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Development of structural composite products made from bamboo I: fundamental properties of bamboo zephyr board

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Abstract A study was conducted to determine the suitability of zephyr strand from moso bamboo (*Pyllostachys pubescens* Mazel) for structural composite board manufacture. Thirty-two 1.8 × 40 × 40 cm bamboo zephyr boards (BZB) were produced using four diameters of zephyr strand (9.5, 4.7, 2.8, and 1.5 mm) and four target densities (0.6, 0.7, 0.8, and 0.9 g/cm^3). Results indicate that BZB exhibits superior strength properties compared to the commercial products. The size of the zephyr strand and the level of target density had a significant effect on the moduli of elasticity and rupture, internal bond strength, water absorption, and thickness swelling, but they did not have a significant effect on linear expansion. With regard to the physical properties, BZB exhibited less thickness swelling and exhibited good dimensional stability under dry–wet conditioning cycles.

Key words Bamboo zephyr board · E-MDI resin · Strength properties · Dimensional stability

Introduction

In recent years the demand for structural lumber products for building materials has increased with increasing construction of housing. On the other hand, the quantity and quality of wood resources from the forest have been decreasing. Consequently, the search for substitute materials in place of the traditional uses of wood has been the focus of renewed interest. Bamboo, in particular, is considered a promising alternate raw material because of its fast growth rate, short rotation age, and high tensile strength. Increased research during recent years has contributed considerably to the understanding of these important arborescent grasses and to improved processing for wider use.[1] The use of bamboo has expanded to include its manufacture into various structural composite boards, such as plywood, particleboard, concrete formwork board, sandwich board,[2] strand board,[3] and superior strength timber.[4]

Up to now, few investigations have been done on the utilization of zephyr strands for manufacturing woodbased composite products.[5,6] Zephyr is a sheet material of fibrous net-like structure prepared similar to scrimber, which was developed in Australia.[7,8] The process involves progressive crushing of materials through several sets of rollers until a continuous fibrous sheet is obtained.[9,10]

This research was done to determine the suitability of bamboo zephyr strand as raw material for the manufacture of bamboo zephyr board (BZB). Variations in the physical and mechanical properties with respect to two processing variables (size of diameter zephyr strands and target density level) were analyzed, and average board properties were compared with standard requirements for commercial products.

Materials and methods

Materials

Three-year-old moso bamboo (*Phyllostachys pubescens* Mazel) from Kagoshima prefecture in Japan was chosen as raw material. The air-dried density of moso bamboo was about 0.74 g/cm^3 with an average thickness of 9–15 mm. The adhesive used was emulsion methyldiisocyanate (E-MDI) resin (PB-1605) formulated by Oshika Sinko Co.

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Methods

Preparation

Bamboo clumps were cross-cut to 40 cm length and sliced into quarters. Bamboo zephyr was them produced by a roll press crusher. The number of bamboo clumps passed through the rollers was used as the treatment criterior to make different sizes of bamboo zephyr, as shown in Fig. 1. Because of its long and cylindrical shape, the diameter of the bamboo zephyr strands was measured based on an average of the thickness or width of their strands (Table 1). In the case of large strands, the bamboo zephyr strands were manually separated by hand before being measured. All bamboo zephyr strands were air-dried to a moisture content of 8%–12% before further processing.

Board production

Under controlled conditions, 32 sample boards were produced in the laboratory based on four diameters of zephyr strand (9.5, 4.7, 2.8, and 1.5 mm) and four target densities (0.6, 0.7, 0.8, and 0.9 g/cm^3). Based on the total board weights at these densities, the required zephyr strands were measured. The weighed materials were sprayed with MDI resin at 8% resin content level based on the oven-dried zephyr strand weight. These strands were hand-made into mats and arranged with parallel orientation. After forming, mats measuring 40 × 40 cm were prepressed by hand and covered with Teflon sheets on both the top and bottom surfaces. They were then transferred to a single-opening hydraulic hot press with a platen temperature of 160°C and were pressed into boards at a nominal thickness of 18 mm. The maximum pressure was 35 kgf/cm^2, and a three-step-down pressing method was followed for a total pressing time 15 min. BZB samples are shown in Fig. 2.

