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ORIGINAL ARTICLE

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Structural mechanics of wood composite materials I: Ultrasonic evaluation of internal bond strength during an accelerated aging test

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Abstract This research attempts to observe indirectly the variation of internal bond characteristics for wood composite materials during accelerated aging test treatment using ultrasonic pulse-transmission techniques. Particleboard (PB) and oriented strandboard (OSB) were the representative specimens. The transit time of the ultrasonic wave propagating through the samples along the nominal length and thickness directions was recorded using an apparatus called PUNDIT (C.N.S. Electronic, London). The transit times were measured in the samples under an oven-dried condition after treating them with boiling water at different treating time stages, and the velocity was then calculated based on the transit time. Examination of the internal bond strength conducted on the same samples was done according to JIS A 5908. A study of the relations among springback, internal bond strength, and velocity indicated that a high correlation existed between ultrasonic velocity measured in the length or thickness direction and the internal bond strength for the PB specimen, but no significant correlation was observed between the velocity measured in the length direction and the internal bond strength for the OSB specimen. The results of this research suggested that ultrasound techniques can be applied to predict or evaluate the internal bond state of some wood-composite materials made of relatively small particles, such as PB especially, during accelerated aging test treatment processes.

Key words Wood composite materials · Accelerated aging test · Springback · Internal bond strength · Ultrasonic velocity

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Introduction

The accelerated aging test has been widely accepted as an alternative for evaluating or predicting the severing life for some wood-composite materials, because it is difficult to assess the variation of mechanical properties of the materials during practical use. The test entails boiling the material in water and oven-drying it. This process constitutes an efficient method generally utilized to evaluate the internal bond strength and dimensional stability of the materials as the treatment cycles are short. However, for some wood-composite materials, such as particleboard (PB) bonded with urea-formaldehyde resin, there is rapid loss of its internal bond strength even during the first cycle of treatment.[1] Hence the board is broken down, and the internal bond strength cannot be evaluated accurately by this treatment method. Therefore, an alternative is needed to resolve this problem.

The ultrasonic wave technique has successfully evaluated some physical and mechanical properties of wood products, such as various static elastic and strength properties. They correlate with a dynamic elastic modulus based on the velocity at which ultrasonic stress waves propagate through them.

Gerhards[2] cited 15 investigations in which meaningful correlations were found between the stress wave modulus and tensile, compressive, or flexural modulus (MOE) or strength (MOR) of lumber or veneer. He also summarized the effects various wood factors have on stress wave velocity, which ranged from 10000 to 20000 ft/s parallel to the grain in defect-free wood at 9%–15% moisture content. Wave velocity (1) decreases as the grain angle, wood temperature, or moisture content increases; (2) is higher in latewood than in earlywood; and (3) is lower in decayed wood. Ross and Pellerin[3] revealed that wave attenuation, a measure of energy dissipation properties, is sensitive to bonding characteristics and is a valuable nondestructive technique that contributes significantly to the prediction of tensile and flexural mechanical behavior of wood-composite materials.

Using the velocity of ultrasonic waves propagating through wood-composite materials to evaluate or predict

the internal bond state has not been studied, especially during an accelerated aging test. The objective of this research was to identify an ultrasonic velocity sensitive enough to assess the internal bond state and one that can predict the internal bond strength, especially for wood-composite materials bonded with some wild adhesive.

