Third International Workshop on Green Composites
March 16-17, 2005, Kyoto, Japan

Use of Acousto-ultrasonic Techniques to Determine Properties of Remanufactured Particleboards Made Solely from Recycled Particles

Sumire KAWAMOTO,* James H MUEHL,** and R. Sam WILLIAMS**

**Department of Wood-Based Materials*
Forestry and Forest Products Research Institute,
Ibaraki 305-8687, JAPAN
*** USDA Forest Products Laboratory,*
Madison, WI 53726-2398, USA

Abstract: Properties of particleboard manufactured entirely from recycled particleboard were tested The method for processing three-layer particleboard from all-recycled particles was described. Dynamic MOE (modulus of elasticity) before and after re-manufacturing was tested by a longitudinal stress wave technique. Some stress wave techniques were compared. Nondestructive AU (acousto-ultrasonic) techniques were used to evaluate static, dynamic, and dimensional properties of re-manufactured boards. The results showed a large decrease in mechanical and physical properties for remanufactured boards made from the boards that had higher density. AU parameters corresponded with density in the volume between the surface of transducers. Correlation between static MOE and dynamic MOE was improved by using the AU calculated density. Water absorption and thickness swell corresponded with the AU calculated density.

Key words: *Particleboard. AU (acousto-ultrasonics), Recycle. Remanufacture, Dynamic MOE (modulus ofelasticity), MOR (modulus ofrapture), Density Water Absorption.*

1. INTRODUCTION

For the sake of the environment, raw materials for manufacturing wood-based materials could be derived from unprocessed forest products such as wood material from thinning operations [1,2], industrial waste from veneer manufacture or sawmills, and slabs produced by industrial operations on dry wood. In addition to such wet and dry wood wastes, fibrous agricultural lignocellulosic natural resources such as flax or kenaf can be used as raw materials [3, 4]. Generally, wood-based composites manufactured from recycled materials use a combination of recycled and unused new materials, since recycled materials are pressed and deformed in high temperature processing. It is necessary to add new fiber, particles, or strands to compensate for the decrease in strength resulting from the reuse of materials.

Although new products made from waste wood have been developed in many projects [5,6], few works focusing solely on recycling particleboard have been reported [7]. A long-term goal of this study includes developing better methods for adding new constituents to increase the strength of a recycled structural composite panel.

The objectives of this study[†] are (1) to provide fundamental data regarding the decrease in mechanical properties resulting from the use of recycled materials (2) to compare dynamic MOE values of longitudinal stress wave techniques, and (3) to evaluate the mechanical and physical properties of particleboard using acousto-ultrasonic (AU) technique.

Properties of particleboard before and after re-manufacturing were compared nondestructively by both an AU method and a conventional stress wave technique. The Acousto-ultrasonic technique, a combination of acoustic emission (AE) signal analysis with an ultrasonic characterization method [8], was used to detect and assess damage conditions and variation in mechanical properties of a test material [9]. Vary used AU evaluation to determine the mechanical properties of composite materials [10]. In regard to wood composite research using AU technique, Green reported that AU parameters corresponded with IB (internal strength) [11]. Reis investigated AU behavior concerning the dimensional stability of medium-density fiberboard (MDF) [12]. Few studies have used AU technique to evaluate wood composites, probably because of the difficulty of measuring properties caused by the attenuation of AU waves traveling through wood-based materials [13].

This study provides fundamental data on a processing technique and on the decrease of mechanical properties in boards made with recycled particles from industrial recycled waste wood. Some new AU techniques are suggested for evaluating the mechanical and dimensional properties of particleboard.

[†] This research project at the USDA Forest Products Laboratory, Madison, Wisconsin, was funded by former Science Technology Agency, Government of Japan, in 1997 and 1998.

