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Flexural vibration properties of particle board using acrylic emulsion adhesives with differential glass transition temperature

Kaoru Fujishiro1, Takuya Ito2, Hiroko Sato3, Ryosuke Masunari3 and Masaaki Yamada3*

Abstract
Vibration characteristics of wood-based materials are essential parameters in considering the indoor environment of a building. This study investigates the effect of the physical properties of water-based adhesives on vibration characteristics of wood-based materials. Adhesive films and particle boards (PB) were prepared from acrylic emulsion adhesives (AE) with differential glass transition ($T_g$), and loss tangent of dynamic viscoelasticity ($\tan\delta_D$) and flexural vibration property ($\tan\delta_F$) were compared. The $\tan\delta_D$ master curve and $\tan\delta_F$ showed a similar tendency regarding frequency dependence. The apparent activation energy ($\Delta H$) calculated from the shift factor of the master curve tends to be different depending on the $T_g$ of AE and was especially high for AE with $T_g = 13 \, ^\circ\text{C}$ along with blended AE. The dynamic Young’s modulus ($E_F$) calculated from the flexural vibration tests showed higher values for AE at $T_g = 13 \, ^\circ\text{C}, 41 \, ^\circ\text{C}$, and $90 \, ^\circ\text{C}$ than that of urea–formaldehyde adhesive (UF).

Keywords: Acrylic emulsion adhesive, Glass transition temperature, Dynamic viscoelasticity, Time–temperature superposition, Master curve, Apparent activation energy, Shift factor, Particle board, Flexural vibration, Loss tangent

Introduction
Since the industrial revolution in the latter half of the eighteenth century, the world population, which was less than one billion, has increased rapidly and is forecast to reach 9.7 billion by 2050. Most of the increased population lives in urban areas [1], and living noise due to the increase in apartments is viewed as a problem [2, 3]. In Japan, nearly 2500 complaints of noise originating from home life and store operations were received in 2019; most of them were concentrated in large cities [4]. Therefore, the control of indoor noise in urban areas is an important issue worldwide.

In Japanese urban areas, wooden constructions are used for low-rise buildings, and reinforced concrete (RC) and steel-framed RC (SRC) structures are used for mid-high-rise buildings. Furthermore, the number of wooden mid-high-rise apartments has been gradually increasing due to the recent progress of cross-laminated timber (CLT). Among them, floor impact noise countermeasures during wooden apartment buildings are probably important regardless of the size of buildings. As wooden constructions have lower stiffness and mass than RC and SRC constructions, resulting in lower floor impact sound insulation performance [5–7]. In addition, it has been reported that this tendency does not change even when CLT is used [8, 9]. Accordingly, impact sound countermeasures are essential in wooden apartment buildings, such as dry double floors, suspended ceilings, and damping materials. Failure to do so makes it difficult to satisfy adaptation class 3 [10], which is defined as the standard floor impact sound insulation performance in daily life summarized by the Architectural Institute of Japan. However, improving the floor impact sound insulation performance typically increases the construction

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*Correspondence: yamada.masaaki@shizuoka.ac.jp
1 Faculty of Agriculture, Shizuoka University, 836, Ohyã, Suruga-ku, Shizuoka 422-8529, Japan
Full list of author information is available at the end of the article
cost; therefore, a construction method with low cost and high performance is important.

Research adding vibration damping properties to wood-based materials has been made to solve such problems. First, the vibration damping properties of general wood-based materials have been evaluated by Wang et al. [11] and Guan et al. [12] using the cantilever method, such as logarithmic decrement. Ebihara [13] successfully increased the loss tangent (\(\tan \delta\)) of particle board (PB) by blending pellets of agricultural polyvinyl chloride sheet. Lee et al. [14–18] examined the detailed relationship between laminated wood and \(\tan \delta\) from the dynamic viscoelasticity viewpoint by changing the differential glass transition (\(T_g\)) of nonaqueous adhesives. They successfully developed an adhesive with high \(\tan \delta\) over a wide temperature range by introducing an interpenetrating polymer network into the adhesive. Sargianis et al. [19] maintained bending stiffness and improved \(\tan \delta\) by bonding plant fibers impregnated with a vinyl ester resin to lightweight wood. In this way, various studies have been conducted on imparting vibration damping properties to wood-based materials. However, they are mainly the changes in the physical properties of nonaqueous adhesives and the addition of the resin pellets. A limited number of studies have investigated the relationship between changes in the physical and vibration damping properties of water-based adhesives, which are widely used in the production of wood-based materials.

