Porous Structure of Wood and its Relaxation Modulus, II

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Abstract——The effects of the environmental condition on the relaxation modulus of wood as a porous anisotropic material was discussed with the help of the numerical value of n, which is an index of anisotropy decided by both the geometrical feature of the deformable unit of wood at macroscopic level and its volume fraction.

It was found that the numerical value of n was independent on time, temperature and moisture. Therefore, it may be considered that the relaxation process of wood is due to that of wood substance.

Furthermore, strain dependence of n is descussed. It was found that n is almost independent on the strain in the tangential direction.

Introduction

The purpose of this investigation is to make clear the relationship between the anatomical structure and the viscoelastic anisotropy of wood.

Wood is regarded as a porous material built up with a great number of tubular cells. It is considered that the geometrical feature of these cells gives rise to an anisotropy in mechanical behaviours of wood[1~3]. Considering wood as a porous material consisting of the substance and the void, the empirical equation below is given:

$$E(t)=\theta^n E_s(t) \tag{1}$$

where $E(t)$ is the apparent modulus, $E_s(t)$ is the modulus of wood substance, θ is the volume fraction of wood substance and n is called "*form exponent*". The contribution of the porous structures such as geometry and distribution of cells to the modulus of wood can be evaluated by the two factors, θ and n. In the previous paper[1], the experiments on the stress relaxation of wood were carried out at 20°C, 45 % R.H.. And it was found that n took the value of about 1.1 in the radial direction and about 1.5 in the tangential direction regardless of time.

However, as is generally known, the viscoelastic behaviour of wood is sensitively affected by the environmental conditions. So, in this paper, the similar experiment carried out at different conditions, at which a kind of transition is observed in the viscoelastic properties of wood[4], and n is compared with that obtained in the previous work.

Furthermore, strain dependence of n is also discussed.

Experimental

In this study, efforts were made to choose species which represent a wide variety of wood characteristics. The species whose specific gravity in air dry covers from 0.0838 to 1.09 as shown in Table 1 were selected. The species of which the sizes, excluding the portions to be grasped by the jaws, were 50(R, T) by 5(T, R) by 1(L) mm for both static tensile and stress relaxation tests were prepared. All of these specimens were immersed in water to saturation.

The relaxation moduli in tension were determined from the static and the relaxation tests. The static tensile test gave us the load-deformation diagram. From this diagram the ultimate

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Table 1. Test species.

Wood species	ρ
1. Balsa (*Ochroma* spp.)	0.0838—0.106
2. Kiri (*Paulownia Tomentosa* STEUD.)	0.240 —0.283
3. Sugi (*Cryptomeria japonica* D. Don)	0.380 —0.397
4. Hinoki (*Chamaecyparis obtusa* ENDL.)	0.450 —0.454
5. Kusunoki (*Cinnamomum camphora* SIEB.)	0.471 —0.491
6. Akamatsu (*Pinus densiflora* Sieb. et ZUCC.)	0.533 —0.540
7. Hoonoki (*Magnolia obovata* THUNB.)	0.520 —0.540
8. Buna (*Fagus crenata* BLUME)	0.514 —0.567
9. Keyaki (*Zelkowa serrata* MAKINO)	0.705 —0.729
10. Shirakashi (*Quercus Myrsinaefolia* BLUME)	0.874 —0.901
11. Isunoki (*Distylium racemosum* SIEB. et ZUCC.)	0.958 —1.09

ρ: Specific gravity in air dry.

tensile stress and the relaxation modulus at 10 seconds were calculated. The stress relaxation was measured for 10^2 minutes at stress of 30 percent of the ultimate tensile stress, and the relaxation moduli at 10^2 and 10^3 seconds were computed. Both experiments were carried out in wet

