FAILURE MECHANISM OF THE WOOD PLASTIC COMPOSITES

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ABSTRACT

Wood plastic composites (WPC) are composite materials made of wood fiber/wood flour and thermosets/thermoplastics. The reinforcement of the wood flour is expected to give filling effects and woody designs, and consequently WPC are used mainly in furniture applications, but automotive, transportation and building applications are also being developed in recent years.

Acoustic emission (AE) is the phenomenon of radiation of acoustic waves that occurs when a material undergoes irreversible changes, such as fiber breakage, matrix crack and interfacial debonding/sliding. In the AE measurement, the damage occurrence in the mechanical test can be identified by measuring this AE waves because the frequency are different with various damages.

In this study, WPC mixed wood flour and polypropylene were prepared with various wood flour addition rate, kneading speed, kneading temperature and compatibilizer. In addition, the tensile and 3-point bending tests were performed, and the influences of the mechanical properties were clarified by the fracture surface observation and AE measurement.

As a result, the stress-strain curve showed nonlinear behavior, and the strength and elastic modulus were increased with wood flour addition rate. On the other hand, kneading speed and kneading temperature have almost no influence on strength and elastic modulus. In addition, the damages during tensile test can be measured by AE measurement, and it was confirmed that the specimen breaks due to a large matrix crack. Furthermore, by the addition of the compatibilizer, the interface state was improved, and consequently the strength was increased, but there was no difference depending on the kind of compatibilizer. On the other hand, the load-displacement curve of the 3-point bending tests showed nonlinear behavior, and the strength and elastic modulus were increased with wood flour addition rate. But, there were no difference in the fracture toughness.

1 INTRODUCTION

Wood plastic composites (WPC) are composite materials made of wood fiber/wood flour and thermosets/thermoplastics. The reinforcement of the wood flour is expected to give filling effects and woody designs, and consequently WPC are used mainly in furniture applications, but automotive, transportation and building applications are also being developed in recent years [1-3]. In addition, the mechanical properties of the general fiber reinforced plastics (FRP) are influenced by the fiber addition rate, temperature and strain rate etc.

Acoustic emission (AE) is the phenomenon of radiation of acoustic waves that occurs when a material undergoes irreversible changes, such as fiber breakage, matrix crack and interfacial debonding/sliding. In the AE measurement, the damage occurrence times, scales and types in the mechanical test can be identified by measuring this AE waves because the frequency are different with various damages. For example, the frequency are resin fracture (250[kHz]), interfacial sliding (500[kHz]), interfacial debonding (750[kHz]) and fiber breakage (1000[kHz]) respectively [4-7].

In this study, WPC mixed wood flour and polypropylene (PP) were prepared with various wood flour addition rate, kneading speed, kneading temperature and compatibilizer. In addition, the tensile and 3-point bending tests were performed, and the influences of the mechanical properties were clarified by the fracture surface observation and AE measurement.

2 EXPERIMENTAL METHOD

2-1 Tensile test

The tensile specimens were made of cell bridit N (wood flour:PP=70:30, wood powder particle diameter 150μm, Toclas Co., Ltd.) and polypropylene (Poly primer Co., Ltd.), the predetermined wood flour rate specimens were prepared by mixing both materials. For kneading, a single screw extruder (Musashino Kikai Co., Ltd.) was used, and the specimens were prepared with various wood flour addition rate (0, 5, 25, 55[wt%]), kneading temperature (175, 180, 190[°C]), kneading speed (5, 10, 15, 25[rpm]) and compatibilizer (molecular weight=30000, 36000, 58000, 75000, 153000).

As shown in Figure 1(a), the tensile specimens are dumbbell-shaped specimens of 173[mm]× 18.7[mm]×3.1[mm] with parallel part of the central part 80 mm, and 3 specimens were prepared with each conditions. For the strain measurement, a strain gauge (KFG-2-120-D16-11L1M2S, Kyowa Electronics Co., Ltd.) with gauge length of 2[mm] was used. When attaching the strain gauge, the adhesion part was filed with waterproof abrasive paper #80, and the surface was cleaned up with ethanol, then strain gauge was attached to the center of the specimen using cyanoacrylate adhesive (CC-33A, Kyowa Electronics Co., Ltd.).