2. EXPERIMENTAL

2.1. Original Materials

Raw materials were commercial three-layered particleboard (Tokyo Board Co. Ltd.). Dimensions were 0.9 m in width, 1.8 m in length, and 20 mm in thickness. Boards were manufactured from industrial waste wood such as plywood or slabs that were discarded as a waste in the same company chain. Species used in the original particleboard were identified as a mixture of hemlock, Douglas-fir, and tropical species. Three boards, 150 mm in width, were sawn from edge of those commercial particleboards for remanufacture into three 3-layered particleboards. These three boards were selected from 50 boards, based on dynamic MOE (modulus of elasticity) values that were measured nondestructively. The dynamic MOE was calculated by a longitudinal stress wave technique using a PVDF (polyvinylidene fluoride) transducer [14]. Density of original boards was 0.675, 0.754, and 0.806 (g/cm^3), and dynamic MOE tested by Metrigard equipment was 2.98, 4.09, and 4.60 GPa, respectively.

2.2. Remanufacturing Method

Original particleboard were cut into 50 by 50 mm square pieces by a table saw, then hammer milled through screens of 1 5 inch and then 025 inch Particles were classified by size using screen, after drying to 3% moisture content Particles were then screened by 16-mesh filter For core layer, 16 mesh-on were used For surface layers, particles of 16 mesh-off were used Weight loss from size reduction process by table saw was 12% to 13% and by hammer mill 3% to 4%, respectively.

Phenolic resin binder, 10% of total weight of mat, was sprayed in blender Forming (spreading particles in 12- by 12-inch square mat former) was conducted by hand The weight ratio of the surface layer and core layer was 1.5:7:1.5. Planned densities and thickness were the same as values of the original particleboards

Hot pressing temperature was 180°C. Pressing time was 20 min

Boards were trimmed to 280 by 280 mm and stored in a conditioning room at 20°C and 65% relative humidity, before and during the property test

For the control, a single-layered particleboard was manufactured using industry sawdust The species was identified as a mixture of yellow pine and spruce (636 kg/m^3)

2.3. Testing Properties of Remanufactured Particleboard

Properties of remanufactured particleboard were measured both by dynamic and static methods Fig. 1 shows locations of each specimen for property tests, which included dynamic and static MOE and modulus of rapture (MOR), density, internal bond strength (IB), thickness swelling (TS), and water absorption (WA).

Static bending and internal bond (IB) strength tests were performed primarily on the basis of JIS A 5908 [15], after conducting AU measurements. TS and WA tests were performed by quarter size of a standard size specimen after AU measurements. For determing density from AU tests, it is important that surfaces of AE transducer cover large area of the specimen surface. Standard sue specimens (50 x 50 mm) were too large to obtain AU results by 20 mm diameter AE transducers. TS, WA specimens were immersed into water for 6.5 hours at first, then up to 16.5 hours, until constant weight. To avoid considering effect of water repellant added to original materials, specimens cut from the remanufactured board for control were used.

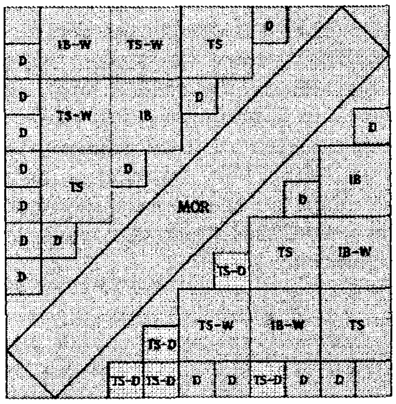

Fig. 1. Geometry for testing properties. Measurement for: D, density; IB, internal bond strength, TS-D, thickness swell and water absorption; MOE, dynamic and static modulus of elasticity; and MOR, modulus of rapture.

2.4. AU Measurements

AU equipment included a pulse generator, transmitting and receiving transducer, and AE equipment. Resonant 1.5 MHz, in 20-mm diameter, and 150 kHz, in diameter, AE transducers were used. The pulse generator generated a square wave, which excited a transmitting transducer. The output signal was amplified by 40 dB. The maximum amplitude (up to 50-μs from start of signal) and time differential, observed by oscilloscope, were taken as AU parameters.