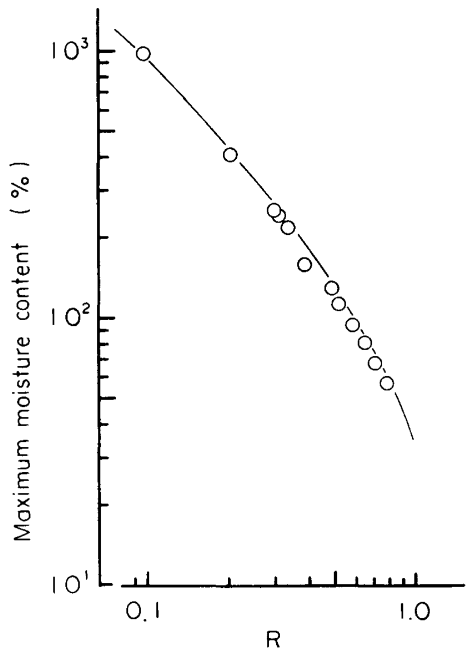

Fig. 1. Comparison of the experimental results with calculated results.
—; Calculated,
○; Experimental,
R; Density based on dry weight and wet volume.

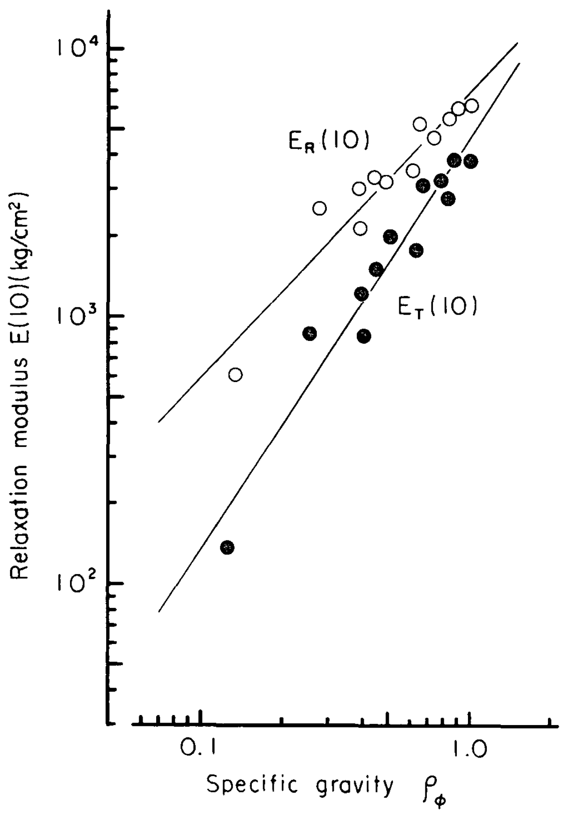

Fig. 2. The relation between relaxation modulus at 10 sec. and specific gravity (wet condition at 50°C). R: Radial direction,
T; Tangential direction,
$E(t)$; Relaxation modulus,
ρ_ϕ; specific grvity of wet wood without the free water in cell lumina.

condition at 50°C.

A 5-ton Instron type testing machine (TOM-5000X, Shinkoh Communication Industry, Co. Ltd.) was used. Under the moving crosshead of this testing machine a water bath was equipped to keep the temperature of the specimen constant. In order to remove the various effects due to the temperature, the specimen was immersed in the water bath for two hours before the measurements.

The experimental error caused by deformation in the load sensing divice was 5 percent at the most.

Result and Discussion

Eq. (1) representing the relationship between the relaxation modulus and the volume fraction of wood substance can be rewritten in the following logarithmic form using the specific gravity ρ,

$$\log E(t) = n \log \rho + \log C(t). \qquad (2)$$

n is obtained as the slope of a modulus vs. specific gravity curve plotted on a log scale. Practically, the regression lines were calculated by the least squares technique.