The tensile tests were performed for the above specimens using Tensilon universal testing machine (RTF-1350, A&D Co., Ltd.) with crosshead speed 10[mm/min], and AE measurements were also performed at the same time. In addition, after the tensile tests, the fracture surfaces of the specimens were observed using scanning electron microscope (VE-7800, KEYENCE Co., Ltd.). For SEM observation, in order to make the observation surface easier to see, gold vapor deposition treatment was performed using an ion sputtering film formation apparatus (MSP-Mini, Vacuum Device Inc.).

As described above, in this study, the fracture behaviors of the WPC were observed by the fracture surface observation and AE measurement, and the influence of the fabrication conditions was evaluated.

2-2 Fracture toughness test (3-point bending test)

The three-point bending specimens were prepared using kneading / extrusion molding evaluation test apparatus (Laboplast Mill) with various wood flour addition rate (0, 5, 25, 55, 65[wt%]). Where, kneading temperature is 190[°C], kneading speed 60[rpm], and 3 specimens were prepared with each conditions.

The fracture toughness of 3-point bending test were evaluated using ASTM D 5045-93 "Plane strain fracture toughness and strain energy release rate of plastic material" [8]. In accordance with this evaluation method, the strip specimens of 60[mm]×6.5[mm]×13[mm]with pre-crack at the central part of the specimen with a length of 6.5 mm were used as shown in Figure 1(b). 3-point bending tests were performed for these strip specimens using a universal testing machine (SC-5H, manufactured by JT Toshiba Corporation) at a distance between support points of 52[mm] and a crosshead speed of 10[mm/min], then fracture toughness K_Q was evaluated by Eq.(1) and (2).

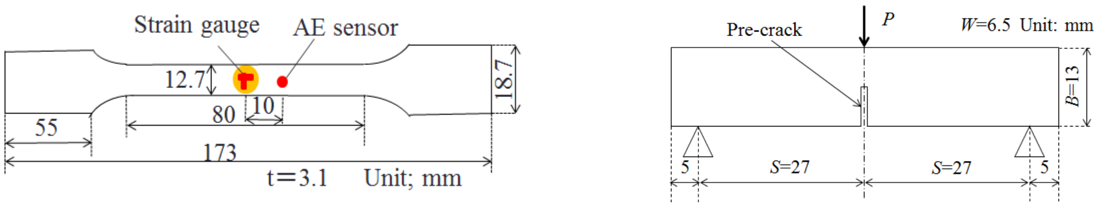
$$K_Q = \frac{PS}{BW^{3/2}} f(a/W) \tag{1}$$

$$f(X) = f(a/W) = \frac{1.5X^{1/2} - X(1-X)(2.15 - 3.93X + 2.7X^2)}{(1+2X)(1-X)^{3/2}} \tag{2}$$

Where, a is crack length, B is specimen thickness, W is specimen width, S is distance between jigs (1/2 of fulcrum distance), P is $P = P_{max}$ (maximum load) or $P = P_Q$ (fracture load), and S/W was set to S/W=26/6.5=4. Further, after calculating the value of K_Q using Eq.(1), it was confirmed whether or not the following expression was satisfied.

$$B, a, (W-a) > 2.5(K_Q/\sigma_Y)^2 \tag{3}$$

Where, σ_Y the yield stress. If Eq.(3) is satisfied, K_Q is defined as the planar strain fracture toughness value K_{IC}, and its value was evaluated. If Eq.(3) isn't satisfied, the result of the 3-point bending test was rejected.



(a) Tensile test (b) 3-point bending test

Figure 1: Schematic of the specimen.

2-3 Acoustic emission measurement

As described in INTRODUCTION, Acoustic emission (AE) is the phenomenon of radiation of acoustic waves that occurs when a material undergoes irreversible changes, such as fiber breakage, matrix crack and interfacial debonding/sliding. In the AE measurement, the damage occurrence times, scales and types in the mechanical test can be identified by measuring this AE waves because the frequency are different with various damages [4-7].