Fig. 1. Bamboo zephyr strand from moso bamboo. From left to right: bamboo culm and bamboo zephyr strands with diameters of 9.5, 4.7, 2.8, and 1.5 mm, respectively

Table 1. Dimensions of bamboo zephyr strands

No. of bamboo passes through the rollers	Diameter (mm)				Length (cm)			
	Min	Max	Avg	SD	Min	Max	Avg	SD
5	6.4	12.1	9.5	1.63	8.6	40.0	39.6	0.46
10	2.7	6.8	4.7	1.05	32.3	40.0	37.3	2.15
20	1.6	4.1	2.8	0.61	23.9	39.2	32.1	4.55
40	0.7	2.3	1.5	0.37	13.6	38.3	25.9	7.27

Number of samples, 40; min, minimum value; max, maximum value; avg, average value; SD, standard deviation from the sample mean

Testing properties

Prior to conventional evaluation of the mechanical and physical properties, the BZB specimens were conditioned at 20°C and 65% relative humidity (RH) for at least 2 weeks. The boards were tested based on Japanese Industrial Standard for Particleboard (JIS A-5908, 1994).[11]

All the boards were trimmed and cut into various test specimens as follows: 5 × 32 cm for static bending; 5 × 5 cm for internal bond (IB) strength; 5 × 5 cm for thickness swelling (TS) and water absorption (WA) tests, and 5 × 10 cm for linear expansion (LE) determination. The static bending tests were conducted on four specimens from each treatment (total 64 samples), using a three-point bending test over an effective span of 26 cm at a loading speed of 10 mm/min. Three test specimens were prepared from each treatment (total 48 samples) for the IB, TS, WA, and LE tests. In addition to the TS standard testing, the specimens were subjected to dimensional stability evaluation under the following dry-wet conditioning cycles: air-drying at 20°C and 65% RH (AD); soaking in ambient temperature water at 20°C for 24 h, (W1); oven drying at 60°C for 24 hours

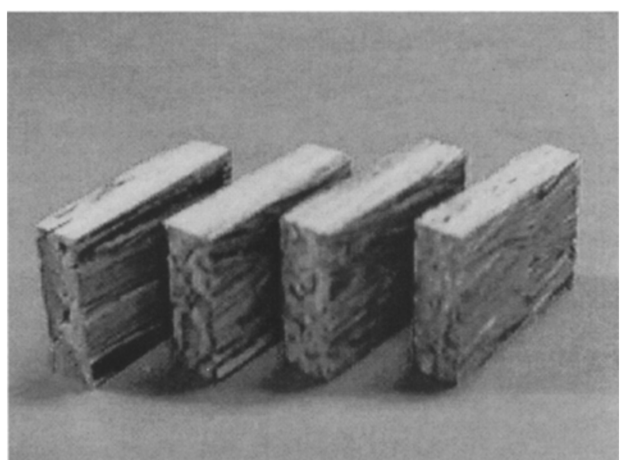

Fig. 2. Samples of bamboo zephyr boards (BZBs). From left to right: BZB 9.5 mm, BZB 4.7 mm, BZB 2.8 mm, and BZB 1.5 mm, respectively

(OD); hot water soaking at 70°C for 24h, boiling for 2h, soaking in water at 20°C for 1h (W3). The thickness changes of boards were calculated based on the board thickness at the initial air-dried condition.

Comparison of MOR and MOE values of the BZB with those of commercial products can describe the position of BZB among the well-known commercial boards. In this research, BZB were compared with plywood, oriented strand board (OSB), particleboard, medium-density fiberboard (MDF), hardboard, glue-laminated (glulam), laminated veneer lumber (LVL), and solid wood. The boards and wood samples were tested according to JIS A-5908, whereas glulam and LVL were tested according to JIS Z-2113.[12] The static bending test was conducted with eight replications for each commercial product.

Results and discussion

Board appearance

One disadvantage of zephyr strands is the effect it can have on the surface condition of the resulting board. Board made from bigger zephyr strands showed a rough surface, high thickness tolerance, and scattered voids. Because of its cylindrical shape, an uneven surface, large cavity, and voids or gaps might result. Conversely, the board made from smaller-diameter zephyr strand exhibited a better surface condition and was denser than the board made from bigger strands.

Mechanical properties

The static bending properties of BZB are listed in Table 2. Results indicate that both MOE and MOR of BZB increased with increasing target density. Similar tendencies were seen with decreasing size of zephyr strand. The BZB using small-diameter zephyr strands (1.5 and 2.8mm) shows higher MOR and MOE values than the BZB using large zephyr strands. Almost of the BZB products had higher MOR and MOE values than cited by JIS A-5908.