Experiments

Before the experiment we considered various ultrasonic frequencies that could influence the velocities by which the waves propagated through the samples; four commercial PB specimens with varying density were selected. The velocities of the waves passing through them in the nominal three directions were investigated using 54- and 200-kHz probes of the PUNDIT apparatus. The results indicated that different frequencies have no significant influence on the velocity measured in either the longitudinal or the transverse direction. Moreover, the different frequencies seem to have had little influence on the velocity measured in the thickness direction. The velocity measured with 200-kHz probes showed relatively lower values compared to those measured with 54-kHz probes, suggesting that the propagation of ultrasonic waves of a higher frequency is easily influenced by the internal structure of the specimen (compared to the waves of lower frequency). In this case, because the tested PB samples were of a three-layer structure, and the surface layer was a more precise structure than the core layer during the hot-pressing processes, when the ultrasonic waves with higher frequencies pass through the specimen in the thickness direction there are more reflections and more loss of energy. This is due to the fact that waves must travel through differential interfaces of the medium,[4] which also can be reflected in the velocities. However, these phenomena may not occur with the waves propagating in the length direction. These findings seems to indicate that waves of higher frequency are more sensitive to the internal structure of medium. In this study, the 200-kHz probes were selected for measuring the transit time of the waves traveling through the specimens.

Materials and methods

The construction of the constituent elements in the wood-composite materials were obviously different; commercial PB (bonded with urea-formaldehyde resin) and OSB (bonded with phenol-formaldehyde resin) were the representative specimens used in this experiment. Their air-dried densities were 0.63 and 0.62 g/cm^3 and their nominal thickness 1.5 and 1.0 cm, respectively. All samples were cut from each full board to 5 × 5 cm, measured precisely in millimeters, within 1%. To minimize the variability, all samples were equilibrated to approximately 12% moisture content prior to testing. A total of 120 samples were used for each specimen in this study; the samples were divided into 10 groups with 12 in each group. One group was randomly chosen as a control and was subjected only to the oven-drying treatment. The remaining nine groups were immersed in boiling water for the designated treatment time, increasing stepwise, and then dried to the oven-dried condition using an oven set at 105°C. The oven-dried condition was estimated by checking the samples until their weight reached approximately constant values during the oven-drying process.

To avoid the effects of moisture content and temperature on the velocity of the ultrasonic wave propagating through the specimens, the treated samples were kept in a desiccator with silica gel until their temperature decreased to room temperature, at which time the velocities were measured.

The transit time of ultrasonic waves propagating through the samples in both nominal length (the dominant direction of particle arrangement inside the panels) and thickness directions, was recorded precisely to 1% in microseconds by the PUNDIT apparatus with 200-kHz probes. The velocity of the ultrasonic wave was calculated according to the distance between the two probes divided by the transit time, as shown in Fig. 1. The retention of internal bond strength of the sample after these measurements was examined according to the JIS A9805 test method in an effort to analyze its relation to the velocity.[5]

Results and discussion

Relation between treatment time and springback

In general, the swelling that occurs when the board is exposed to moisture or immersion in water is the sum of two components: (1) swelling due to absorption of water by the hygroscope particles of wood and (2) release of compression stress imparted to the board during pressing of the mat in the hot-press. The latter is not recovered when the specimen is reverted to the dry condition. This unrecovered thickness swelling is called springback.[1]

In this experiment, results showed that the increase of springback corresponds to the increase in treatment time for both PB and OSB specimens. For the PB specimen, a higher rate of increase of springback was found within 20 min from the start of the treatment. Subsequently, this increasing trend slowed with the increase in the treatment time (Fig. 2). However, compared to the results with PB, the springback of OSB increased rapidly only within the first 10 minutes; after that no clear variation was found except that deviations in the measurements became greates (Fig. 3).

Such changes may be due to the following factors. First, the PB specimen used was a three-layer structure. The face layer, which consisted with smaller particles than the core layer, was pressed more precisely during the hot-pressing processes. Such structural characteristics may help to keep the boiling water from entering the internal space of the board during treatment. The OSB specimen, in contrast, was of a nonlayered structure, and its component chips were geometrically larger than the particles of the PB, which could lead to boiling water being absorbed more easily

