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ORIGINAL ARTICLE

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Dynamic properties of three types of wood-based composites

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Abstract This study used a vibration test method to show that grain angles of face veneer have substantial effects on sound velocities and dynamic Young's moduli of three types of wood-based composites. The sound velocity at 0° grain angle of face veneer was the highest, and it decreased with increasing grain angle in the range of 0° to 90°. This tendency was similar to that for dynamic Young's modulus. The relationship between the grain angle of face veneer and the sound velocity of three types of wood-based composites can be expressed in the form of Hankinson's equation or a second-order parabolic equation. This study also showed that the application of orthotropic elasticity theory was valid for the three types of wood-based composites. The relationship between the grain angle of the face veneer and the Young's modulus of three types of wood-based composites can be expressed in the form of the Jenkin equation, Hankinson's equation, or a second-order parabolic equation. Rule of mixture can also be used to predict the Young's modulus of wood-based composite from the Young's moduli of the two elements.

Key words Wood-based composite · Sound velocity · Dynamic Young's modulus · Grain angle · Vibration method

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Introduction

Wood is an anisotropic orthotropic material. Its ultrasonic (or sound) velocity and Young's modulus are greatly affected by grain angles. Suzuki and Sasaki[1] indicated that the ultrasonic velocity of sugi (*Cryptomeria japonica* D. Don) and lauan (*Shorea negrosensis*) decreased rapidly with increases of grain angle up to 45°, and in the range of 45° to 90° they decreased gradually with increasing grain angles. When grain angle is up to 45°, their ultrasonic velocities decreased to be 50% of the original values of specimens with 0° grain angle.

Mishiro[2] investigated the effect of grain angles on ultrasonic velocity of spruce (*Picea* sp.) and katsura (*Cercidiphyllum japonicum* Sieb. et Zucc.). He indicated that the ultrasonic velocity decreased rapidly with increasing grain angle, a tendency that is similar to those of Young's modulus and strength in both softwoods and hardwoods.[2]

Kabir et al.[3] studied the ultrasonic velocity and elastic stiffness constant of rubber wood using ultrasonic techniques in three main symmetry axes and an angle rotating from the symmetry axes. They indicated that the longitudinal direction showed the highest velocity and hence the highest elastic stiffness constant. Linear regression equations were obtained between velocity and grain angle with R^2 values ranging from 0.86 to 0.99.[3]

Sobue and Iwasaki[4] measured the dynamic Young's modulus and loss modulus of red meranti (*Shorea* sp.) plywood by the method of flexural vibration of free–free beams. They indicated that good agreement was obtained between the experimental values and the calculated values of Young's modulus and loss modulus when experimental values in three directions (0°, 45°, and 90°) were used in the calculations by means of the Jenkin equation.[4] Ueda[5] studied the relationship between the modulus of elasticity by bending and grain direction of face veneer of lauan (*Shorea* sp.) plywood. He indicated that the modulus of elasticity decreased with increasing grain angle from 0° to 45° (or 60°). However, in the range of 45° (or 60°) to 90° they increased gradually with increasing grain angles. The modulus of elasticity had a minimum value at a grain angle of 45° (or 60°).[5]

As indicated above, there are many reports on the effects of the grain angle on the sound velocity and Young's modulus; however, most of them were conducted in wood and plywood. This research deals with an experimental study on the effects of the grain angle of face veneer on the sound velocities and the dynamic Young's moduli of three types of wood-based composites whose core layers were plastic, fiberboard, and metal material. The densities of the core-layer materials were much less, less, and much greater than the density of the face-layer material (wood element), respectively. The possibility that sound velocities and dynamic Young's moduli of wood-based composites can be predicted by means of some empirical formula is also discussed. The properties of wood-based composites can be designed before production if the predicted values from theoretical equations lie close to the measured values.

