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Behavior of acoustic emission generation during tensile tests perpendicular to the plane of particleboard II: effects of particle sizes and moisture content of boards

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Abstract Particleboard specimens with various particle sizes were conditioned into two ranges: low and high moisture content. One set was investigated for internal bond (IB) strength and acoustic emission (AE) events during tensile tests perpendicular to the plane and the other for ultrasonic wave transmission characteristics in the thickness direction. The particleboard structural mechanics were changed as a result of the moisture effect. Specimens conditioning to higher moisture content had lower IB strength and lower cumulative acoustic emission event counts (T_{AE}). The decrease in IB strength indicated that the irreversible thickness swelling was seen when recovery forces of the particles exceed the restraining action of the adhesive. This was attributed to stress release, which resulted in internal failure of the board. The change in the internal structure caused an increased stress level at the initiation of AE generation. No events were recorded before this stress level, obeying the *Kaiser effect*. The decrease in T_{AE} was not only related to the decrease in IB strength but was also affected by the transformation (attenuation) of the AE signals during IB tests according to the mesh size used.

Key words Particleboard · Internal bond strength · Acoustic emission · Particle size · Moisture content

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Introduction

Internal bond (IB) strength, one of the important mechanical properties, is the strength perpendicular to the plane of the particleboard. Testing particleboard IB strength provides direct information on the adhesion of the wood particles. The IB strength is also related to evaluation of the adhesive condition within the particleboard. In particleboard, the internal failure mechanism generally involves the size of the particles and the change in moisture content (MC).

Acoustic emission (AE) is generated at the point of fracture in a material undergoing deformation and is then transmitted in the material as an elastic stress or strain wave. The transient elastic waves are generated by the rapid release of energy from localized sources in the material. The energy of AE waves monitored during a single test represents the progress from a minute fracture to the end of failure. AE testing uses the attributes of particular waves to characterize the material based on localized sources within it. AE generation can be used to detect and evaluate the mechanical properties throughout an entire structure because it is profoundly related to the development of minute fracture in a material.[1]

Previous work[2] has established a clear relation between the cumulative AE event counts (T_{AE}) and IB strength for particleboard, which involves various internal structural factors. The IB strength of particleboard was influenced by particle size and the relations among particle size (mixture proportion), board density, board thickness, resin content, and hot-press schedule. A generalized conclusion based on the results of previous research[2] and the reports by Beall[3,4] indicated that the higher the IB strength, the more the T_{AE}

Table 1. Length and width of particles for each fraction

Particle size (mesh)	Length (mm)	Width (mm)
8	19.32 (7.94)	4.32 (2.16)
9–12	13.66 (5.75)	2.01 (0.50)
13–23	7.03 (2.99)	1.10 (0.33)
24	3.53 (1.47)	0.66 (0.19)

Values in parentheses are the standard deviations

was monitored during IB tests. The IB strength was closely related to T_{AE}. Furthermore, the ratio (R_a) of the stress level at the initiation of AE generation (σ_G) to that at failure (IB strength) was negatively correlated with both IB strength and T_{AE}.

The objectives of this study were to obtain basic knowledge of the influence of particle size on IB strength and to determine the influence of MC on AE behavior during tensile tests perpendicular to the plane of the laboratory-made single-layer particleboards. To understand the effects of particle size and MC on the transmission characteristics of the AE wave, the velocity and maximum amplitude of the transmitted ultrasonic waves were evaluated using acousto-ultrasonic (AU) measurement.

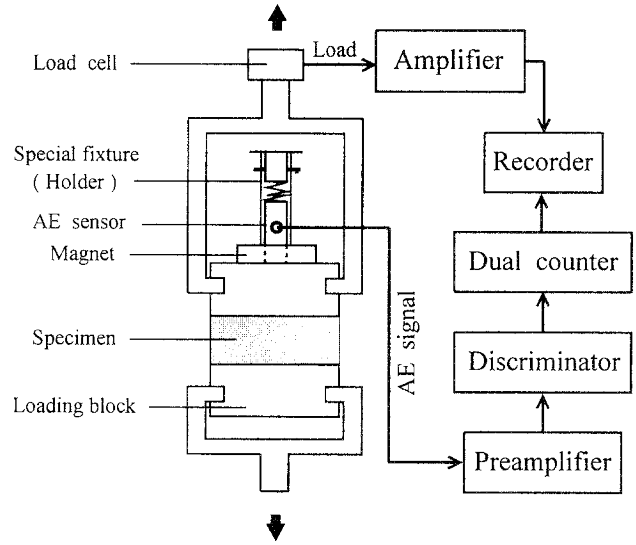

Fig. 1. Tensile tests perpendicular to the plane of the board obtained with the aid of the acoustic emission (*AE*) monitoring system. Holder was composed of a pin and block, spring, aluminum tube, and magnet base