In AE measurement, broadband type AE sensor (NF circuit block, AE - 900 M) was used, and the AE sensor was fixed using grease (Dow Corning Toray high vacuum grease, Toray Industries, Inc.) to the center of the specimen (Figure.1(a)). As shown in Figure 2, the AE measurement conditions was set using the preamplifier (2/4/6 ch preamplifier power supply, Physical Acoustics Corporation), and the preamplifier gain is 40[dB], the preamplifier input threshold value is 10[μV], and the measurement frequency band is 50~1300[kHz]. The AE waves was recorded and processed by FFT analysis at a sampling frequency of 5[MHz] by PC oscilloscope (Picoscope 4424, Pico Technology Inc.) and the AE measurement program using the LABVIEW (R) language (National Instruments Corp.). Furthermore, the evaluation was carried out using the cumulative value of the AE amplitude defined by the square of the AE amplitude and peak voltage value.

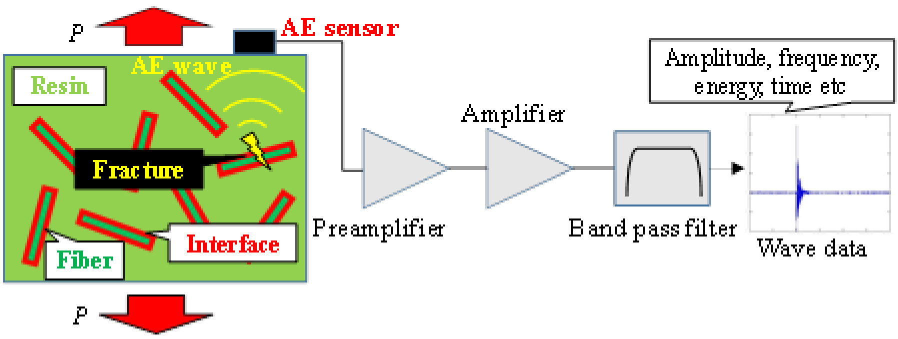


Figure 2: Schematic of the AE measurement.

3 RESULT AND DISCUSSION

3-1 Tensile test

Tensile test results of WPC specimens with various wood flour addition rate, kneading speed, kneading temperature and compatibilizer are shown in Figures 3~6 and Table 1. In any specimens, the stress-strain curves show non-linear behavior. As shown in Figure 3, the dynamic behavior are changed with wood flour addition, and the fracture strain are decreased with wood flour addition rate. This is because that PP matrix are ductile materials, and wood flours with poor ductility were added. In addition, the tensile strength and Young's modulus are increased with wood flour addition rate, thus it is thought that the fracture mechanism of the WPC were changed.

To confirm this fact, the result of SEM observation of the fracture surface after the test are shown in Figure 7. As shown in Figure 7, the fractured surface showed a large irregular shape in 0[wt%]

specimen (Figure 7(a)), while microscopically irregular fracture surfaces were observed in high wood flour addition rate specimen (Figure 7(d)). Such fracture surfaces are due to the micro void growth as shown in Figure 8, that is, i) At surface, PP matrix tends to deform largely due to free surface. ii) Internal PP matrix is restricted in deformation, expansion stress occurs, and this stress cause the formation of micro voids. iii) Further given load leads to a fibrillation of PP molecular chains mechanism of whitening. Of course, the frequency of this disturbance increases with wood flour addition rate. Thus, if flour addition rate is small, micro void can grow greatly, while if flour addition rate is large, the growth are disturbed by wood flour, consequently, micro void can't grow greatly. From the above, the fracture surface becomes finer irregular shape with wood flour addition rate, thus the fracture energy was increased, consequently, these specimens showed high strength and modulus.

The results of AE measurements to identify damage occurring during tensile tests are shown in Figure 9. Where, Figure 9(a), (a’) show time history of the stress and damage occurrence, while Figure 9(b), (b’) show the frequency and magnitude of the damage. As shown in these figures, in either case of 0 and 55[wt%], the micro damages were occurred in the initial loading stage, and the stress-strain curve shows nonlinear behavers. After that, with increase of the load, these micro damages were accumulated, and large damage occurred just before specimen fracture. As described in **Section 2-3**, the frequency of the AE are differs depending on the kind of damage, the each frequencies of the fiber breakage, interfacial debonding, sliding and resin fracture are 1000, 750, 500 and 250[kHz] respectively. Based on this fact and Figure 9 (b), (b'), microscopic damages such as fiber breakages, interfacial dedondings / slidings and resin fracture were occurred intermittently, finally, the specimens were fractured by large resin fracture.