Most water-based adhesives recently used in producing wood-based materials are formaldehyde-based adhesives using urea resin, melamine resin, and phenol resin. However, we hope that these shift to non-formaldehyde adhesives such as aqueous emulsions because they contain formaldehyde of hazardous substance. One of the non-formaldehyde adhesives is a thermoplastic acrylic emulsion adhesive (AE). AE is made from emulsion polymerization of acrylic acid and methacrylic acid esters. AE characteristics are abundant in many monomers compared with other resins; they can be copolymerized or otherwise modified to obtain a variety of physical properties at a relatively low cost. For example, AE products with \(T_g\) of 0 °C or lower are used as pressure-sensitive adhesives. In addition, products with \(T_g\) of 0 °C or higher are used as paints and adhesives. Furthermore, \(T_g\) is strongly related to vibration damping properties, which is an essential parameter for its evaluation [20].

Therefore, this study investigates the relationship between the physical properties of water-based adhesives and the damping properties of wood-based materials. Master curves using the temperature–time conversion law were created from loss tangent of dynamic viscoelasticity (\(\tan \delta_D\)) obtained from the dynamic viscoelasticity of AE films with different \(T_g\)s and blends. In addition, \(\tan \delta_D\) was compared with flexural vibration property (\(\tan \delta_F\)) in lower and higher modes obtained from the flexural vibration tests of PBs made from the same AE.

### Materials and methods

#### Materials

Table 1 summarizes the five types of AE used in the experiment and urea–formaldehyde adhesion (UF), and Table 2 presents these compounding ratios. The properties of AE were referred to the manufacturer’s website [21, 22]. UF was evaluated as a comparative adhesive in the PB flexural vibration test. Ammonium sulfate [(NH₄)₂SO₄] 20% solution was used as a hardener of UF at 9.1%. The viscosity of UF was measured at 23 °C and 30/min using Brookfield viscometer (BMII viscometer, Toki sangyo, Tokyo, Japan).

The particles of PB are Japanese cypress (Chamaecyparis obtusa). The Japanese cypress chips were processed with a hammer mill (HM-3, Nara Machinery, Tokyo, Japan) and classified into a mesh size of 0.85–2.0 mm for 30 min using a sieve shaker (Analysette 3, Fritsch, Idar-Oberstein, Germany). The particles were dried absolutely in a heat air oven at 105 °C for ≥3 days.

#### Preparation of AE films

AE was cast into a polytetrafluoroethylene (PTFE) resin mold with a depth of 0.5–2 mm and formed a film at

| Adhesive name | Product name | Resin type | \(T_g\) (°C) | MFT (°C) | Viscosity (mPa s, 23 °C) | Solid content (%) | Manufacturer |
|---------------|--------------|------------|-------------|----------|-------------------------|------------------|--------------|
| Ac-65         | RIKABOND AP-96 | Acrylic emulsion | −65        | 0        | 3500                    | 55.0             | Japan coating resin |
| Ac-15         | MOWINYL LDM7522 | −15        | 0          | 100–1000 | 50.4                    |                 |              |
| Ac13          | MOWINYL DM774  | 13         | 23         | 3000–10000 | 46.2                  |                 |              |
| Ac41          | MOWINYL 6520  | 41         | 50         | 200      | 45.8                   |                 |              |
| Ac90          | RIKABOND ES-90 | 90         | 110        | 125–375  | 50.6                   |                 |              |
| UF            | UB-S1        | Urea–formaldehyde resin | − | − | 900 | 60.0 | J-CHEMICAL |
20 °C and 65% RH for ≥ 1 day. The Ac41 and Ac90, with a minimum film-forming temperature higher than room temperature \( T_r = \sim 20 \, ^\circ\text{C} \), formed a film by oven-drying at 150 °C for 20–40 min by covering the PTFE resin mold with aluminum foil. The Ac90 after oven-dry with cracks on the surface was molded with a thickness of 0.2 mm by hot pressing for 10 s at 200 °C. The prepared films were cut to 30 mm × 6 mm with a cutter, which were dried using a vacuum dryer at 60 °C.

**Dynamic viscoelastic measurements**

The thermomechanical properties were determined using a dynamic thermomechanical analyzer (DMA 242 E, Netzsch, Selb, Germany). The AE films were analyzed from −80 to 150 °C at a ramp of 3 °C/min in tension mode with a span of 10 mm; amplitude of 10 μm; and frequency of 1, 5, 10, and 20 Hz.