Materials and methods

Particleboard production

The particles used were shaving-type wood particles from the Dantani Corporation, a particleboard plant in Japan. Single-layer particleboards were manufactured in the laboratory after the particles were sifted through four screen sizes: 8, 9–12, 13–23, and 24 mesh. The length and the width of the particles screened for each particle size were measured with a caliper. The size of the particles was larger with the decrease in mesh number. The results are shown in Table 1. The average moisture content of the particles before spraying adhesive ranged from 7% to 8%. The nominal board density was $0.7\,g/cm^3$, and the resin (phenol-formaldehyde resin, PB-1310; Oshika Shinko) content was 8%. A constant weight of wood particles was sprayed with resin containing 48.5% resin solids in a transparent vinyl bag and mixed by hand (by palpating the bottom of the bag). Mats were hand-formed using a 36.5 × 25.5 cm rectangular frame. Boards were manufactured with hot pressing at 3 MPa at 180°C for 12 min, with the distance bars at 20 mm (board thickness). Three replicates were manufactured for each laboratory-made particleboard according to the mesh size used. The 50 mm square particleboard specimens were cut and then conditioned to equilibrium at 20°C and 65% relative humidity (RH) for at least 4 weeks.

Conditioning the moisture content

The specimens was randomly assigned to three groups of six each. The specimens remaining at equilibrium served as controls. Two of the other specimens were conditioned into two ranges: specimens for high MC and specimens for low MC. Low MC specimens were conditioned for about 1 week at 40°C and 3 mmHg using a vacuum oven (Oak; Satake Chemical Equipment). High MC specimens for AE monitoring during IB tests were conditioned for about 2 weeks at 20°C and 95% RH using a humidified cabinet (LH-112; Tabai espec). High MC specimens for AU evaluation were treated similarly for about 1 and 2 weeks. The target MC range for these two groups of specimens was gradually obtained by checking the specimens until the desired weight had been reached. To prevent uneven moisture distribution in the specimen, these specimens were separated and individually wrapped with thin polyethylene sheets and allowed to sit for about 1 month to equalize their internal moisture content. For AE monitoring during IB tests, the actual MC was obtained from 3 to 5 mm layers taken from each side of the fractured surfaces. For the AU experiment, the specimens were put into a convection oven (LC-122; Tabai espec) at 105°C for more than 24 h prior to determining the MC.

Experimental AE monitoring method during IB tests

The AE monitoring apparatus and the tensile tests perpendicular to the plane of the particleboard specimen are illustrated in Fig. 1. Epoxy resin and polyamide curing agents were mixed and used to bond the specimen to steel loading blocks. The tensile force was run through a 500 kgf load cell at a loading speed of 2 mm/min (JIS A 5908-1994)[5] by the Instron mode strength test machine (Tensilon STM-F-1000; Toyo Baldwin). A special fixture (holder) located on the upper loading block with a magnet base was used to facilitate attachment of the AE sensor (140 kHz) (AE-910-U; NF Corporation). Silicone grease was used to adhere the AE