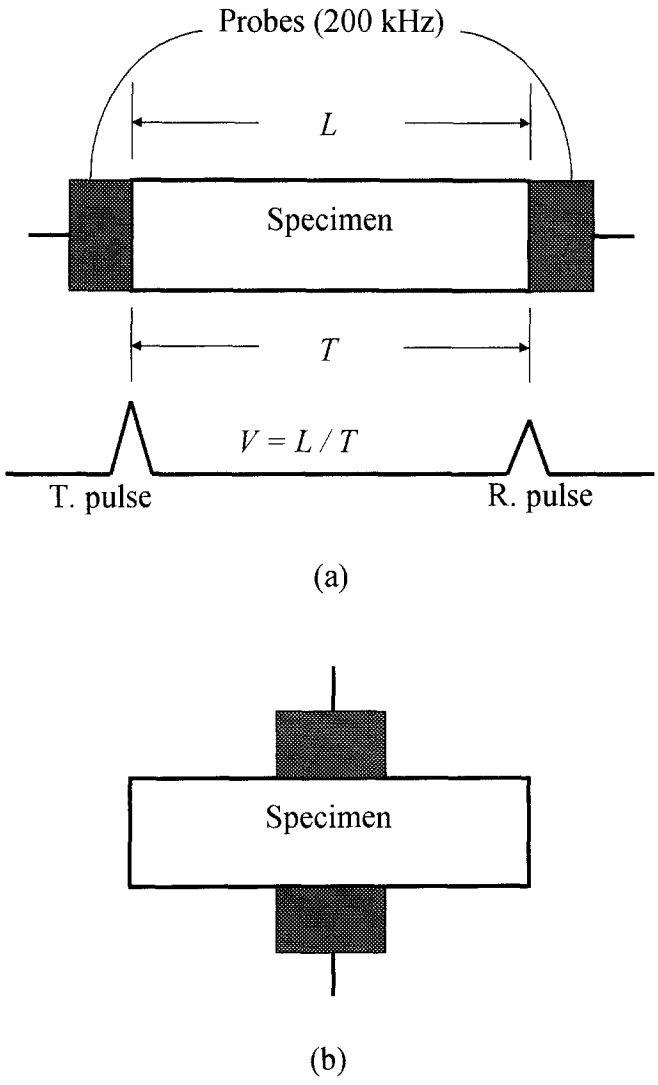

Fig. 1. Methods for measuring transit time and calculating velocity in which ultrasonic waves propagating though specimens. **a**, **b** Measuring in length and thickness directions, respectively. *L*, length of specimen; *T*, transit time; *V*, ultrasonic velocity; *T. pulse*, transmitted pulse; *R. pulse*: receiving pulse

during the treatment. Second, differences of the internal structures and dimensions of the component elements affected the regularity of the surface and the accuracy of dimensional measurements after the treatment.

Relation between springback and internal bond strength

Corresponding to the increase in springback, the internal bond strength decreased considerably for both specimens. For the PB specimen (Fig. 4) the internal bond values decreased to near zero when the springback reached about 40%; after that no clear change was observed. These findings agree with those of others.[1] Figure 5 shows the relation between springback and internal bond strength for the OSB specimen. Compared to the PB results, the internal bond strength decreased rapidly until the springback reached