**Fabrication of PB**

The particles put into a polyethylene bag with a capacity of 70 L were sprayed with AE using a spray gun. Distilled water was added to the highly viscous adhesives until they were sprayable. The spread rates were made to 9:1 for the oven-dry particles and AE nonvolatile content. The adhesive-coated particles were spread manually onto the press plate. Subsequently, the particles were pressed with a target board density of 0.8 g/cm³, hot plate temperature of 180 °C, compression pressure of 2 MPa, compression time of 15 min, and a thickness of 10 mm. After 15 min of compression, the hot plate heater was turned off, and the pressure was maintained while cooling for ≤ 100 °C. In addition, eight specimens of 300 mm × 30 mm (length and width) were produced from PBs controlled at 20 °C and 65% RH for ≥ 2 weeks.

**Flexural vibration test of PB**

Figure 1 shows a diagram of the flexural vibration test with PB. The specimens were suspended by two threads at the positions of the diagram. The two threads were placed at the nodes position (ratio to length = 0.2242) of the first resonance mode of the specimens. A microphone (MI-1235, Ono sokki, Yokohama, Japan) with a preamplifier (MI-3111, Ono sokki, Yokohama, Japan) was installed at one end of the specimens. The vibrations were measured by hammering the end surface of the other end with a metal rod with such force that the specimens did not move from the top of the two threads. Almost no longitudinal vibration occurred during hammering the end surface at the specimen shape and thread positions. Moreover, obtaining flexural vibration with less noise in the resonance frequency of higher modes than the flat surface hammering was possible. The details are described later in this section. The measured values were Fourier-transformed using an FFT analyzer DS-3000 (DS-3000, Ono sokki, Yokohama, Japan). The dynamic Young’s modulus (\( E_F \)) was calculated from Eq. (1) [23] using the first resonance frequency (\( f_1 \)) of a power spectrum. The measurement environment was 20 °C and 65% RH. In the following equation, \( l \) is the specimen length, and \( \rho \) is the density:

\[
E_F = \frac{4\pi^2 \cdot l^4 \cdot \rho \cdot f_1^2 \cdot A}{m_n^4 \cdot l}
\]  

(1)

Then, \( \tan \delta_F \) of PB are calculated from Eq. (2) [24] using the resonance frequency of each mode (\( f_n \)) obtained from the power spectra and the slope of the vibration

![Fig. 1 Schematic of the flexural vibration test with PB; a PB specimen; b threads; c metal bar; d tapping point; e microphone with amplifier; and f FFT analyzer](image-url)
damping (a) obtained from Hilbert transformed time base waveforms:

\[ \tan \delta_f = 0.1151 \cdot |a| \cdot \frac{1}{\pi f_n} \]  

(2)

Figure 2 shows the relationship between \( f_1-f_3 \) for different hammering positions on the end and flat surfaces in the vibration test. The specimens were a flat-grain board of solid Japanese cypress wood with grains in the longitudinal direction with the moisture content of 11.8% and PB made from UF. The dimensions of the solid wood were the same of PB. Therefore, almost no difference in \( f_1 \) of the present measurement was 200–600 Hz, whereas \( f_1 \) of the longitudinal vibration using the 400–900-mm (length) specimens of keyaki (Zelkova serrata) in the previous report was approximately 5 kHz, confirming that the present results were due to flexural vibration [25].

Results and discussion

Dynamic viscoelasticity of AE films

Figure 3 shows the storage elastic modulus (\( E' \)), loss of elastic modulus (\( E'' \)), and \( \tan \delta_f \) of AE and blended AE at the measurement frequency of 10 Hz. The \( E'' \) of single AE peaked at a temperature slightly higher than \( T_g \) presented by the manufacturer. The \( E'' \) of single AE peaked at a temperature slightly higher than \( T_g \) presented by the manufacturer, and \( E' \) showed a glassy state up to around that temperature; it also dropped sharply as increased temperature. The \( \tan \delta_f \) of single AE showed a clear peak according to each \( T_g \). This suggests that the molecular structure is in the form of homopolymers or random copolymers [26]. However, \( E' \) and \( E'' \) of blended Ac-65/90 decreased more gradually than AE single from -60 to 120 °C and decreased significantly with a different slope after 120 °C. The \( \tan \delta_f \) of Ac-65/90 showed peaks at -30 °C and 120 °C similar to single Ac-65 and Ac90, showing flat behavior between them. This phenomenon, in which separate peaks appeared, suggests that the two AEs may be phase-separated in the film [27]. The \( E' \) and \( E'' \) of blended Ac-65/13/90 showed the same tendency as those of Ac-65/90. Besides, the \( E' \) peak based on \( T_g \) of Ac13 was confirmed after 50 °C. However, the \( \tan \delta_f \) of Ac-65/13/90 showed almost no peak at -30 °C derived from Ac-65, showing a higher value for the peak on the higher temperature side. It indicates that Ac90 forms a continuous layer during the film formation [27].