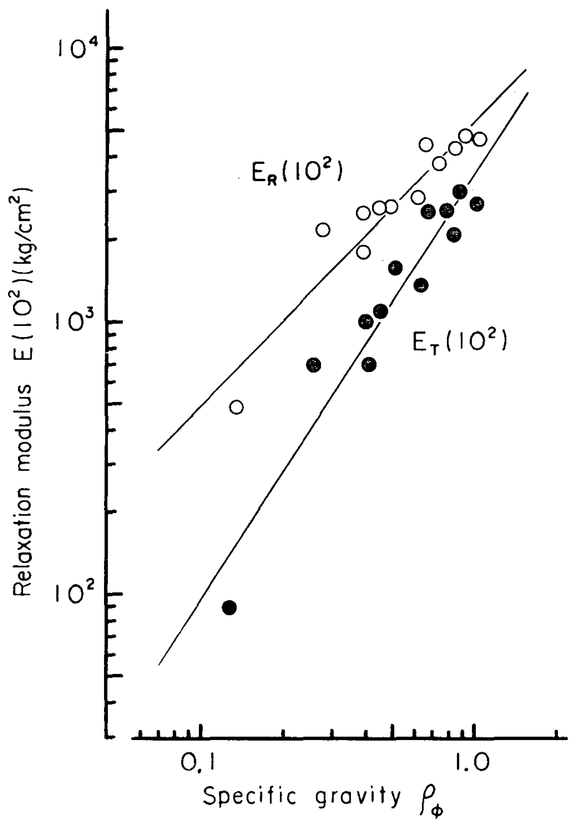

Fig. 3. The relation between relaxation modulus at 10^2 sec. and specific gravity (wet condition at 50°C).
R; Radial direction,
T; Tangential direction,
$E(t)$; Relaxation modulus,
ρ_ϕ; specific gravity of wet wood without the free water in cell lumina.

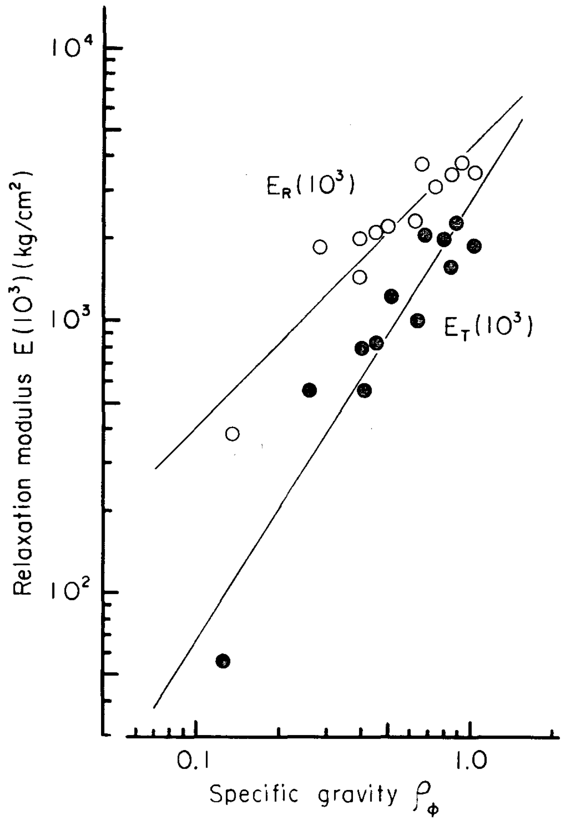

Fig. 4. The relation between relaxation modulus at 10^3 sec. and specific gravity (wet condition at 50°C).
R; Radial direction,
T; Tangential direction,
$E(t)$; Relaxation modulus,
ρ_ϕ; Specific gravity of wet wood without the free water in cell lumina.

If the volume of cell lumina remains unchanged during moisture change, the maximum moisture content of wood may be computed as

$$u_{max}=(1.50-R)/1.50, \tag{3}$$

where R is the density based on dry weight and wet volume. The comparison of the experimental results with those calculated from eq. (3) is shown in Fig. 1. As is evident from the figure, both agree precisely. Therefore, the specific gravity of wet wood without the free water in cell lumina is written as

$$\rho_\phi=1.28R. \tag{4}$$

In this paper, the specific gravity in eq. (2) were calculated from eq. (4).