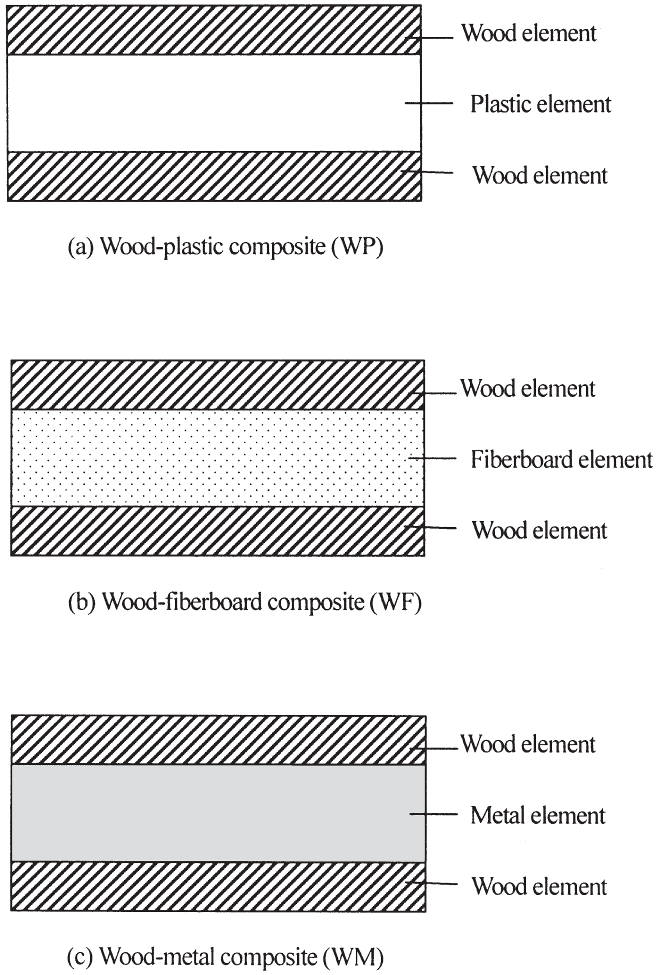

Fig. 1. Construction of wood-based composites **a** wood–plastic composite, **b** wood–fiberboard composite, **c** wood–metal composite

Materials and methods

Materials

Experimental materials used in this study were three-layered structures of wood–plastic composite (WP), wood–fiberboard composite (WF), and wood–metal composite (WM). The construction is shown in Fig. 1. The face layers of the composite were wood (grain angle: 0°, 15 °, 30°, 45°, 60°, 75°, and 90°) and the core layers of the composite were plastic, fiberboard, and metal. Japanese larch (*Larix leptolepis* Gordon) veneer (density: $0.64\,g/cm^3$, thickness: 3.5 mm) was used as the wood element (W). Polystyrene foam (density: $0.01\,g/cm^3$, thickness: 20 mm), insulation fiberboard (density: $0.25\,g/cm^3$, thickness: 10 mm), and aluminum plate (density: $2.75\,g/cm^3$, thickness: 2 mm) were chosen as the plastic (P), fiberboard (F), and metal (M) elements. Specimen size was 300×100 mm.

Vibration method

The experiment was carried out using the longitudinal transmission vibration method as shown in Fig. 2. The sound transmission time propagating through the specimen was measured with a fast Fourier transform (FFT) analyzer.

The sound velocity and dynamic Young's modulus were calculated based on Eqs. 1 and 2.[2]

$$V = L/T \tag{1}$$

$$E = \rho V^2 \tag{2}$$

where V is sound velocity, L is length of the specimen, T is transmission time, E is dynamic Young's modulus, and ρ is density of the specimen.

The measurements were carried out in a room maintained at 20°C and 65% relative humidity.

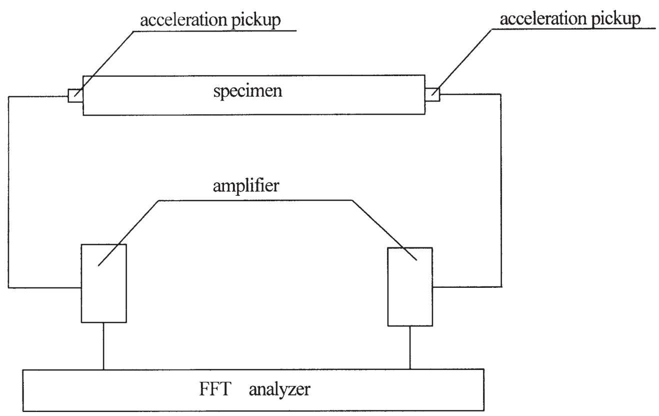

Fig. 2. Longitudinal transmission vibration method. *FFT*, fast Fourier transform