Analysis of \( \tan \delta_f \) due to master curve

To study the frequency characteristics of \( \tan \delta_f \) in a wider range, the master curves were prepared at the reference temperature of \( T_0 = 20 \) °C and the measured temperature of \( T = -20 \) °C to 50 °C using the time–temperature conversion rule [28]. \( T_0 \) is presumed to be the room temperature in Japan. During the preparation, it was arranged around \( T_0 \) so that the results on the low- and high-temperature sides were translated to the high- and low-frequency sides, respectively, to form a single curve. Figure 4 shows the details of the master curve creation.

Figure 5 shows the master curves of \( \tan \delta_f \) at \( T_0 \) in the scope of 1–10,000 Hz. The solid lines in the master curve are the result of visually connecting the rough trend of the plot. The \( \tan \delta_f \) of Ac-65 with the lowest \( T_g \) showed a leveling off to ~1–400 Hz. However, there were some variations; a gradual upward trend was observed as the frequency increased. We presumed that this variation is due to the difficulty of measuring rubber-state samples from \( T_g \) to high-temperature ranges in tensile mode. The \( \tan \delta_f \) of Ac-15 was the largest value among the specimens and peaked at ~50 Hz. The measured temperature of ~7 °C on the viscoelasticity corresponds to one digit of the reduced frequency on a master curve [17]. In this study, a similar tendency was shown in the master curve because the \( \tan \delta_f \) peak measured at 10 Hz of Ac-15 in Fig. 3 is 16 °C. The \( \tan \delta_f \) of Ac13, Ac41, and Ac90 was lower than that of the aforementioned two types at any reduced frequency. Because the three types of AE have \( T_g \) greater than or equal to \( T_0 \), it is considered that the master curves strongly reflected the results of the glassy state. The \( \tan \delta_f \) of blended Ac-65/90 showed an intermediate value between Ac-65 and Ac90. However, the value shifted to the Ac90 side as the reduced frequency increased. It is possible that the phase-separated
Fig. 3 Dynamic viscoelastic properties of AE and blended AE films

Fig. 4 Details of the master curve creation; a the value of low temperature is shifted to the high frequency side and the value of high temperature is shifted to the low-frequency side based on $T_0$ so that they overlap on the single line; b the master curve overlapped on the single line; c calculate $\Delta H$ by finding the slope of the tangent line from an Arrhenius-type plot with the reciprocal of the absolute temperature on the horizontal axis and natural logarithm of $\alpha_i$ on the vertical axis
adhesive formed a sea–island structure with Ac90 and Ac-65 on the sea and island sides, respectively, making it more susceptible to Ac90. The tan δD of Ac-65/13/90 was lower than that of Ac-65/90. The reason is that the addition of Ac13 increased the proportion of glassy components in T₀.

The shift factor (aᵣ), which is the amount of parallel translation at the placement time, was expressed by the Arrhenius equation using Eq. (3) [29]. Therefore, the apparent activation energy ΔH in viscous flow was calculated from the slope of the tangent by plotting ln aᵣ at 1/T. R is the gas constant:

$$\ln aᵣ = \frac{ΔH}{R} \left( \frac{1}{T} - \frac{1}{T₀} \right)$$

Figure 6 shows the relationship between ln aᵣ of each AE and 1/T. Table 3 presents ΔH in the viscous flow of each AE. First, in all AEs, the high correlation with a coefficient of determination $R^2 ≥ 0.95$ was observed using linear approximation, confirming the validity of the master curve. The ΔH of single AE achieved a maximum value at Ac13 and decreased with the change of temperature. This is owing to the fact that ΔH depends on the scale of molecular motion, and the micro-Brownian motion, called the main dispersion, shows an extreme near Tₙ [26]. Therefore, ΔH becomes progressively smaller as the Tₙ of AE moves away from T₀. The ΔH of Ac-65 and Ac90 are considered to have shown almost the same value because $Tₙ$ was far away from $T₀$ and $T$. The ΔH of blended AE differs depending on its $Tₙ$. Ac-65/90 blended with only AE with low ΔH and was almost the same as the two AEs before blending. However, Ac-65/13/90 shows similar results to Ac13, suggesting that AE with a high ΔH may have a strong effect on ΔH even after blending. In addition, Ac13 and Ac-65/13/90 can be seen as if the slope of ln $aᵣ$ changed at ~10 °C (Fig. 7). This temperature is close to $Tₙ$ of Ac13; the fluidity of both AEs likely changed at the boundary of $Tₙ$ [29]. In addition, Ac-15 and Ac41, whose $Tₙ$ is in the range of $T$, are assumed to have the same trend. However, no clear trend was observed, probably due to the fact that the $Tₙ$’s deviated significantly from T₀.