For determination of density and dimensional properties of whole specimen using AU technique, 25- by 25-mm specimens were used so that a face of the 1.5-MHz transducer covered most of the surface area of the specimens. AU waves that propagated through the thickness of specimens were observed. It was confirmed that AU parameters detected in using a specimen conventional test size (50 by 50 mm) did not correspond to actual density and dimensional properties determined by preliminary tests.

For measurement of AU transmission time traveling in the through longitudinal direction, 150-kHz AE transducers, 9-mm diameter, were used.

For determination of dynamic MOE by AU transmission time, an impact source was a sudden stress release generated by breaking the lead of a mechanical pencil at the edge of the specimen. The lead length was always about 10 mm. This stress wave signal was very similar to the AE signal and was thus called the artificial

AE. Transmission of longitudinal direction was observed. AU transmission time (the time it took for the signal to travel between the two 150 kHz transducers), difference of the time reaching to two 150-kHz transducers, was observed by using an oscilloscope. For this AU technique, refer to author's original report [16].

2.5. Determination of Dynamic MOE by Longitudinal Stress Wave Technique

2.5.1. Stress Wave Technique by Transmission Time

Stress wave transmission time was measured two different ways. AE transducers and PVDF transducers were used to pick up stress waves. With AE transducers, an impact was induced by sudden break of lead of a mechanical pencil. This artificial AE wave method that uses a mechanical pencil as an AU source, is included in a AU technique. With PVDF transducers, an impact was induced by tapping an end of each specimen. Dynamic MOE for this longitudinal stress wave was obtained by the following equations:

$$C = L/\Delta t \qquad (1)$$

where

L: length between two transducers,

Δt: transmission time, and

C : longitudinal stress wave velocity.

$$E = \frac{C\rho^{2}}{g} \qquad (2)$$

ρ: density,

g : gravitational acceleration constant, and

E : dynamic modulus of elasticity from impact inducing.

2.5.2. Stress Wave Technique by Resonant Frequency of Longitudinal Vibration

Tapping the end of each specimen generated a stress wave. The signal detected by a PVDF transducer was processed through an FFT (Fast Fourier Transform) analyzer, and resonant frequency of the first resonance mode was observed. Resonant frequency for tapping was obtained by the following equation:

$$f_r = \frac{1}{2l}\sqrt{\frac{Eg}{\rho}} \qquad (3)$$

where,

l : length of specimen,

E: dynamic modulus of elasticity from longitudinal vibration,

g: gravitational acceleration constant,

ρ: density, and

f_r : resonant frequency of longitudinal vibration.

3. Result and Discussions

3.1. Properties of Original and Remanufactured Board

3.1.1. Decrease of Properties of Remanufactured Particleboard

Table 1 shows properties of the original and remanufactured boards. Original particleboard with a higher density showed a larger decrease of properties. Property decrease was the largest for the particleboard (III) that had the largest density and dynamic MOE in original boards. The remanufactured boards were intended to have the same density as the original boards, however, their density decreased to 94, 87, and 84 %. This is because larger density raw materials are subjected to larger deformation by pressure and heat during the processing.

Decrease of dynamic MOE obtained by resonant frequency of longitudinal vibration was 40%-65%. Compared to representative values of samples saved by the company that provided original specimens, static MOE of remanufactured board decreased to 53 % to 40 %. Static MOR decreased to 44 % to 26 %. It is likely that MOR values showed larger decrease than MOE.

