalized loss tangent (tanδ/tanδ_0) of wetwood and normal wood during heating and cooling. The ratios were calculated based on the values measured after oven drying at 105°C before the heating test

between the wetwood and normal part. To clarify this, a normalized value based on the value at room temperature after oven-drying was examined.

Figure 7 shows the change in the normalized resonance frequency (f_r/f_{r0}) and Fig. 8 shows the change in the normalized loss tangent (tanδ/tanδ_0). Values at room temperature after oven-drying are shown by subscript 0. Because the changes in dimensions were negligible as mentioned above, the change in the resonance frequency corresponds to that in the specific Young's modulus.

The comparisons of the normalized f_r/f_{r0} and ($\tan\delta/\tan\delta_0$) of the wetwood with the normal part at each set temperature by *t*-test indicated that there was no significant difference as a whole, although there were significant differences at some temperatures. Therefore, we concluded that there was no difference in the elastic and viscoelastic properties by temperature between the wetwood and the normal part under the changing temperature conditions. These results will be the basis to investigate the behavior of the wetwood during a drying process. We think that the wetwood shows the same mechanical behavior as the normal part during the drying process.

Conclusions

Vibration tests were conducted from room temperature to 200°C using the wetwood and normal wood of todomatsu. The results obtained were as follows:

1. The resonance frequency decreased in the heating process, and increased in the cooling process. A comparison of f_r/f_{r0} of the wetwood with that of the normal part showed that there was no significant difference at any set temperature.
2. The loss tangent had a minimum value at about 100°C in both the heating and cooling processes. A comparison of ($\tan\delta/\tan\delta_0$) of the wetwood with that of the normal part indicated that there was no significant difference between them.
3. These results suggest that the wetwood shows the same mechanical behavior as the normal part during the drying process.

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