$\log E(t)$ at 10, 10^2 and 10^3 seconds are plotted against $\log \rho_\phi$ in Figs. 2 to 4. In Table 2, regression lines and correlation coefficients are shown. The regressions between $\log E(t)$ and $\log \rho_\phi$ were significant. The values of n were almost equivalent to unity in the radial direction and 1.6 in the tangential direction. The results agreed well with those reported in the previous

Table 2. Experimental results.

	Regression line	r
Relaxation modulus at 10 sec.	R: $\log E(10)=3.838+1.063 \log \rho_\phi$ T: $\log E(10)=3.657+1.532 \log \rho_\phi$	0.957 0.966
Relaxation modulus at 10^2 sec.	R: $\log E(10^2)=3.744+1.046 \log \rho_\phi$ T: $\log E(10^2)=3.555+1.571 \log \rho_\phi$	0.945 0.956
Relaxation modulus at 10^3 sec.	R: $\log E(10^3)=3.649+1.026 \log \rho_\phi$ T: $\log E(10^3)=3.451+1.621 \log \rho_\phi$	0.932 0.942

R: Radial direction, T: Tangential direction, r: Correlation coefficient, $E(t)$: Relaxation modulus (kg/cm^2), ρ_ϕ: Specific gravity of wet wood without the free water in cell lumina.

Table 3. Strain dependence of the numerical value of n.

Strain (%)	Regression line	
	Radial direction	Tangential direction
0.2	$\log E=3.889+1.140 \log \rho_\phi$	$\log E=3.671+1.541 \log \rho_\phi$
0.4	$\log E=3.846+1.097 \log \rho_\phi$	$\log E=3.638+1.530 \log \rho_\phi$
0.6	$\log E=3.811+1.067 \log \rho_\phi$	$\log E=3.605+1.533 \log \rho_\phi$
0.8	$\log E=3.779+1.044 \log \rho_\phi$	$\log E=3.572+1.544 \log \rho_\phi$
1.0	$\log E=3.743+1.020 \log \rho_\phi$	$\log E=3.540+1.554 \log \rho_\phi$
1.2	$\log E=3.714+0.999 \log \rho_\phi$	$\log E=3.508+1.554 \log \rho_\phi$
1.4	$\log E=3.683+0.979 \log \rho_\phi$	$\log E=3.478+1.558 \log \rho_\phi$
1.6	$\log E=3.656+0.964 \log \rho_\phi$	$\log E=3.449+1.559 \log \rho_\phi$
1.8		$\log E=3.423+1.559 \log \rho_\phi$
2.0		$\log E=3.396+1.552 \log \rho_\phi$
2.2		$\log E=3.371+1.548 \log \rho_\phi$
2.4		$\log E=3.349+1.546 \log \rho_\phi$
2.6		$\log E=3.329+1.542 \log \rho_\phi$
2.8		$\log E=3.308+1.534 \log \rho_\phi$
3.0		$\log E=3.287+1.525 \log \rho_\phi$

E: Secant modulus, ρ_ϕ: specific gravity of wet wood without the free water in cell lumina. All the regression lines have correlation coefficient above 0.925.

paper[1]. As a matter of course, it may be considered that this difference is principally caused by the different geometrical features in both directions: in the radial direction walls of adjacent cells provide continuous and nearly straight paths of material over a wide area, whereas in the tangential direction the material path is invariably more tortous.

On the other hand, n in both directions were almost unchanged with the loading time.

Thus, it can be concluded that under 30 percent of the ultimate stress there is no effects of loading time and environmental condition on n, which represents the contribution of porous structures of wood to the relaxation modulus. In other words, these facts show that the relaxation process for wood is primarilly due to that of wood substance.

The results of strain dependence of n are shown in Table 3. These values were obtained by using the secant modulus which is calculated from stress-strain diagram every 0.2 percent strains. This diagram was corrected for error caused by deformation in the load sensing device.

It can be seen from the table that in the tangential direction n at each strain level are almost constant, whereas, in the radial direction n decreases slightly with increasing strain. Therefore, it can be concluded that the contribution of the geometrical change of the deformable element to the modulus is almost independent on the strain.

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