3.1.2. Comparison of Stress Wave Techniques

Generally dynamic MOE values obtained by vibration of resonant frequency are smaller than dynamic MOE values obtained by stress wave transmission time. However, in the case of particleboard, that relationship is reversed Comparing the stress wave technique by using PVDF, dynamic MOE values by stress wave transmission time (Table 1, (c)) were smaller than values by longitudinal vibration technique calculated by resonant frequency (Table 1, (b)). This is probably because the transmission time would be extended by attenuation of waves reaching the further transducer. Attenuation of stress waves in particleboard is much larger than in solid wood. Observing wave signals by oscilloscope, larger attenuation caused difficulty identifying starting points of signal waves. If it attenuated below the noise level, the real initiation point would be missed. Several cycles of wave would be hidden under the noise level Thus the initiation point would be extended and longer wave transmission time was observed in particleboard.

The stress wave method by artificial AE (Table 1, (a)), showed larger dynamic MOE values than the static MOE values, which was the same as the trend for solid wood. Sudden break of mechanical pencil lead generated a sharp gradient of the initial start of artificial AE waves. Compared to output signal by PVDF, the artificial AE signal was easy to identify at the starting point.

Comparing three techniques (a), (b) and (c) in Table 1, dynamic MOE values obtained by resonant frequency (b) corresponded with static MOE the best. MOE values (a) obtained by artificial AE transmission time also showed the same trend and corresponded with static MOE as much as the conventional method (b). The advantage of the artificial AE transmission method is that specimens don't need to be cut, and can be measured just using a mechanical pencil without using large equipment to induce a pulse.

Table 1. Physical and mechanical properties of original and remanufactured particleboards.

Specimen Number	Density (kg/m^3)		Dynamic MOE (GPa)				Static MOE*5 (GPa)	Static MOR*5 (MPa)	IB*6 (MPa)
	Original*1	Re-manufactured*2	Original*3	Remanufactured (a)*4	(b) *5	(c) *5			
I	675	640	2.98	1.59	1.62	1.25	1.36	7.68	0.39 (0.09)
II	754	656	4.09	1.46	1.45	1.35	1.25	6.09	0.22 (0.11)
III	806	677	4.60	1.95	1.90	1.44	1.48	6.98	0.56 (0.20)
Control		664		1.96	1.89	1.52	1.84	11.2	0.27 (0.06)

Notes: Stress wave techniques: (a) artificial AE wave transmission time, (b) resonant frequency of longitudinal vibration, detected by PVDF, and (c) stress wave transmission time by PVDF.
Numbers in parentheses are standard deviations (n=3). *1 Specimen dimensions: 150 mm x 20 mm x 1.8 m. *2 Specimen dimensions: 280 mm x 280 mm x 20 mm. *3 Specimen dimensions: 150 mm x 20 mm x 1.8 m. Measured by longitudinal stress wave technique using PVDF transducer [14]. *4 Lead of a mechanical pensile was broken on 280 by 280 remanufactured particleboards before MOR specimens were cut. *5 Specimen dimensions: 345 mm x 50 mm x 20 mm. Refer to MOR specimens in Fig 1. *6 Specimen dimensions: 50 mm x 50 mm x 20 mm. Refer to IB specimens in Fig 1.

3.1.2. Adjusted Dynamic MOE

The static bending MOR versus MOE of remanufactured board showed a good correlation (r = 0.99). This indicates that the estimation of strength properties can be predicted by estimation of static MOE. Static MOE was smaller than dynamic MOE except for three values obtained by transmission time to PVDF transducers.

Dynamic MOE values were adjusted by using a partial density at the center of a specimen under a loading point, using the calculated density determined by AU through thickness transmission (refer to Fig 2-1 and Fig. 3). This adjustment was taken according to author's previous work that reported a partial density at the center of a specimen, below a loading point, affected MOE and MOR values more than using average density of solid wood [17]. As a result, regression coefficient between dynamic MOE obtained by artificial AE transmission time and static MOE was improved from 0.83 to 0.96 for adjusted MOE determined by calculated density from the AU transmission time that propagated through thickness of specimens.