As shown in Figures 4 and 5, the stress-strain curves are also showed nonlinear behavior, there are no difference of the behavior depending on kneading speed and temperature. In addition, in SEM observation, there are also no difference of the fracture surface. Furthermore, as shown in Figure 6, the strength and modulus are increased by addition of the compatibilizer. This is because that the interface state was improved by compatibilizer, and the interfacial bonding became strong. But there was no difference depending on the kind of compatibilizer.

As described above, in tensile test, the influence of the wood flour addition rate are large, while there are almost no influence of the kneading speed, kneading temperature and compatibilizer. This is because that the major damage growth component of the WPC is void growth, fibrillation formation and void progress suppression by wood flour, and the wood flour effect is increased with wood flour addition rate.

3-2 Fracture toughness test (3-point bending test)

Bending test results of WPC specimens with various wood flour addition rate are shown in Figure 10 and Table 2. As shown in Figure 10 and Table 2, the stress-displacement curves of the 3-point bending tests show nonlinear behavior. As shown in Figure 11 and 12, the bending strengths are almost the same, while the bending modulus and fracture toughness are increased with wood addition rate. This is because that the specimens were prepared by extrusion molding, thus the wood flour are oriented in the longitudinal direction of the specimen. In tensile test, the wood flours orientation and loading direction are the same, thus wood flours receives more load. However, in 3-point bending tests, the fibers are oriented in a direction perpendicular to the loading direction, thus wood flours can't receive much load. Therefore, even if the wood flour addition rate are increased, it seems that there are not much change in the behavior.

4 CONCLUSION

In this study, WPC mixed wood flour and polypropylene were prepared with various wood flour addition rate, kneading temperature, kneading speed and compatibilizer. In addition, the tensile and 3-point bending tests were performed for these specimens, and the influences of the mechanical properties were clarified by the fracture surface observation and AE measurement.

As a result, the strength and elastic modulus were increased with wood flour addition rate. In addition, by AE measurement and fracture surface observation, it is confirmed that the microscopic damages such as micro void growth, interfacial debondings were occurred and accumulated, and finally any specimens were fractured by large matrix crack. Furthermore, in tensile test, the influence of the wood flour addition rate are large, while there are almost no influence of the kneading speed, kneading temperature and compatibilizer. This is because that the major damage growth component of the WPC is void growth, fibrillation formation and void progress suppression by wood flour, and the wood flour effect is increased with wood flour addition rate. On the other hand, in the 3-point bending tests, the strength and elastic modulus were increased with wood flour addition rate. But, there were no difference in the fracture toughness. From the above results, it is considered that the interface properties of WPC used in this study are good, thus increase of mechanical properties were occurred by wood flour addition.

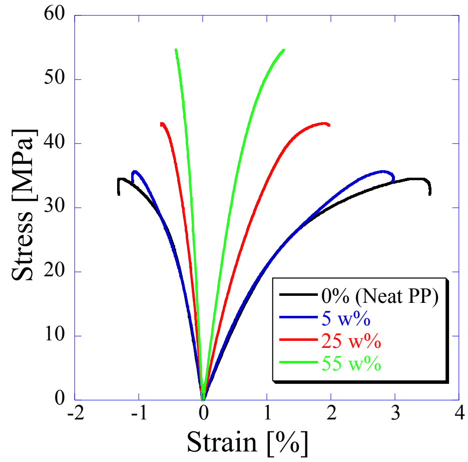


Figure 3: Stress-strain curves of tensile test with various wood addition rate.