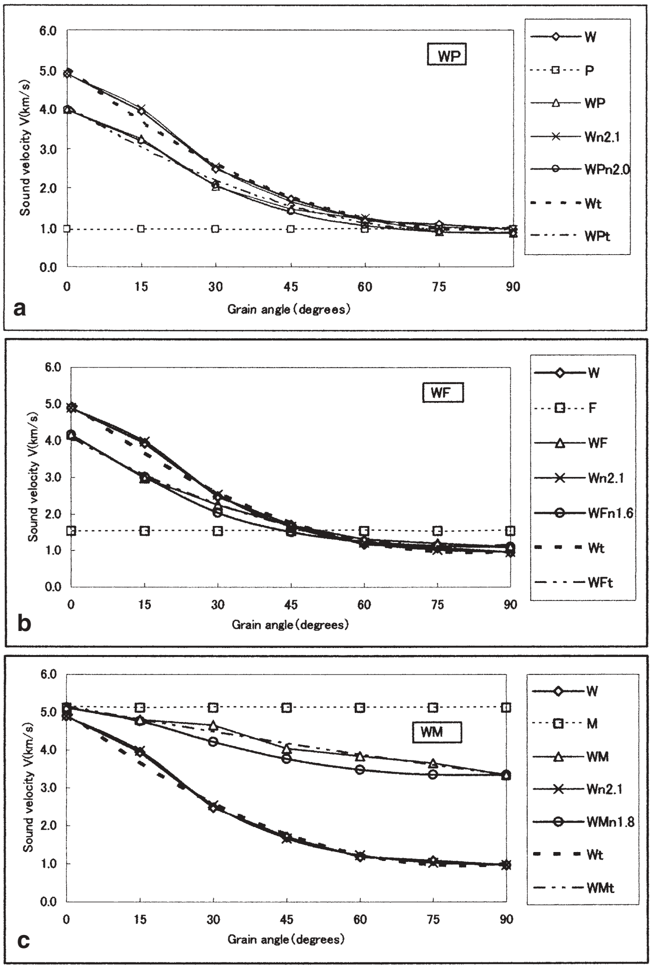

Fig. 3. Relationship between sound velocity (V) and grain angle of face veneer for **a** wood–plastic composite, **b** wood–fiberboard composite (WF), and **c** wood–metal composite. *W*, *P*, *F*, *M*, *WP*, *WF*, and *WM* represent the sound velocities from vibration tests for wood, plastic, fiberboard, metal, wood–plastic composite, wood–fiberboard composite, and wood–metal composite, respectively. *Wn2.1*, *WPn2.0*, *WFn1.6*, and *WMn1.8* are the sound velocities calculated from Hankinson's equation (Eq. 3) for wood, wood–plastic composite, wood–fiberboard composite and wood–metal composite respectively. *Wt*, *WPt*, *WFt*, and *WMt* are the sound velocities calculated from Eq. 4 for wood, wood–plastic composite, wood–fiberboard composite, and wood–metal composite, respectively

Results and discussion

Sound velocity

The relationships between sound velocity and grain angle of face veneer of three types of wood-based composites are shown in Fig. 3. It is clear that the sound velocity decreased with increasing grain angle. This implies that the grain dependence of sound velocity in wood also exists for the sound wave propagating through a wood-based composite with core layers of plastic, fiberboard, or metal. In addition, for WP and WF, the sound velocities decreased rapidly with increases of grain angle up to 45°, and in the range of 45° to 90° they decreased gradually with increasing grain angles. Because the density and mechanical properties of the plastic and fiberboard elements were lower than the wood element, the anisotropy of WP and WF were mainly affected by the wood element and the effect of the plastic or fiberboard element was secondary. However, for WM, because the density and mechanical properties of metal element were much greater than the wood element, the anisotropy of WM was mainly affected by the metal element. Therefore, the sound velocity decreased slowly with increasing grain angle.

In Fig. 3, the sound velocities of the wood (W), plastic (P), fiberboard (F), metal element (M), wood–plastic composite (WP), wood–fiberboard composite (WF), and wood–metal composite (WM) from the vibration test are shown. The Hankinson equation[6] (Eq. 3) was also used to calculate the sound velocities of the wood element (Wn2.1), wood–plastic composite (WPn2.0), wood–fiberboard composite (WFn1.6), and wood–metal composite (WMn1.8).

$$V_\theta = \frac{V_0 V_{90}}{V_0 \sin^n \theta + V_{90} \cos^n \theta} \tag{3}$$

where V_θ is the sound velocity at angle θ from the grain direction, V_0 is the sound velocity parallel to the grain, V_{90} is the sound velocity perpendicular to the grain, and n is an empirically determined constant. The values of n in this study were 2.1 for wood, 2.0 for wood–plastic composite 1.6 for wood–fiberboard composite, and 1.8 for wood–metal composite.