3.2. Output of AU Signals

Typical AU signal output is shown in Fig. 2. Fig, 2-1 shows the output signal that propagated through thickness, using AE transducers that has a diameter of 20 mm. This geometry of transducers were used for AU measurement of density and dimensional properties. It is important that AE transducers cover major area of surfaces of specimens.

Basically AU amplitude was higher through the dense surface (Fig 2-2). AU wave through core layer attenuate more (Fig. 2-3) than the propagation through a surface layer. AU amplitude that was observed through a core layer was much smaller than the one observed through the surface layer.

3.3. AU and IB Strength

AU amplitudes and AU transmission time of AU signals that propagated through the thickness of IB specimens were observed at five locations on IB specimens. Unlike other properties, AU result did not correlated with IB strength.

AU amplitude and AU transmission time through thickness did not correlated with IB strength. This was because AU values corresponded with density in the volume between the surfaces of transducers (20 mm in diameter), whereas IB strength values were measured in specimens, 50 by 50 (mm). This result also indicates that AU measurement should be taken with considerable attention to make sure to use the right AE transducers.

Green [11] reported high correlation of IB strength and AU amplitude of signal propagating through the thickness of IB specimens, In the study, he used transducers having large diameters that covered major areas of the surface of IB specimens,

3.4. AU and Density

AU amplitude and transmission time through thickness of specimens correlated with density. Regression coefficient between AU transmission time and density was higher (Fig. 3, r = 0.99) than the one obtained by AU amplitude (r=0.94). This indicates that the AU technique to determine density can be used to estimate property values that correlate with density. In this study, it was used to determine dynamic MOE and the dimensional properties (Fig. 4). Benefit of this method is that specimens don't require cutting, since this AU technique that uses AU values in propagation through the thickness of specimens can be done on a large specimen.

3.5. AU and Dimensional Properties

Water absorption and TS correlated with density (r=0.97 for 16.5 h, r=0.96 for 6.4 h). Water absorption corresponded more than TS. Water absorption was

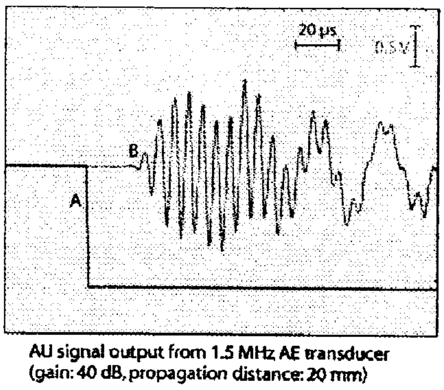

Fig. 2-1. AU signal output through thickness transmission of remanufactured particleboard. A is a square wave signal (30 V) to induce AE transducer (B), 20 mm in diameter.

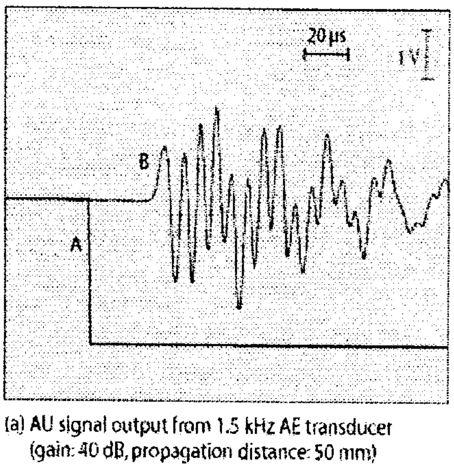

Fig. 2-2. AU signal output through surface layer of remanufactured particleboard. A is a square wave signal (30 V) to induce AE transducer (B), 9 mm in diameter.