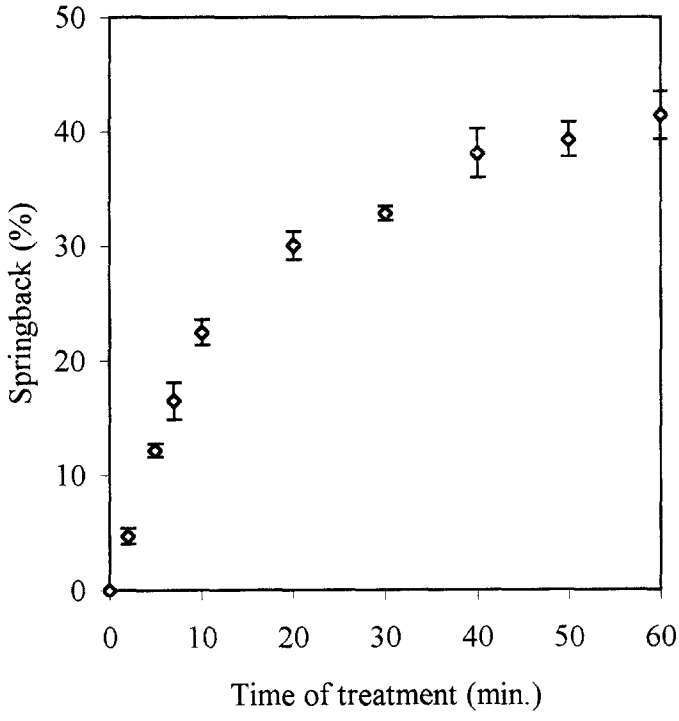

Fig. 2. Relation between treatment time and springback for particleboard (PB) specimen. Each vertical bar indicates standard deviation form 12 samples

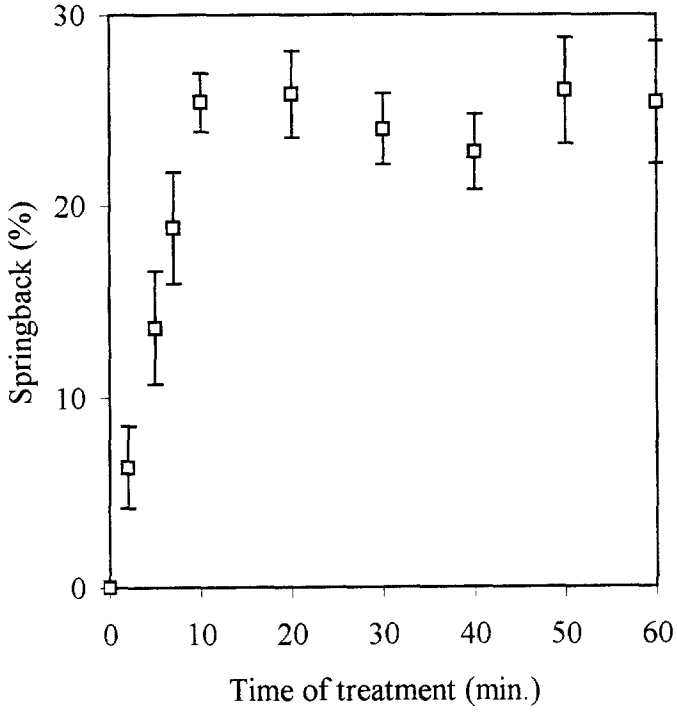

Fig. 3. Relation between treatment time and springback for oriented strandboard (OSB) specimen. Each vertical bar indicates standard deviation form 12 samples