The sound velocity was also estimated from the grain angle using statistical regression analysis. For doing so, a second-order parabolic equation was used, which takes the form:[7]

$$V_\theta = A + B\theta + C\theta^2 \tag{4}$$

where V_θ is the sound velocity, θ is the grain angle in degrees, and A, B, and C are the constants from the regression between sound velocity and grain angle. The sound velocities of the wood element (Wt), wood–plastic composite (WPt), wood–fiberboard composite (WFt), and wood–metal composite (WMt) calculated from Eq. 4 are also shown in Fig. 3. Regression analyses between sound velocity and grain angle indicate that the second-order parabolic equations provide good fit of the data with R^2 ranging between 0.980 and 0.997, as reported in Table 1. The regression constants are, for wood, A 5.022, B − 0.0996, C 0.0006; for wood–plastic composite, A 4.052, B −0.0765, C 0.0005; for wood–fiberboard composite, A 4.096, B −0.0748, C 0.0005; and for wood–metal composite, A 5.150, B −0.0231, C 0.00003.

Figure 3 and the above analysis show that the predicted sound velocities from Hankinson's equation and the second-order parabolic equation lie close to the measured values from the vibration method. This indicates that Hankinson's equation can be used to predict the sound velocity of wood-based composite from the grain angle and the relationship between the grain angle of the face veneer and that the sound velocity of three types of wood-based

Table 1. Results of regression analysis for the second-order parabolic equations for predicting sound velocity from grain angle in wood and three types of wood-based composites

Materials	Parabolic equation	R^2
Wood (W)	$V_{Wt} = 5.022 - 0.0996\theta + 0.0006\theta^2$	0.991
Wood–plastic composite (WP)	$V_{WPt} = 4.052 - 0.0765\theta + 0.0005\theta^2$	0.989
Wood–fiberboard composite (WF)	$V_{WFt} = 4.096 - 0.0748\theta + 0.0005\theta^2$	0.997
Wood–metal composite (WM)	$V_{WMt} = 5.150 - 0.0231\theta + 0.00003\theta^2$	0.980

V_{Wt}, V_{WPt}, V_{WFt}, and V_{WMt} are the sound velocities of the wood element, wood–plastic composite, wood–fiberboard composite, and wood–metal composite, respectively, from the second-order parabolic equations
θ, grain angle

composites can be expressed in the form of a second-order parabolic equation.

Dynamic Young's modulus

Figure 4 shows the relationship between dynamic Young's modulus and the grain angle of the face veneer of three types of wood-based composites. The trends are similar to those of Fig. 3.

In Fig. 4, the dynamic Young's moduli of the wood (W), plastic (P), fiberboard (F), metal element (M), wood–plastic composite (WP), wood–fiberboard composite (WF), and wood–metal composite (WM) from the vibration test are shown. The Jenkin equation[8,9] (Eq. 5) was also used to calculate the dynamic Young's moduli of the wood element (Wc1), wood–plastic composite (WPc1), wood–fiberboard composite (WFc1), and the wood–metal composite (WMc1).

$$\frac{1}{E_\theta} = \frac{1}{E_L}\cos^4\theta + \left(\frac{1}{G_{LT}} - \frac{2\sigma_{LT}}{E_L}\right)\cos^2\theta\sin^2\theta + \frac{1}{E_T}\sin^4\theta \tag{5}$$

where E_θ is the Young's modulus in a direction θ to the grain, E_L is the Young's modulus in a direction parallel to the grain, E_T is the Young's modulus in a direction perpendicular to the grain, G_{LT} is the shear modulus in the LT plane, and σ_{LT} is Poisson's ratio.