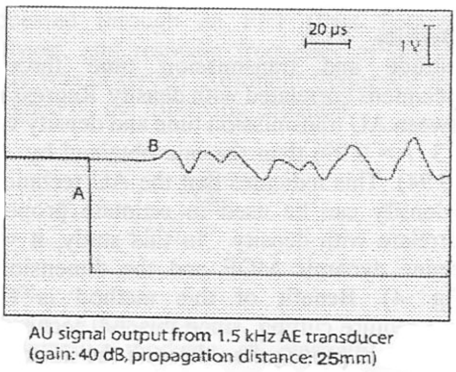

Fig. 2-3. AU signal output through core layer of remanufactured particleboard. A is a square wave signal (30 V) to induce AE transducer (B), 9 mm in diameter

determined by calculated density determined with AU transmission time propagating through thickness (Fig. 3). The regression coefficient was the highest in the relationship between calculated density and water absorption after 16.5 h (Fig. 4).

Although only five specimens were used in this work, it shows the possibility for using AU techniques to estimate dimensional proprieties.

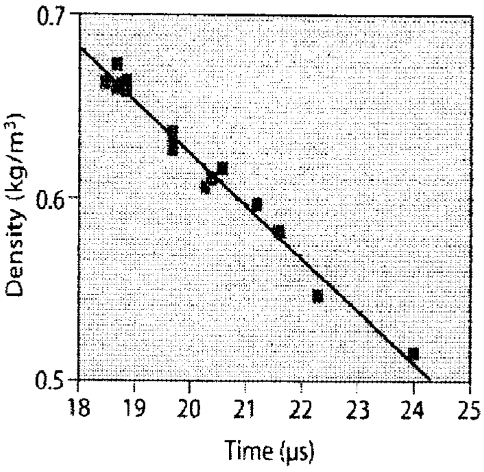

Fig.3. AU transmission time versus density for particleboard (control). AU transmission time was measured in propagation through thickness.

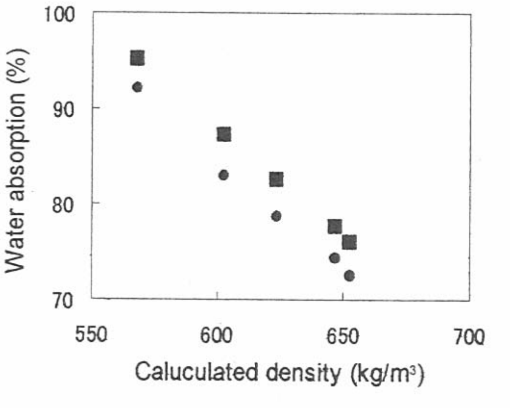

Fig. 4. Calculated density versus water absorption for particleboard (control). ■: 16.5 h, ●: 6.5 h. Density was determined from AU transmission time refereed to Fig. 3.

4. CONCLUSIONS

(1) Mechanical and physical properties of remanufactured board decreased more with original particleboard having larger density. This indicates that it is important to use lower density material as a raw material.
(2) The decrease in static MOR, caused by the manufacturing, was larger than in static MOE.
(3) The decrease in dynamic MOE obtained by resonant frequency of longitudinal vibration, measured by PVDF transducer, was 40 %- 75 %.
(4) Dynamic MOE obtained by stress wave transmission time was smaller than the one by frequency of longitudinal vibration that showed the best correlation with static MOE.
(5) Dynamic MOE obtained by artificial AE wave signals induced by breaking the lead of a mechanical pencil was similar to conventional stress wave MOE values calculated by longitudinal vibration.
(6) Correlation between static MOE and dynamic MOE was improved by using calculated density determined by AU transmission time propagating through thickness of specimens.
(7) AU behaviors highly corresponded with density in the volume between the surfaces of the transducers. Properties involved with density can be estimated by AU techniques. Scanning of AU signals that propagated through the thickness of particleboards can provide density value nondestructively, thus properties that correspond with density can be estimated by this AU techniques.
(8) For the specimens that did not contain water repellent, water absorption correlated with calculated density determined by AU techniques.