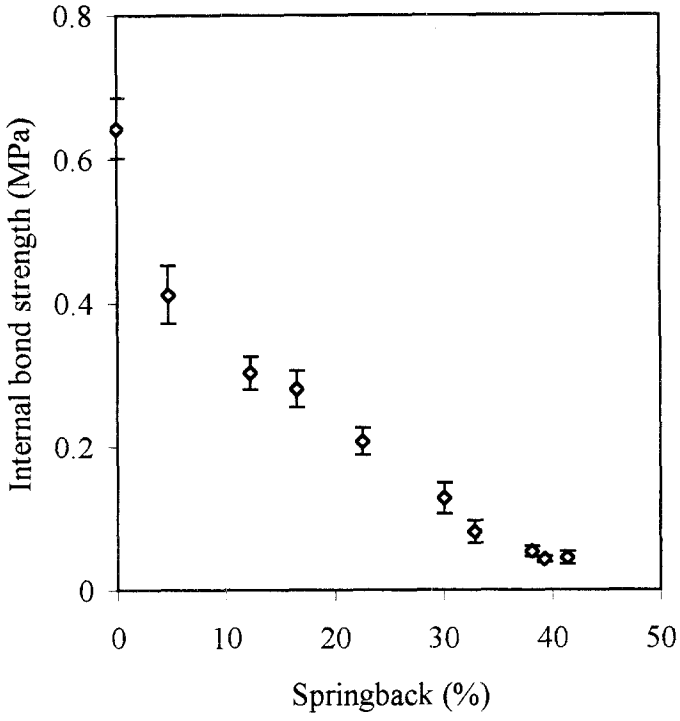

Fig. 4. Effect of springback on internal bond strength for PB specimens

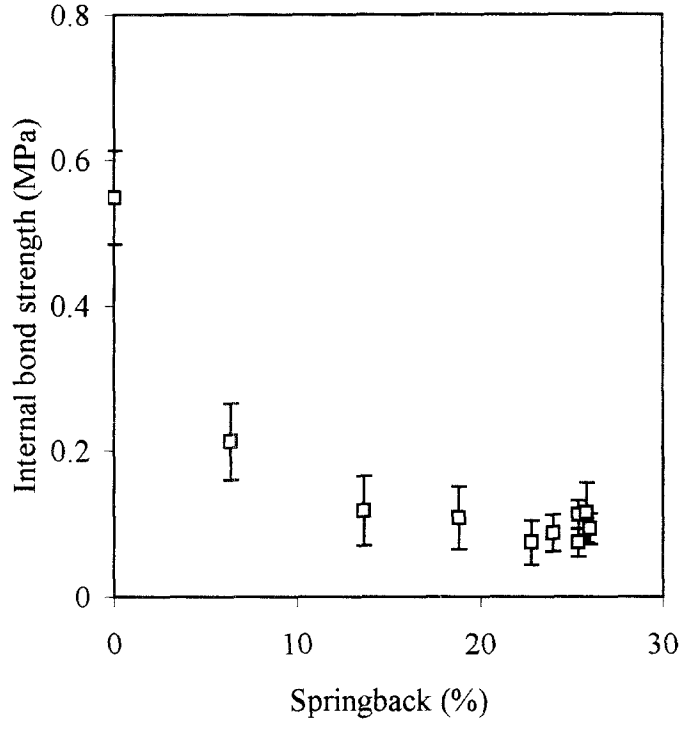

Fig. 5. Effect of springback on internal bond strength for OSB specimens

about 20%. After that no marked variation was found. This finding means that the internal bond state could be damaged or weakened easily, as the boiling water easily entered the internal space of the OSB samples during the treatment.