When $\theta = 45°$, Eq. 5 can be represented as follows:

$$\frac{2\sigma_{LT}}{E_L} = \frac{1}{E_L} + \frac{1}{E_T} + \frac{1}{G_{LT}} - \frac{4}{E_{45}} \tag{6}$$

Substituting Eq. 6 into Eq. 5, E_θ can be calculated as follows:

$$\frac{1}{E_\theta} = \frac{1}{E_L}\cos^4\theta + \frac{1}{E_T}\sin^4\theta + \left(\frac{4}{E_{45}} - \frac{1}{E_L} - \frac{1}{E_T}\right)\sin^2\theta\cos^2\theta \tag{7}$$

namely,

$$\frac{1}{E_\theta} = \frac{1}{E_0}\cos^4\theta + \frac{1}{E_{90}}\sin^4\theta + \left(\frac{4}{E_{45}} - \frac{1}{E_0} - \frac{1}{E_{90}}\right)\sin^2\theta\cos^2\theta \tag{8}$$

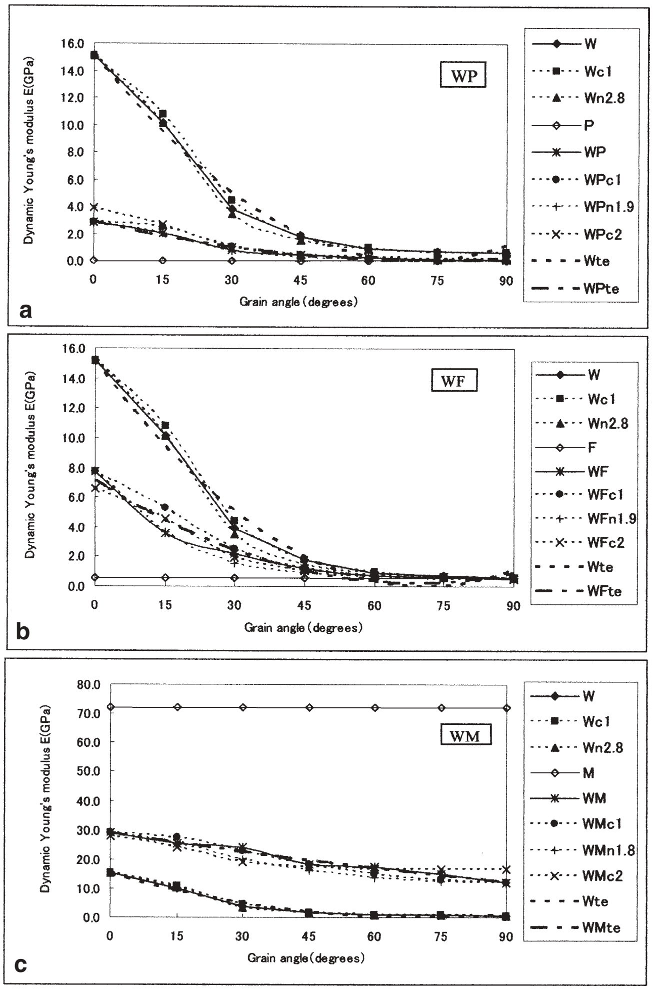

Fig. 4. Relationship between dynamic Young's modulus (E) and grain angle of face veneer for **a** wood–plastic composite, **b** wood–fiberboard composite, **c** wood–metal composite. Notations are analogous to those in Fig. 3. *W*, *P*, *F*, *M*, *WP*, *WF*, and *WM* are the dynamic Young's moduli from the vibration test. *Wc1*, *WPc1*, *WFc1*, and *WMc1* are the Young's moduli calculated from the Jenkin equation (Eq. 8). *Wn2.8*, *WPn1.9*, *WFn1.9*, and *WMn1.8* are the Young's moduli calculated from Hankinson's equation (Eq. 9). *Wte*, *WPte*, *WFte*, and *WMte* are the Young's moduli calculated from Eq. 10, and *WPc2*, *WFc2*, and *WMc2* are the Young's moduli calculated from the rule of mixture (Eq. 11)

The relationship between the Young's modulus of wood and the grain angle may also be expressed as a form of the Hankinson equation:

$$E_\theta = \frac{E_0 E_{90}}{E_0 \sin^n \theta + E_{90} \cos^n \theta} \tag{9}$$

where E_θ is the Young's modulus at angle θ from the grain direction, E_0 is the Young's modulus parallel to the grain, E_{90} is the Young's modulus perpendicular to the grain, and n is an empirically determined constant. In Fig. 4, the Young's moduli calculated from the Hankinson equation for the wood element (Wn2.8), wood–plastic composite (WPn1.9), wood–fiberboard composite (WFn1.9), and wood–metal composite (WMn1.8) are also shown. The values of n were 2.8 for wood, 1.9 for wood–plastic composite, 1.9 for wood–fiberboard composite, and 1.8 for wood–metal composite.