Flexural vibration of PB

Figure 8 shows $E_F$ and $ρ$ in the flexural vibration test of PB prepared with various AEs and UF. $E_F$ of single AE was maximum at Ac13 and declined as $Tₙ$ of AE increased and decreased. The reason is that the shear bonding strength of AE could influence $E_F$ [30]. The Young’s moduli in the flexure of PB are proportional to the shear bonding strengths of adhesives [31]. In addition, shear bonding strengths of thermoplastic adhesives have a maximum value at $T_r$ when $Tₙ$ is the $T_r$ [32]. $E_F$ of blended AE showed a similar tendency to that of Ac41 and Ac90. It had a value slightly higher than the average value calculated from the compounding ratios of AE (Table 4). We presumed that this result is because the phase structure of blended AE is susceptible to AE with high $Tₙ$ (Fig. 7). UF’s $E_F$ is also equivalent to Ac90.
Figure 9 shows the relationship between $f_n$ and $\tan \delta_F$ of PB prepared with various AEs and UF. Table 5 shows the average value and standard deviation (SD) of $f_n$ and $\tan \delta_F$. The $\tan \delta_F$ of Ac-65 and Ac-15 values are higher than other AEs. In addition, Ac-15 showed a decreasing
tendency with an increase in $f_n$. The reason is that the two AEs in the glass transition or rubber regions at $T = 20 \, ^\circ{\text{C}}$ easily absorb vibration (Fig. 3). All other AEs showed small values since they were in the glassy or glass transition regions near it. When the vertical axis was expanded, Ac13 showed a gradual decreasing tendency and Ac-65/90 showed a gradual increasing tendency. The tendencies of other AEs and UF were broadly flat, although there were some variations.

| Adhesive name     | Calculated ratio | $E_f$ (MPa) |
|-------------------|------------------|-------------|
| Ac-65/90          | –                | 4958        |
| Measured value    |                  |             |
| Averaged value    | 1:1              | 3648        |
| Ac-65/13/90       |                  | 6761        |
| Measured value    | –                |             |
| Averaged value    | 1:1:1            | 5347        |

Fig. 8 $E_f$ and $\rho$ in the flexural vibration test of PB; the error bars indicate standard deviation.

Table 4 Measured value of blended AE and averaged value calculated from an AE simple substance in $E_f$ of particle board.

Fig. 9 Relationships between frequency and $\tan\delta_f$ in the flexural vibration test of PB.
Comparison of $\tan\delta_D$ and $\tan\delta_F$

Figure 10 shows the comparison results of $\tan\delta_D$ and $\tan\delta_F$ in the frequency of 1–10,000 Hz. The magnitudes of the two $\tan\delta$s differed by ~ 3–10 times; however, they have the same tendencies. We presumed that this is because the relationship between the adhesive and particles in PB is similar to the sea–island structure. It was strongly influenced by adhesives as the sea side. Furthermore, regarding frequency dependence, similar tendencies were observed for all AEs, except for Ac-65. Generally, Ac-65 should show a similar tendency.

However, there were variations during tapping since it was in a rubber state at this measurement temperature.