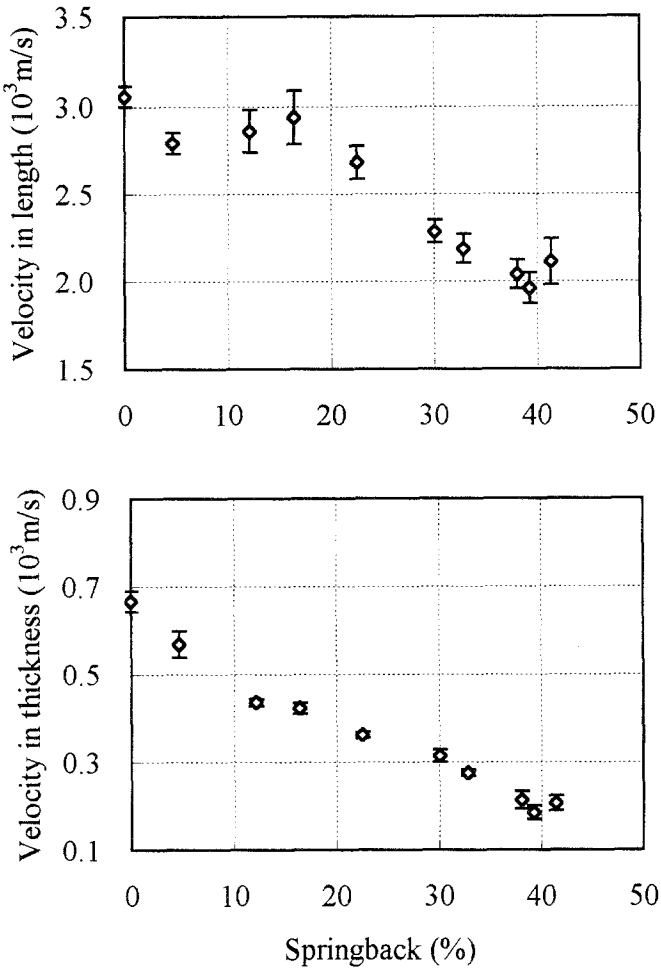

Fig. 6. Relation of springback and ultrasonic velocity for PB specimens

Relation between springback and ultrasonic velocity

Figure 6 shows the variation in ultrasonic velocities in regard to the springback changes for the PB specimen. The ultrasonic velocities measured in both the length and thickness directions decreased linearly with an increasing springback. The correlation between the velocity and springback was close, as expressed by the high correlation coefficients ($R = -0.88$ and -0.96 for the velocity in length and thickness directions, respectively). These results suggest that the pathways of ultrasonic waves propagating through the samples change with the springback. In other words, the pathways of the wave propagation became longer than the apparent distances measured between the two probes.

Figure 7 shows the relation between the ultrasonic velocity and springback for the OSB specimen. The velocities measured in the thickness direction decreased linearly with an increase in springback ($R = -0.78$). These results show a tendency similar to that seen with PB. However, in the length direction, the velocity has no meaningful relation with the variation in springback. These results suggested that pathways of ultrasonic waves traveling through the