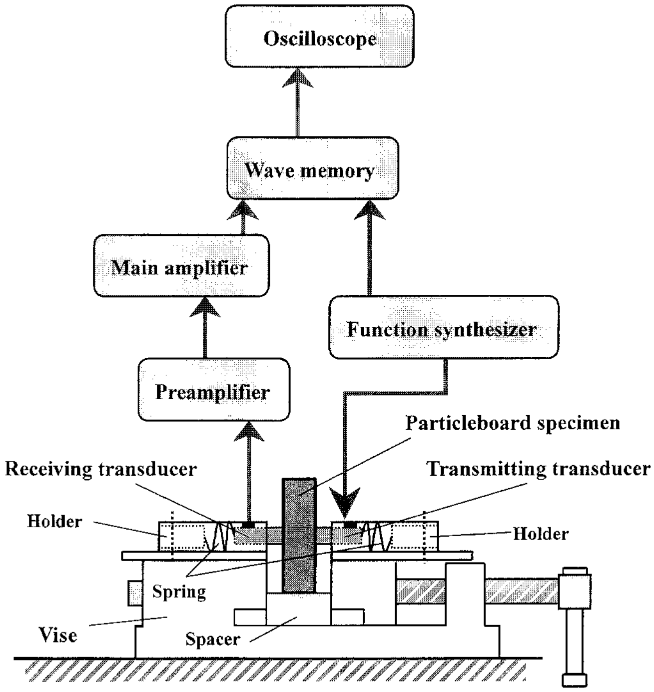

Fig. 2. Acousto-Ultrasonic measurement system

sensor to the loading block. The AE signal during the IB tests was amplified to 40dB by a preamplifier and additionally amplified by 40dB in the main amplifier within a discriminator (AE-912 and AE-992; NF Corporation). The discriminator was set at the 200mV threshold level with a 0.1- to 1.0-MHz filter. AE events were obtained using a dual counter (AE-932; NF Corporation). The load and the cumulative AE events were recorded with a recorder (LR-4219; Yokogawa). The behavior of AE in the IB tests relating to the particle size or MC influence was examined in terms of the parameters T_{AE} and R_a.[2]

Experimental acousto-ultrasonic method

The experimental arrangement used for the ultrasonic wave transmission tests is shown in Fig. 2. This AU apparatus consisted of two wide-range-type AE sensors (AE-900S-WB; NF Corporation) 12mm in diameter. One of the AE sensors was used for the transmitting transducer and the other for the receiving transducer. An auxiliary apparatus was designed[6] to obtain an accurate, steady measurement. The transducers were mounted on the opposite faces of the specimen and fixed uniformly with two built-in holders of the auxiliary apparatus. Silicone grease was used to adhere the AE sensors to the specimen. The output of the function synthesizer (1915, NF Corporation) was set to 5V with a frequency of 200kHz because this condition was the most sensitive for detecting both the velocity and maximum amplitude through the thickness direction of the particleboard.[6] The pulsed ultrasonic wave was sent using the transmitting transducer and was transmitted through the specimen. The ultrasonic wave detected by the receiving

Table 2. Effect of particle size on internal bond strength and cumulative acoustic emission event counts

Particle size (mesh)	Board density (g/cm^3)	IB strength (MPa)	T_{AE}
8	0.65 (0.02) a[a]	0.60 (0.01) a[a]	3738 (533) a[a]
9–12	0.68 (0.01) a	0.51 (0.04) b	1833 (225) b
13–23	0.66 (0.03) a	0.37 (0.03) c	1290 (43) c
24	0.67 (0.01) a	0.24 (0.01) d	877 (40) d

Mean (standard error) differences within the columns were determined by Duncan's multiple range test at the 5% significance level
[a] Same letters indicate an insignificant difference between two variable factors; in contrast, significant differences are expressed by different letters
IB, internal bond; T_{AE}, cumulative acoustic emission event counts

transducer was amplified 20dB using a preamplifier (AE-912; NF Corporation) and then amplified 40dB by the main amplifier (AE-922; NF Corporation). The pulsed and transmitted ultrasonic waves were stored using wave memory (WM-852; NF Corporation). An oscilloscope (CF-910; Ono Sokki) was used to collect the transit time and maximum amplitude. Calculation of the velocity of the transmitted ultrasonic wave and the definition of the maximum amplitude were the same as reported previously.[6,7]

Results and discussion

Particle size effect on IB strength and AE

To examine the influence of particle size on IB strength and T_{AE}, boards of constant thickness and resin content but different particle size were manufactured and tested. The relations among board density, IB strength, and T_{AE} for each particleboard specimen are shown in Table 2. Based on the change in particle size, the difference in IB strength and T_{AE} was significant (5%) according to Duncan's multiple range tests, expressed by different letters. The IB strength decreased with decreasing particle size because the total particle surface area increased when the particle size decreased. The particleboard manufactured with small particles with the same resin content consisted of a bonded area (adhesion point) with insufficient or no resin. T_{AE} is affected by the particle size because T_{AE} is closely related to IB strength.[2,3]

Effect of MC on IB strength and AE for boards with various particle sizes

The MC influence (including the influence of low and high MC) on the IB strength and T_{AE} for particleboard specimens with various particle sizes is shown in Fig. 3. Our previous report[2] and reports by Beall[3,4] clarified that the higher the IB strength, the greater the T_{AE} for various particleboard specimens having different internal structure factors, especially different particle sizes. Results showed that the larger the particle size, the stronger is the IB strength