Conclusions

In this study, we evaluated $\tan\delta_D$ of films made from AEs with different $T_g$ and $\tan\delta_F$ of PB to investigate the relationship between the physical properties of water-based adhesives and the vibration damping properties of wood-based materials. We obtained the following conclusions:

Table 5 - Average value and SD of $f_n$ and $\tan\delta_F$ for various AEs

| Adhesive name | Avg./SD | Resonance frequency (Hz) | $\tan\delta_F$ |
|---------------|---------|--------------------------|----------------|
|               |         | $f_1$ | $f_2$ | $f_3$ | $f_4$ | $f_5$ | $f_1$ | $f_2$ | $f_3$ | $f_4$ | $f_5$ |
| Ac-65         | Avg.    | 112.3| 289.8| 550.2| 849.6| – | 0.147| 0.142| 0.134| 0.146| – |
| SD            |         | 7.5 | 21.5 | 49.3 | 73.1 | – | 0.0463| 0.0384| 0.0306| 0.0147| – |
| Ac-15         | Avg.    | 153.5| 417.5| 842.1| – | – | 0.283| 0.188| 0.140| – | – |
| SD            |         | 8.1 | 16.2 | 34.3 | – | – | 0.0775| 0.0471| 0.0158| – | – |
| Ac13          | Avg.    | 252.3| 673.1| 1272.3| 2002.3| 2836.5 | 0.029| 0.028| 0.026| 0.026| 0.022 |
| SD            |         | 5.0 | 9.0 | 16.4 | 22.9 | 37.3 | 0.0011| 0.0011| 0.0032| 0.0011| 0.0019 |
| Ac41          | Avg.    | 232.1| 615.0| 1162.2| 1836.9| 2620.8 | 0.021| 0.021| 0.024| 0.022| 0.023 |
| SD            |         | 11.0| 24.6| 49.7 | 69.7 | 97.0 | 0.0006| 0.0006| 0.0041| 0.0008| 0.0026 |
| Ac90          | Avg.    | 209.2| 558.8| 1062.1| 1684.4| 2406.0 | 0.023| 0.021| 0.023| 0.022| 0.022 |
| SD            |         | 7.3 | 20.4| 40.6 | 63.1 | 84.1 | 0.0011| 0.0014| 0.0023| 0.0017| 0.0013 |
| Ac-65/90      | Avg.    | 197.5| 524.4| 1009.4| 1608.8| 2324.4 | 0.027| 0.029| 0.029| 0.030| 0.029 |
| SD            |         | 11.7| 33.8| 66.8 | 100.8| 151.3 | 0.0009| 0.0006| 0.0038| 0.0035| 0.0017 |
| Ac-65/13/90   | Avg.    | 225.6| 610.0| 1165.0| 1848.8| 2640.7 | 0.022| 0.022| 0.025| 0.023| 0.023 |
| SD            |         | 6.8 | 20.8| 38.5 | 61.5 | 94.2 | 0.0003| 0.0003| 0.0024| 0.0006| 0.0017 |
| UF            | Avg.    | 205.6| 551.9| 10596| 1695.6| 2455.3 | 0.022| 0.021| 0.025| 0.021| 0.021 |
| SD            |         | 8.1 | 15.6| 29.9 | 44.5 | 60.0 | 0.0005| 0.0003| 0.0018| 0.0003| 0.0006 |

Fig. 10 Relationships between frequency, $\tan\delta_D$, and $\tan\delta_F$ in various AEs
1. The peaks of $E'$, $E''$, and $\tan\delta_D$ with a single AE obtained from $\tan\delta_D$ were confirmed according to each $T_g$, $E'$ and $E''$ of blended AE decreased gradually from $-60$ to $120$ °C; more than $120$ °C changed its slope. $\tan\delta_D$ of blended AE was confirmed as the peak-based phase separation; its peak was smaller than AE alone.

2. $\tan\delta_D$ of the master curve at a frequency of $1$–$10,000$ Hz showed a high value at $T_g$ for Ac-65 in the rubber state and Ac-15 in the glass transition state. However, it showed a low value for the other AEs for the glassy state. $\Delta H$ calculated from $\ln a_T$ showed high values for Ac13 and Ac-65/13/90.

3. $E_F$ of single AE in the flexural vibration test showed the maximum value at Ac13 and declined as $T_g$ of AE increased and decreased. The $E_F$ values of blended AE and UF were similar to Ac41 and Ac90. The $\tan\delta_T$ values were high in Ac-65 in the rubber state and Ac-15 in the transition state; it was low in other cases.

4. According to these results, $\tan\delta_D$ and $\tan\delta_T$ showed a similar tendency in most AEs in terms of frequency dependence.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

Author details
1 The United Graduate School of Agricultural Science, Gifu University, 1-1 Yanaigido, Gifu 501-1193, Japan. 2 Graduate School of Integrated Science and Technology, Department of Agriculture, Shizuoka University, 836, Ohyaa, Suruga-ku, Shizuoka 422-8529, Japan. 3 Faculty of Agriculture, Shizuoka University, 836, Ohyaa, Suruga-ku, Shizuoka 422-8529, Japan.

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