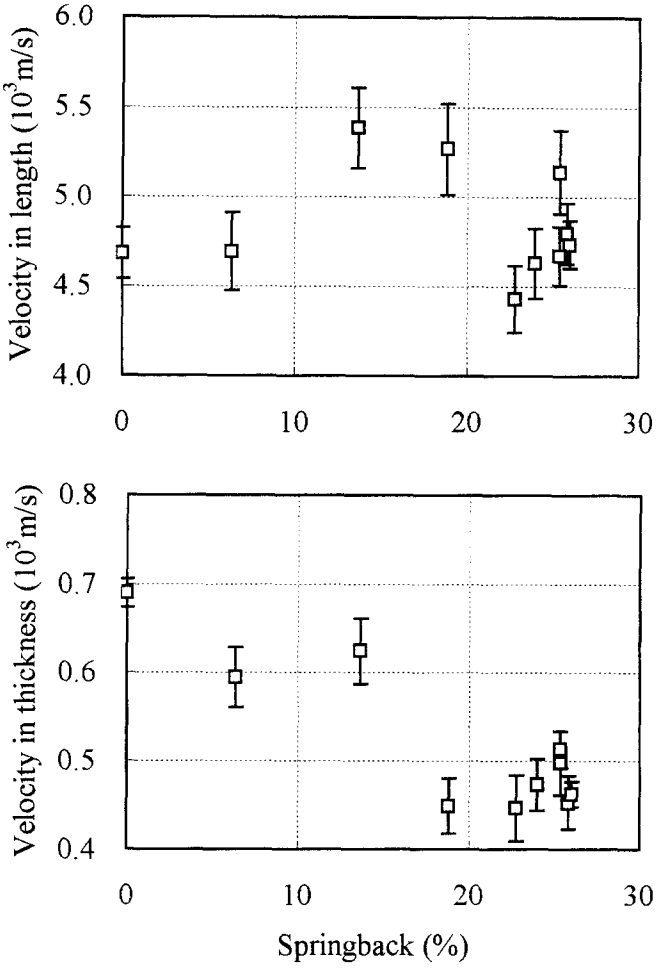

Fig. 7. Relation of springback and ultrasonic velocity for OSB specimens

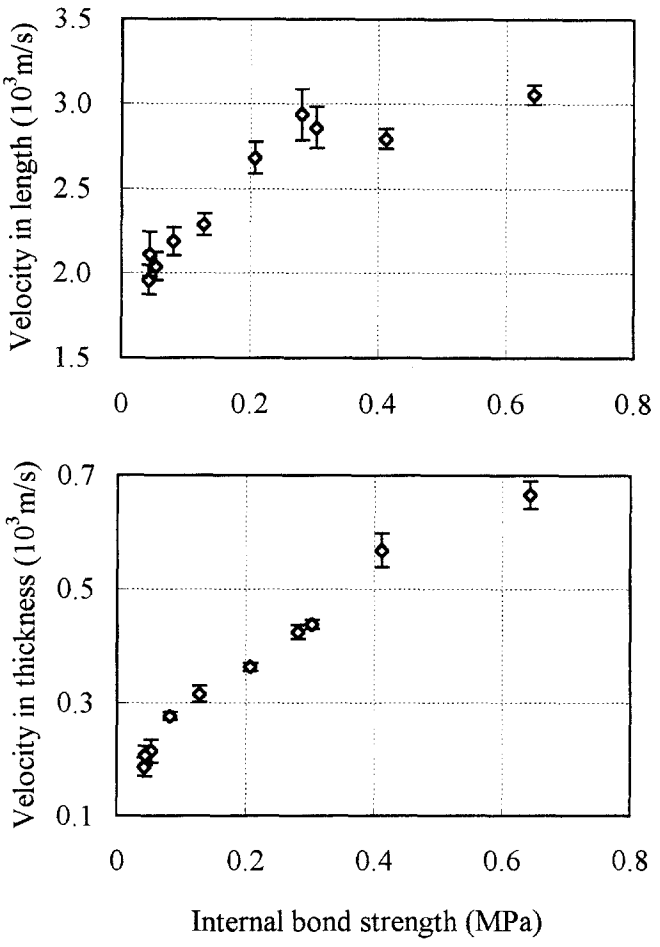

Fig. 8. Ultrasonic velocity dependence on internal bond strength for PB specimens

OSB samples in the length direction exhibited no remarkable change. These phenomena were due to the differences of dimension and alignment of the component chips in the specimens.

Relation between ultrasonic velocity and internal bond strength

It is well known that internal bond strength is determined by the quantity and quality of the bonding points inside wood-composite materials. The quantity of bonding points is determined predominantly by dimension, alignment direction, and the distribution state of the component elements in the materials if they were produced under the same conditions. After the accelerated-aging test treatment, the internal bond strength of the board is decreased. In fact, corresponding with the development of the treating processes, a considerable number of bonding points among the component particles or chips would be damaged owing to the release of the compress-stress seen with hot-pressing during board production.

Figure 8 shows the relation between internal bond strength and ultrasonic velocities measured in the nominal length and thickness directions for the PB specimen. With increased treating time, the internal bond strength decreased, and the velocity of ultrasonic waves passing through these samples decreased for both measuring directions. As described above, voids or discontinuities occur as a result the decreasing quantities of bonding points inside the samples because of the change in springback during treatment. The ultrasonic pulses take much more time to propagate in the samples, as the pulses must circumvent the voids or discontinuities by the quickest route. In other words, the pathways of the ultrasonic waves propagating through the samples change depending on the degree of treatment.