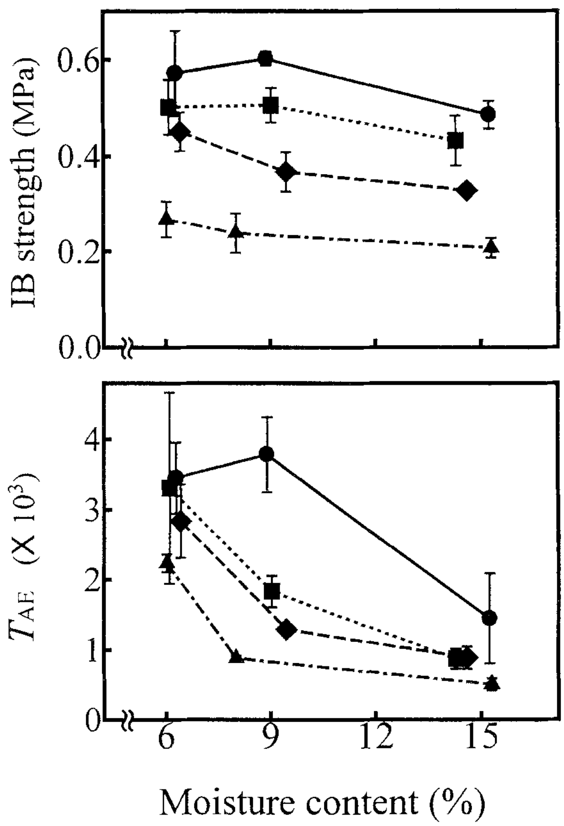

Fig. 3. Effects of moisture content on internal bond (*IB*) strength and cumulative AE event counts (T_{AE}) for various particle sizes of particleboard specimens. *Circles*, 8 mesh; *squares*, 9–12 mesh; *diamonds*, 13–23 mesh; *triangles*, 24 mesh. Each vertical bar indicates the standard deviation

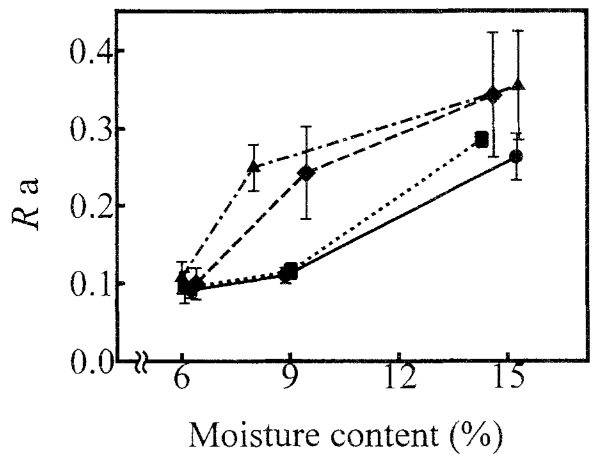

Fig. 4. Effects of moisture content on the ratio (R_a) of the stress level at the initiation of AE generation to that at failure (IB strength) for various particle sizes of particleboard specimens. Symbols are the same as those used in Fig. 3

and the greater are the AE signals detected, even if the particleboard structural mechanics were changed as a result of the MC effect. This is because the adhesion points (areas) on the total surface area of the particles are strongly correlated with the IB strength.

For specimens with various particle sizes and low MC (about 6%), IB strength increased somewhat with increasingly larger particle size. The maximum values for the particleboard mechanical properties (e.g., moduli of rupture and elasticity, IB strength) were achieved at 7%–10% MC, depending on the board type.[8] However, the IB strength for specimens with the largest particle (on 8 mesh) decrease was considered to be the result of a change in the (wood) particles' property.[8] T_{AE} decreased slightly at low MC (about 6%) for boards with the largest particles (on 8 mesh).

The IB strength at high MC (about 15%) decreased for specimens with various particle sizes. The decrease in IB strength indicated that irreversible thickness swelling was caused when the particles' recovery forces exceeded the restraining action of the adhesive. The internal failures of particleboard were attributed to stress release and signified adhesive damage among the particles. This is because swelling stress and particle deterioration accompanied the moisture change.[8–10] The decrease in IB strength at high MC resulted in a decrease in T_{AE}.

The effects of MC on R_a for boards with various particle sizes are shown in Fig. 4. The smaller the particle size, the larger is the R_a, even if the particleboard structure was changed as a result of the MC effect. Compared to the stress level at the initiation of AE generation (σ_G) in the control specimens, the value of σ_G increased for specimens at higher MC. The R_a was larger because of the larger σ_G value relative to the smaller stress level at failure. These results approximated those in our previous study[2] in which the R_a was negatively correlated to both IB strength and T_{AE}.