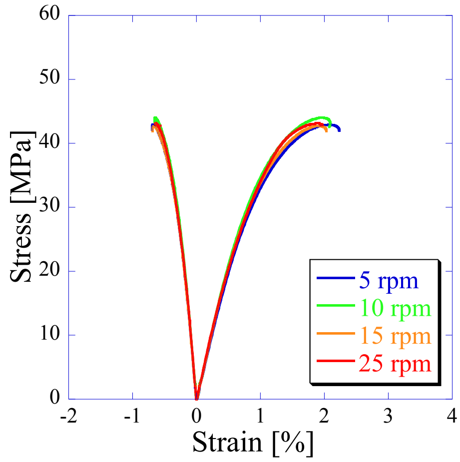


Figure 4: Stress-strain curves of tensile test with various kneading speed.

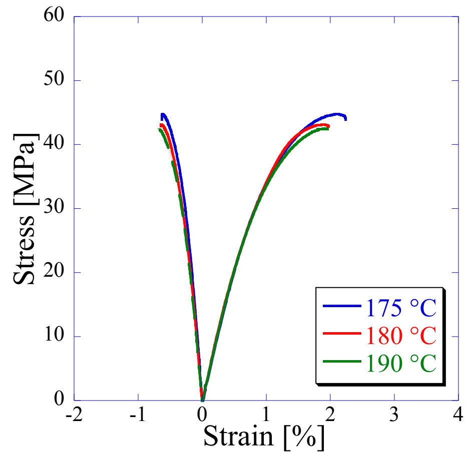


Figure 5: Stress-strain curves of tensile test with various kneading temperature

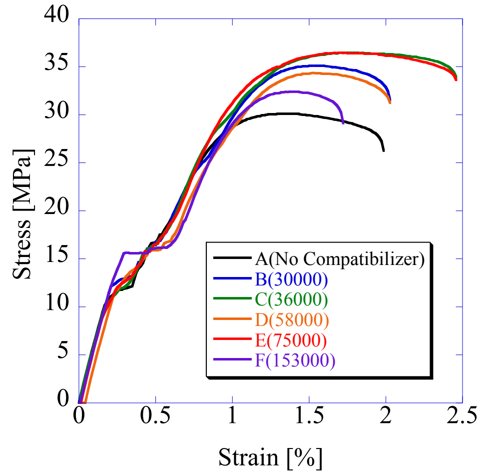
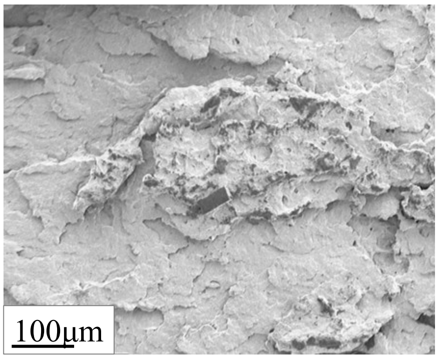


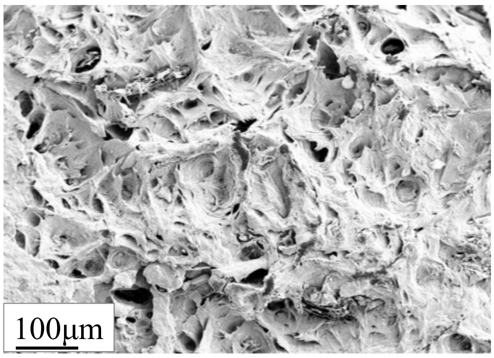
Figure 6: Stress-strain curves of tensile test with various compatibilizer.

Table 1: Tensile mechanical properties.

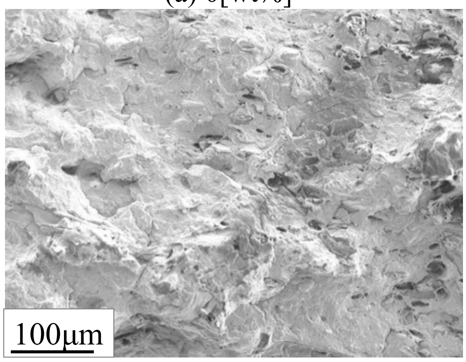
Wood flour [wt%]	Kneading temperature [℃]	Kneading speed [rpm]	Compatibilizer (Molecular weight)	Tensile strength [MPa]	Young's modulus [GPa]
0	180	25	-	34.0	2.32
5				35.0	2.47
25				42.1	3.50
55				54.3	6.85
25	**175**	25	-	42.7	3.86
	180			42.1	3.5
	190			42.3	3.97
25	180	**5**	-	42.6	4.03
		10		42.6	4.06
		15		42.5	3.96
		25		42.1	3.50
25	180	25	**A(-)**	30.4	3.31
			B(30000)	35.1	3.24
			C(36000)	36.8	3.38
			D(58000)	34.8	4.13
			E(75000)	36.4	3.56
			F(153000)	32.4	4.31