Acknowledgments –The authors wish to thank Mr. Saito, Tokyo Board Co. Ltd. for providing commercial particleboard, Mr. Yasuto Chiba, Japan Fiberboard and Particleboard Manufacturers Association, for conducting the internal bond strength test, Dr. Regis Miller, USDA Forest Service, Forest Products Laboratory, for identifying species of particles. First author thanks Dr. Robert Ross, Forest Products Laboratory, for the opportunity to visit the Forest Products Laboratory in 1997 and 1998, and for nondestructive testing of Japanese commercial particleboard.

REFERENCES

1. T. Shibusawa, S. Kawamoto, H. Korai, and T. Fujii. Manufacturing Wood Composite Layered Material. US Patent No. 5814170. (1998)
2. H. Spelter, R. Wang, and P. Ince. Economic Feasibility of Products from Inland West Small-Diameter Timber. General Technical Report. FPL-GTR-92. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory. May (1996) 17 p.
3. R. M. Rowell. Composites from Agri-Based Resources. In: R. Falk, ed. Proceedings, The use of recycled wood and paper in building applications. Proceeding No. 7286. Madison, WI: Forest Products Society. (1996) 217-222.
4. S. Kawai, Current Trends in Research and Development on Wood Composite Products. *Mokuzai Gakkaishi*. **43**(8) (1997) 617-622 (in Japanese).
5. Forest Products Laboratory. Forest Products Research Program on small diameter materials. General Technical Report. FPL-GTR-110. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory. May (2000) 31 p.
6. T. Shibusawa, S. Kawamoto, H. Korai, and T. Fujii.. Manufacturing method for a wood composite layered material. United state patent 5814170. (1998)
7. T. Shibusawa, Y. Hatano, S. Kawamoto, M. Zhang, Y. Okuno and Y. Chiba. Production and Properties of Recycled Particleboards made from Wood-based Materials (I). 50th Annual Meeting of Japan Wood Research Society. (2000) 286. (in Japanese)
8. ASTM E 1316-99. Standard terminology for nondestructive evaluations. Annual Book of ASTM Standards. Philadelphia, PA: American Society for testing and Materials. (1999)
9 ASTM E 1495-97. Standard guide for acousto-ultrasonic assessment of composites, laminates, and bonded joints. Annual Book of ASTM Standards. Philadelphia, PA: American Society for testing and Materials. (1997)
10. A.Vary, Computer signal processing for ultrasonic attenuation and velocity measurements for material property characterizations. NASA Technical Memorandum 79180. (1979)
11. A. T. Green, Correlation of internal bond strength of particleboard with acousto-ultrasonics. Journal of Acoustic Emission. **8**(1/2). (1989) S306 S310.
12. H. L. Reis and D. M. McFarland, , On the acousto-ultrasonic characterization of wood fiber hardboard. Journal of Acoustic Emission. **5**(2). (1986) 67-70.
13. S. Kawamoto and R.S.Williams, Acoustic Emission and Acousto-ultrasonic Techniques for Wood and Wood-Based Composites-A Review. General Technical Report. FPL-GTR-134. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory. May (2002) 16p.
14. R.J. Ross and R.F. Pellerin, Nondestructive Testing for Assessing Wood Members in Structures. General Technical Report. FPL-GTR-70. Madison, WI: US Department of Agriculture, Forest Service, Forest Products Laboratory. May (1994) 40 p.
15. JIS A 5908. Particle boards. Japanese Industrial Standard. Tokyo, Japan. (1994)
16. S. Okumura, S. Kawamoto and M. Toyada and M. Noguchi. Propergation Properties of AE Waves in Wood. Bulltin of the Kyoto University Forest. **60**(1988) 299-309. (in Japanese)
17. S. Kawamoto. Use of Artificial AE Wave Techniques for Evaluation of MOE in Solid Wood. 41th Annual Meeting of Japan Wood Research Society. (1991) 56. (in Japanese)