The mechanical properties perpendicular to the plane are closely related to the particleboard bond quality and the AE behavior. Table 3 provides an overview of the specimens with various particle sizes after conditioning to high MC (about 14%–16%). The MC effect caused the change in the internal structural mechanism of the board. The internal failures resulted in the thickness swelling, the increase in σ_G, and the decrease in IB strength. The decrease in T_{AE} was related to the decrease in IB strength. Beall[11] reported that the only events to occur during adsorption were during the first exposure to 90% RH and the absence of events during the second exposure, indicated to be the *Kaiser effect*.[11] The specimen with absorption (high MC) due to swelling of the board thickness had endured stress release before the IB tests with AE monitoring. This finding confirmed that these changes were not reversible and therefore must be caused by bond fracture.[11] The increase in σ_G indicated that no AE events occurred before this stress level in the IB tests. In other words, it is takes into consideration that the Kaiser effect exists.

Furthermore, the decrease in IB strength and T_{AE} showed that the particleboard with large particles (8 mesh) decreased more significantly than those with small particles. The thickness swelling was attributed to stress release caused by internal failure, which resulted in significant mechanical degradation of the adhesive among particles. Hence, the T_{AE} for large particles was less easily detected in these boards during IB testing with AE monitoring because of more severe board thickness swelling.

Table 3. Effect of high moisture content on thickness swelling, decreased IB strength, increased σ_G, and T_{AE} decrease for particleboards with various particle sizes

Particle size (mesh)	TS (%)	Decrease in IB strength (MPa)	Increase in σ_G (MPa)	Decrease in T_{AE}
8	5.10 (0.18)	0.11 (0.02)	0.13 (0.01)	2340 (589)
9–12	3.81 (0.09)	0.07 (0.03)	0.12 (0.01)	966 (184)
13–23	3.73 (0.16)	0.04 (0.02)	0.11 (0.03)	407 (93)
24	2.78 (0.15)	0.03 (0.01)	0.07 (0.01)	277 (52)

Numbers in parentheses are standard deviations
AE, acoustic emission; TS, thickness swelling; σ_G, stress level at initiation of AE generation; T_{AE}, cumulative AE event counts

Table 4. Particle size influence on ultrasonic velocity and maximum amplitude

Particle size (mesh)	Moisture content (%)	Ultrasonic velocity (m/s)	Maximum amplitude ($\times 10^{-4}$ V)
8	9.0 (0.1) a[a]	598.71 (6.71) a[a]	0.4032 (0.0089) a[a]
9–12	9.1 (0.1) a	636.75 (18.69) a	0.6740 (0.0185) b
13–23	8.9 (0.3) a	757.31 (19.29) b	0.9895 (0.0067) c
24	8.8 (0.1) a	840.70 (11.77) c	1.2729 (0.0226) d

Mean (standard error) differences in the columns were determined by Duncan's multiple range test at the 5% significance level
[a] See explanation in Table 2

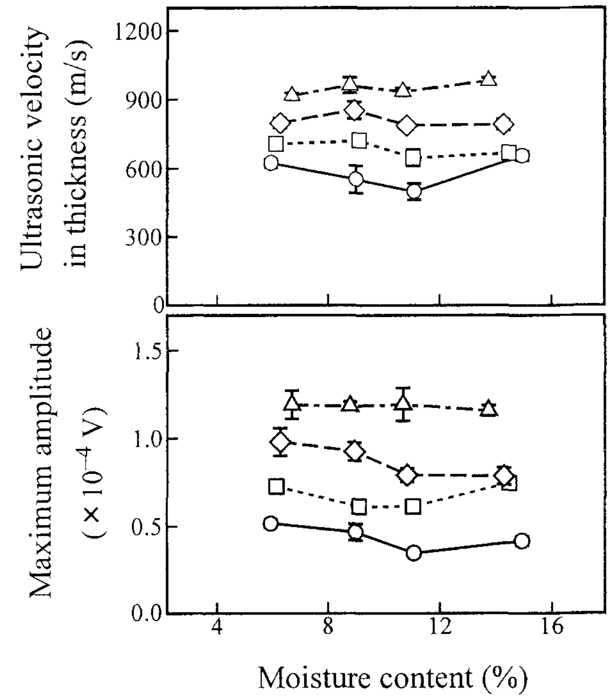

Fig. 5. Effects of moisture content on the ultrasonic velocity and maximum amplitude for particleboard specimens with various particle sizes. *Circles*, 8 mesh; *squares*, 9–12 mesh; *diamonds*, 13–23 mesh; *triangles*, 24 mesh. Each vertical bar indicates the standard deviation