For the OSB specimen (Fig. 9), the velocity in the thickness direction decreased with a tendency similar to that in the PB specimen. However, in the length direction, no meaningful correlation was observed between the velocity and internal bond strength. In this experiment, as previously mentioned, component chips of the OSB are much larger than particles of PB; some of them are even larger than the size of the samples tested (5 cm). When the ultrasonic measurements are conducted on such samples in the length direction, the waves passed directly along the

Table 1. Some correlation coefficients of linear regression between experimental parameters

Specimen	Springback and internal bond	Springback and velocity		Internal bond and velocity	
		Length	Thickness	Length	Thickness
Particleboard	−0.94	−0.88	−0.96	0.81	0.96
Oriented strandboard	−0.84	–	−0.78	–	0.79

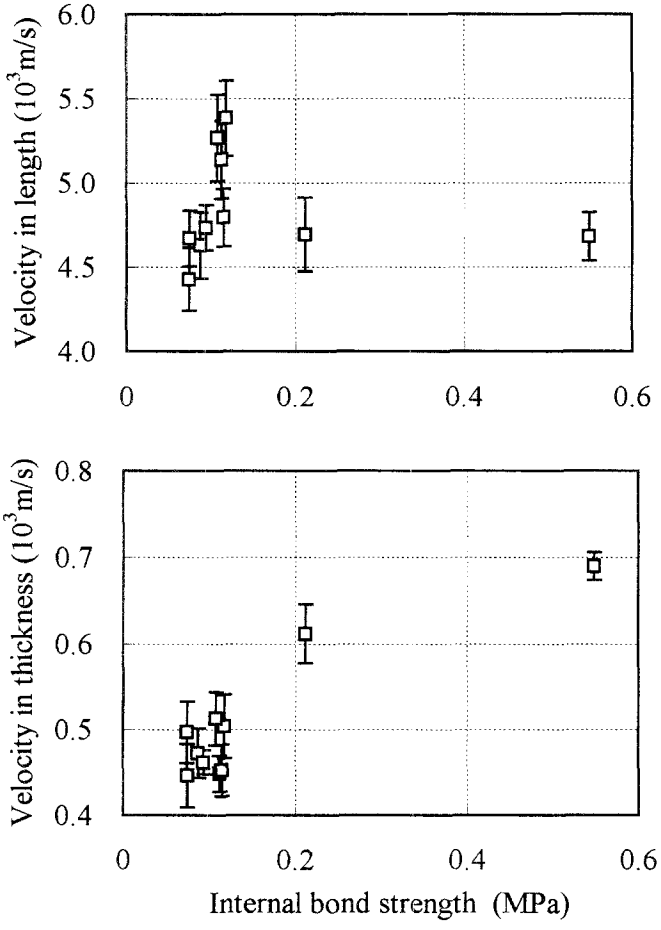

Fig. 9. Ultrasonic velocity dependence on internal bond strength for OSB specimens

straight fiber alignment in some chips, and they uncovered voids or discontinuities in the samples. Such structural characteristics would leave the pathways of the waves unchanged even though some bonding points between the chips had been damaged. However, across the thickness direction, because the component chips were aligned in the OSB specimen in the same manner as particles in the PB specimen, except for the larger dimension the pathways of the waves would also be changed considerably after treatment.

Conclusions

The behavior of the velocity of ultrasonic waves propagating through PB and OSB specimens after treatment with boiling water and oven-drying was investigated. Ultrasonic velocities, measured in the thickness direction for both specimens, decreased corresponding with the levels of treatment. From these results we deduced that as the treatment time increased the quantities of damaged bond points inside the samples increased as well; and as a result voids or discontinuities inside the samples increased. When the waves traveled in such samples, their pathways would be changed owing to the waves having to circumvent the voids or discontinuities. The velocities in the length direction were significantly different in PB and OSB specimens as there was a dimensional limitation of OSB samples in this experiment.

High correlation coefficients between the experimental parameters were observed by statistical analysis for both specimens. The results indicated that the parameters observed in the thickness direction have a closer correlation with the internal bond strength than that in the length direction (Table 1). Therefore, it is strongly suggested that ultrasonic velocity is sensitive to the internal bond status of wood-composite materials bonded with some wild adhesives, especially during accelerated aging treatment processes. Our next study will employ this technique to investigate the effects of the component elements on the internal bond state.

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