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<tr>
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<tr>
<td>Citation</td>
<td>Wood research : bulletin of the Wood Research Institute Kyoto University (1996), 83: 40-42</td>
</tr>
<tr>
<td>Issue Date</td>
<td>1996-09</td>
</tr>
<tr>
<td>URL</td>
<td><a href="http://hdl.handle.net/2433/53212">http://hdl.handle.net/2433/53212</a></td>
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<td>Right</td>
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<tr>
<td>Type</td>
<td>Departmental Bulletin Paper</td>
</tr>
<tr>
<td>Textversion</td>
<td>publisher</td>
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Modelling the Effects of Chemical Modification on Dynamic Mechanical Properties of Wood

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(Received May 31, 1996)

Keywords: Dynamic modulus, loss tangent, biaxial rheological model, chemical modification, amorphous matrix.

The dynamic mechanical properties of the cell wall of chemically modified woods were analyzed by using the model shown in Fig. 1, in which amorphous isotropic matrix is disposed in parallel along the axis of cellulosic fibrils (the 1 direction) inclining at \( \theta \) to the longitudinal direction of wood. The complex dynamic modulus of the model in the longitudinal direction, \( E_L^* \), is expressed by

\[
E_L^* = \frac{1}{E_1^* \cos^4 \theta + \left( \frac{1}{G^*} \frac{2\mu_{12}}{E_1^*} \right) \sin^2 \theta \cos^2 \theta + \frac{1}{E_2^* \sin^4 \theta}}^{-1},
\]

where \( E_1^* \) and \( E_2^* \) are the complex dynamic moduli in the 1 and 2 directions, \( G^* \) is the complex shear modulus in the 1-2 plane, and \( \mu_{12} \) is the Poisson's ratio, respectively.

If \( \theta \) is small enough to ensure \( \sin^4 \theta \approx 0, \cos^4 \theta \approx 1, \sin^2 \theta \cos^2 \theta \approx \theta^2 \), and \( \mu_{12} \) is much smaller than the real part of \( E_1^* \), the dynamic modulus, \( E' \), and the loss tangent, \( \tan \delta \), of wood in the longitudinal direction, as first approximation, can be expressed by

\[
E' = \frac{\Delta \gamma}{\gamma_w} \left[ \frac{1}{E_1'} + \frac{\theta^2}{G'} \right]^{-1} \quad \text{and} \quad \tan \delta = \left[ \frac{E_1'' + \theta^2 G''}{E_1' G' G''} \right] \left[ \frac{1}{E_1'} + \frac{\theta^2}{G'} \right]^{-1},
\]

where \( \Delta \) is the volume fraction of the \( S_2 \) layer in the cell wall, \( \gamma \) and \( \gamma_w \) are the specific gravities of wood and the cell wall, \( E_1' \) and \( E_1'' \) are the dynamic modulus and the loss modulus in the 1 direction, and \( G' \) and \( G'' \) are the dynamic shear modulus and the loss shear modulus in the 1-2 plane, respectively. \( E_1' \) and \( E_1'' \) are expressed by

\[
E_1' = \Psi E_t + (1 - \Psi) E_m = \Psi E_t \quad \text{and} \quad E_1'' = (1 - \Psi) E_m \tan \delta_m,
\]

where \( \Psi \) is the volume fraction of fibrils in the cell wall, \( E_t \) is the dynamic modulus of fibrils, \( E_m \) and \( \tan \delta_m \) are the dynamic modulus and the loss tangent of matrix, respectively. In the model, fibrils with square cross section are embedded in matrix, so that fibrils and matrix are aligned partly in series and partly in parallel to the direction of shear force. According

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Fig. 1. A model for the $S_2$ layer of wood.
Note: L: the longitudinal direction, 1: the axis of cellulosic fibrils, 2: the direction perpendicular to the axis of fibrils, $\theta$: microfibril angle, f: cellulosic fibrils, m: amorphous isotropic matrix.

Fig. 2. The relationships between the logarithms of the dynamic modulus and the logarithm of the loss tangent of matrix for untreated and chemically modified woods.
to the law of mixtures\textsuperscript{1}, $G'$ and $G''$ can be expressed by

\begin{align*}
G' &= G_m \left( 1 + \frac{\psi}{1 - \sqrt{\psi}} \right) \text{ and } G'' = G_m \left( 1 + \frac{\psi}{1 - \sqrt{\psi}} \right) \tan \delta_m. \tag{4}
\end{align*}

The experimental values of $E'$, $\tan \delta$, and $\gamma$ at 20°C and 60% R.H. for the untreated and chemically modified woods reported by Akitsu et al.\textsuperscript{2} were adapted in calculation. For the untreated wood, $\psi=0.5$, $\gamma_w=1.45$, $\Delta=0.84$, $\theta=0.09$ (rad), $E_r=134\,\text{(GPa)}$, and $E_m=2\,\text{(GPa)}$ were used\textsuperscript{2,\textsuperscript{3}}. For the modified wood, $\psi=0.33$ to 0.45 and $\gamma_w=0.92$ to 1.29 were estimated from both weight gains and volume swellings.

The values of $E_m$ and $\tan \delta_m$ for untreated (U), formalized (F), acetylated (A), etherificated (PO), and polyethylene glycol impregnated (PEG) woods were calculated. The relationships between the logarithm of $\tan \delta_m$ and the logarithm of $E_m$ are shown in Fig. 2. In PO and PEG treatments, the decrease in $E_m$ and the increase in $\tan \delta_m$ might be explained by the hydrophilic nature of the bulking agents. In acetylation, however, the introduced hydrophobic bulking agents might decrease both $E_m$ and $\tan \delta_m$. On the other hand, in formalization, the decrease in $\tan \delta_m$ was attributed to matrix crosslinking.

\textbf{References}