The Young's modulus was also estimated from the grain angle using statistical regression analysis. For doing so, a second-order parabolic equation was used, which takes the form:[10]

$$E_\theta = A + B\theta + C\theta^2 \tag{10}$$

where E_θ is the Young's modulus, θ is the grain angle in degrees, and A, B, and C are constants from the regression between Young's modulus and grain angle. The Young's moduli of the wood element (Wte), wood–plastic composite (WPte), wood–fiberboard composite (WFte), and wood–metal composite (WMte) calculated from Eq. 10 are also shown in Fig. 4. Regression analyses between Young's modulus and grain angle indicate that second-order parabolic equations provide good fit of the data, with R^2 ranging between 0.959 and 0.985 as reported in Table 2. The regression constants are, for wood, A 15.15, B −0.4284, C 0.0030; wood–plastic composite, A 2.892, B −0.0777, C 0.0005; wood–fiberboard composite, A 7.126, B −0.2001, C 0.0015; and wood–metal composite, A 28.98, B −0.2255, C 0.0005.

Figure 4 and above analysis show that the Young's moduli predicted using the Jenkin equation, Hankinson's equation, and second-order parabolic equation lie close to the value measured in vibration tests. This indicates that the Jenkin equation and Hankinson's equation can be used to predict the Young's modulus of wood-based composite from the grain angle and the relationship between the grain angle of the face veneer and the Young's modulus of three types of wood-based composites can be expressed in the form of a second-order parabolic equation.

The rule of mixture (ROM) (Eq. 11) was also used to calculate the Young's moduli of wood–plastic composite (WPc2), wood–fiberboard composite (WFc2), and wood–metal composite (WMc2), and the results are plotted in Fig. 4.

$$E_c = E_W V_W + E_f V_f \tag{11}$$

where E_c is the Young's modulus of wood-based composite, E_w is the Young's modulus of wood element, V_w is the volume percent of wood element, E_f is the Young's modulus of another element of the wood-based composite, and V_f is the volume percent of another element of the wood-based composite. As shown in Fig. 4, it is clear that experimental values showed good agreement with those based on the ROM. This indicates that ROM can be used to predict the Young's modulus of wood-based composite from the Young's moduli of the two elements.

Conclusions

The effects of grain angles of face veneer on sound velocities and dynamic Young's moduli of three types of wood-based composites were examined. The results are summarised as follows:

1. Grain angles of face veneer have substantial effects on sound velocities and dynamic Young's moduli of wood-based composites. The sound velocity decreased with increasing grain angle. For WP and WF, the sound velocity decreased rapidly with increasing grain angle up to 45°, while in the range of 45° to 90° they decreased gradually with increasing grain angles. However, for WM, the sound velocity and dynamic Young's modulus decreased slowly with increasing of grain angle.
2. The relationship between the grain angle of the face veneer and the sound velocity of wood-based composites can be expressed in the form of Hankinson's equation or a second-order parabolic equation.
3. The grain dependence of the Young's modulus of three types of wood-based composites was similar to that of sound velocity. This study has shown that the application of orthotropic elasticity theory was valid for three types of wood-based composites. The relationship between the grain angle of face veneer and the Young's modulus of three types of wood-based composites can be expressed

Table 2. Results of regression analysis for the second-order parabolic equations for predicting Young's modulus from grain angle in wood and three types of wood-based composites

Materials	Parabolic equation	R^2
Wood	$E_{Wt} = 15.15 - 0.4284\theta + 0.0030\theta^2$	0.985
Wood–plastic composite	$E_{WPt} = 2.892 - 0.0777\theta + 0.0005\theta^2$	0.984
Wood–fiberboard composite	$E_{WFt} = 7.126 - 0.2001\theta + 0.0015\theta^2$	0.959
Wood–metal composite	$E_{WMt} = 28.98 - 0.2255\theta + 0.0005\theta^2$	0.980

E_{Wt}, E_{WPt}, E_{WFt}, and E_{WMt} are the Young's modulus of the wood element, wood–plastic composite, wood–fiberboard composite, and wood–metal composite, respectively, from the second-order parabolic equations in the form of the Jenkin equation, Hankinson's equation, or a second-order parabolic equation.

4. Rule of mixture can be used to predict the Young's modulus of wood-based composites from the Young's moduli of the two elements.

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