Effect of particle size on AU

The velocity and maximum amplitude increased when the particle size decreased by degrees at nominal board density ($0.7\,g/cm^3$) for particleboard with various particle sizes (Table 4). The velocity and maximum amplitude were significant (5%) according to Duncan's multiple range tests. Thus, it seems that the particle size and the quality and distribution of the bonded areas and voids among the particles can alter the pathway of the ultrasonic wave. The ultrasonic wave always transmits through a material in the shortest possible pathway.[7,12] The transmitted pathway was elongated by the need to bypass voids and discontinuities. This indicated that the longer the transit time, the slower was the velocity. The ultrasonic wave attenuation was caused by the decrease in maximum amplitude when the particle size gradually increased.[13] Hence, the voids and number of discontinuities predominantly determine the velocity and maximum amplitude for the boards with various particle sizes.

Effect of MC on AU for particleboards with various particle sizes

The transformation (attenuation) of the AE signal transmission during IB tests was taken into account in this study. The AE signal transmission was an elastic wave generated by the sudden release of energy from the beginning of a minute fracture to the end of failure.[1] The ultrasonic wave, instead of AE generation during IB tests, was transmitted to a particleboard specimen. The influence of low and high MC for particleboard specimens with various particle sizes was examined using the ultrasonic pulse-transmission technique (Fig. 2). Notably, Sun and Arima[14] theorized that ultrasonic techniques could be applied to predict the internal bond state of wood-composite materials, especially for evaluating the IB state of particleboard. Ross and Pellerin[15] also noted that wave attenuation, a measure of energy dissipation properties, is sensitive to bond characteristics in the prediction of tensile mechanical behavior in wood-based materials.

The results are shown in Fig. 5. The effect of MC at about 6%–16% on the velocity and maximum amplitude of the transmitted ultrasonic wave was insignificant, suggesting that the moisture absorption has less influence on the voids and discontinuities in the internal portion during ultrasonic wave transmission. Thus, the AE signal transmission during IB tests was hardly influenced by a change in

Table 5. Effects of moisture content on board density for particleboard specimens with various particle sizes

Particle size (mesh)	Effect on density, by moisture content (g/cm^3)			
	4–6%	8–10%	10–12%	14–16%
8	0.67	0.65	0.66	0.66
9–12	0.63	0.68	0.68	0.62
13–23	0.69	0.66	0.72	0.68
24	0.71	0.67	0.74	0.70

moisture content. However, the IB strength and T_{AE} decreased with decreasing particle size, even if the particleboard structural mechanics were changed as a result of the MC effect. This suggested that the AE signals during IB tests due to particle size (voids) caused transformation (attenuation) of transmitted elastic waves. These findings (Figs. 3, 5) indicate that the decreased T_{AE} at high MC is related to the change in the internal structure mechanism of particleboard (IB strength decrease) and to the transformation (attenuation) of the AE signal transmission in particleboard due to the different internal structure.

The results (Table 5) indicated that board density insignificantly influences the velocity when the moisture range of the particleboard was 6%–16%, though the board density influenced ultrasonic velocity.[13,16] Hence, board density did not change in direct association with the change in MC. This is because the specimen weight is greater at high MC, and its volume (particularly in relation to its thickness swelling) increases. The transit time of the ultrasonic wave was determined mainly by the particle size (or the voids) and the distribution and quantity of the bonded adhesive points among the particles,[13] but not by the density effect, in this study.

Conclusions

In this research the particle size and moisture content of boards were precisely and strictly controlled to investigate the IB strength and AE generation behavior during tensile tests perpendicular to the plane of the particleboard. IB strength and T_{AE} for various particle sizes decreased with increasing MC. The moisture effect changed the internal structure of the board and caused internal failures, resulting in thickness swelling and increased σ_G. The decrease in T_{AE} involves a decrease in IB strength and attenuation of AE signal transmission in particleboard due to the particle size (voids) effect. The R_a, one of the remarkable parameters in our previous report,[2] at high or low MC was negatively correlated to IB strength and T_{AE}. The stress level at the initiation of AE generation increased in specimens at high MC because of internal failure. AE events did not occur before this stress level, exhibiting the Kaiser effect.[10]

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