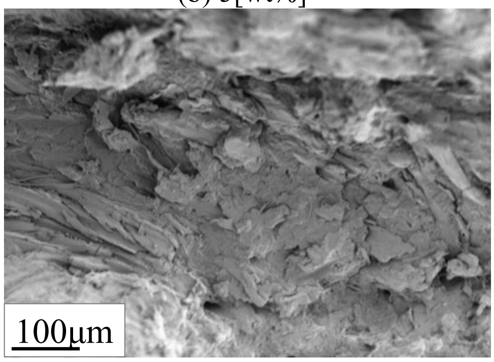
(a) 0[wt%]



(b) 5[wt%]

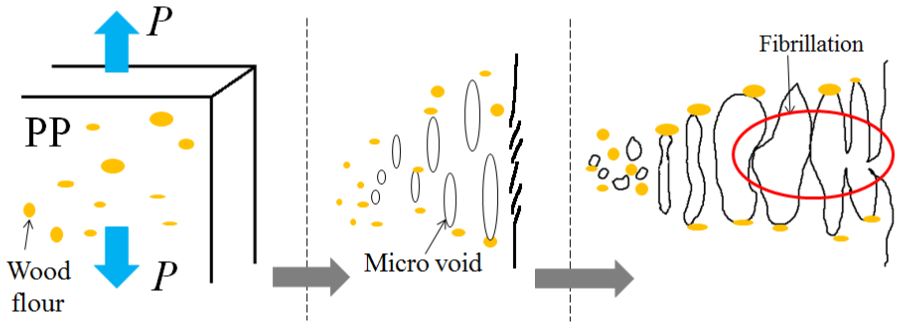


(c) 25[wt%]



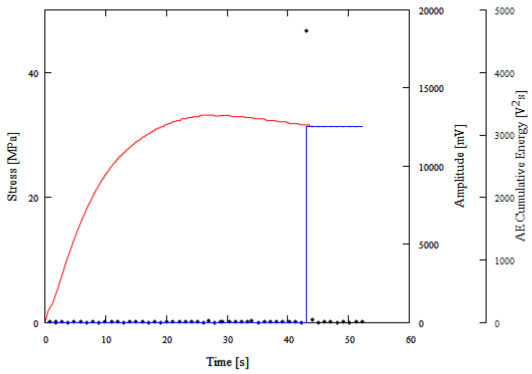
(d) 55[wt%]

Figure 7: SEM image of the fracture surface with various wood flour rate.

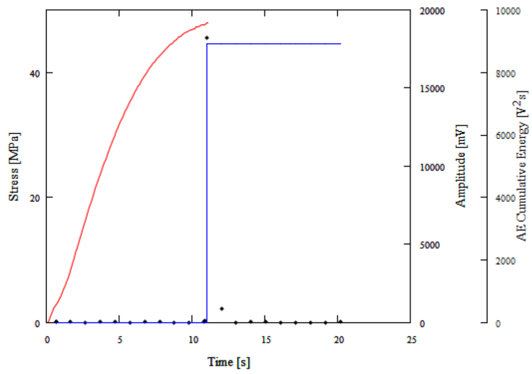


(i) Initial state (ii) Micro void occurrence (iii) Fibrillation cut

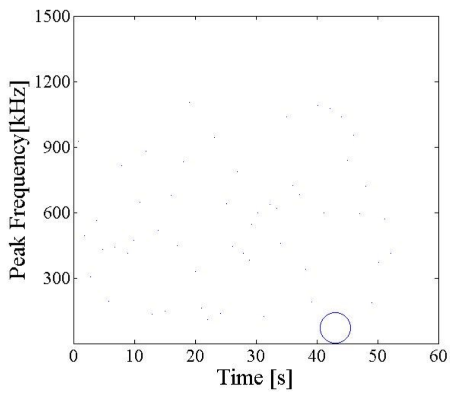
Figure 8: Fracture mechanism of WPC.



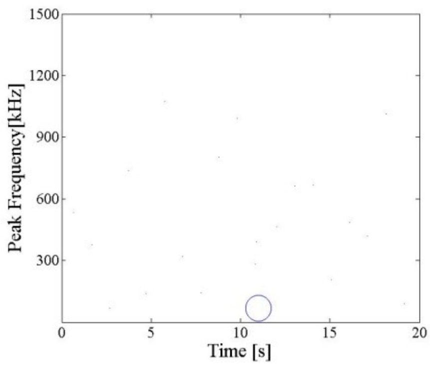
(a) Stress, amplitude and energy (5%)



(a') Stress, amplitude and energy (55%)



(b) Fracture frequency and scale (5%)



(b') Fracture frequency and scale (55%)

Figure 9: Results of the AE measurement.

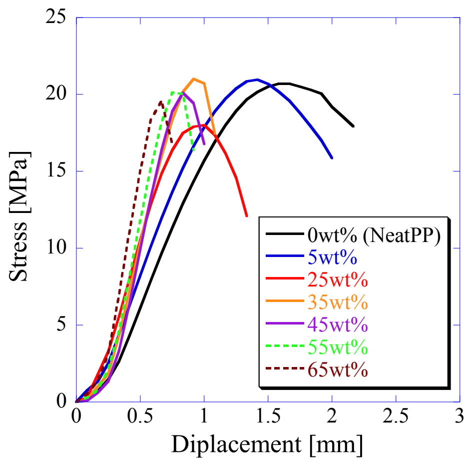


Figure 10: Stress-displacement curves of 3-point bending test with various wood addition rate.

Table 2: Bending mechanical properties.

Wood flour [%]	Bending strength [MPa]	Bending modulus [GPa]	Fracture toughness K_{IC} [MPa]
0	20.7	1.33	50.5
5	21.0	1.58	53.8
25	18.0	2.03	49.0
35	21.0	2.41	60.7
45	20.1	2.80	59.8
55	20.1	2.97	62.8
65	19.6	3.32	62.6

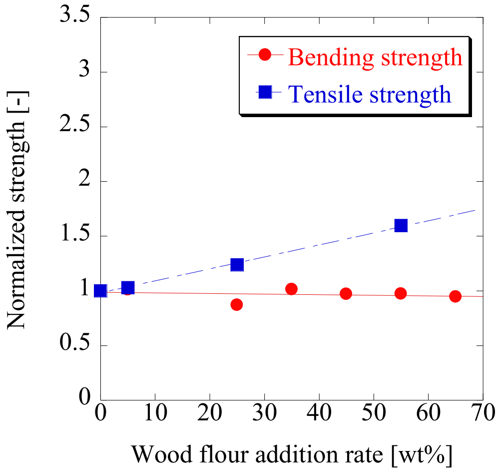


Figure 11: Normalized strength.

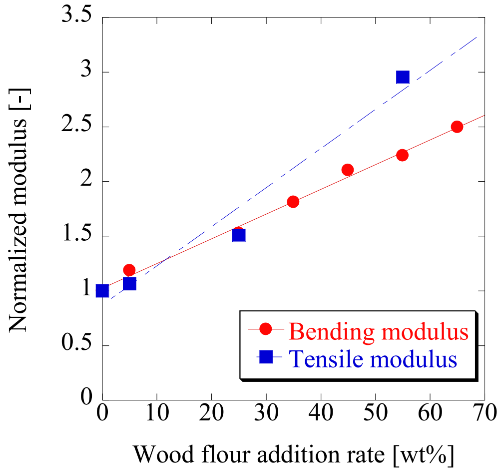


Figure 12: Normalized modulus.

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