Bamboo contains fiber-like structural features known as bundle sheaths and parenchyma, and the volume fraction of bundle sheaths increases from the inner to outer surface of the wall.[13] In the case of small zephyr strands, bamboo zephyr is highly compressed and crushed by rollers,

Table 2. Mean physical and mechanical properties of bamboo zephyr board (BZB)

Target density (g/cm^3)	Diameter of strand (mm)	MOE ($\times 10^3$) (kgf/cm^2)	MOR (kgf/cm^2)	Internal bond (kgf/cm^2)	Water absorption (%)	Thickness swelling (%)	Linear expansion[a] (%)
0.6	9.5	49.2	266	5.06	33.8	2.32	0.38
		(8.2)[b]	(90)	(2.80)	(2.1)	(0.70)	(0.11)
	4.7	55.6	335	5.14	37.3	2.43	0.29
		(8.2)	(88)	(2.72)	(4.2)	(0.15)	(0.09)
	2.8	51.7	327	7.36	42.1	2.79	0.54
		(13.7)	(75)	(2.04)	(1.2)	(0.61)	(0.22)
	1.5	62.9	532	7.4	42.4	3.13	0.30
		(9.8)	(130)	(3.12)	(6.4)	(0.14)	(0.17)
0.7	9.5	59.9	510	6.03	27.7	2.22	0.58
		(7.7)	(159)	(1.15)	(3.5)	(0.57)	(0.28)
	4,7	55.8	543	7.76	30.6	2.47	0.23
		(5.4)	(135)	(3.51)	(1.6)	(0.43)	(0.11)
	2.8	62.2	513	8.13	31.4	3.52	0.37
		(6.9)	(162)	(0.77)	(0.9)	(0.54)	(0.17)
	1.5	67.6	753	7.91	35.1	4.66	0.31
		(13.6)	(185)	(3.02)	(1.1)	(1.03)	(0.02)
0.8	9.5	69.6	587	7.96	24.2	2.38	0.31
		(10.5)	(207)	(3.17)	(3.1)	(0.75)	(0.15)
	4.7	67.6	688	9.54	26.2	2.77	0.24
		(11.0)	(82)	(4.71)	(2.2)	(0.23)	(0.13)
	2.8	89.7	932	18.47	29.9	4.35	0.23
		(10.3)	(197)	(8.71)	(2.4)	(0.58)	(0.10)
	1.5	80.9	857	13.55	33.4	4.68	0.23
		(5.4)	(173)	(6.92)	(3.4)	(0.57)	(0.15)
0.9	9.5	70.7	857	11.72	20.8	3.54	0.20
		(4.6)	(105)	(1.98)	(2.1)	(1.00)	(0.05)
	4.7	72.9	885	12.63	22.8	3.66	0.38
		(16.2)	(214)	(3.74)	(2.9)	(0.50)	(0.08)
	2.8	70.1	827	17.08	26.5	4.66	0.35
		(12.2)	(190)	(3.55)	(3.9)	(1.05)	(0.15)
	1.5	79.8	1105	17.81	27.6	5.21	0.18
		(13.9)	(244)	(7.41)	(4.8)	(0.47)	(0.08)

The number of specimens for static bending, internal bond, and water absorption/thickness swelling/linear expansion for each treatment are, respectively, 4, 4, and 3

[a] Measured along the longitudinal axis of the specimens

[b] Numbers in parentheses are standard deviations from the sample mean

Table 3. Summary of variance analysis for various properties of BZB

Source of variation	Computed F-value					
	MOE (m = 64)	MOR (m = 64)	Internal bond (m = 48)	Water absorption (m = 48)	Thickness swelling (m = 48)	Linear expansion (m = 48)
Density	15.69**	25.94**	7.05**	46.21**	4.91**	1.11^{NS}
	(3.19;5.08)	(3.19;5.08)	(2.90;4.46)	(2.90;4.46)	(2.90;4.46)	(2.90;4.46)
Zephyr strand	3.59**	5.51**	2.94*	12.82**	20.83**	0.98^{NS}
	(3.19;5.08)	(3.19;5.08)	(2.90;4.46)	(2.90;4.46)	(2.90;4.46)	(2.90;4.46)
Interaction	1.10^{NS}	0.72^{NS}	0.92^{NS}	0.54^{NS}	1.86^{NS}	0.76^{NS}
	(2.08;2.80)	(2.08;2.80)	(2.19;3.01)	(2.19;3.01)	(2.19;3.01)	(2.19;3.01)

Numbers in parentheses are critical F-values at α = 0.01 and α = 0.05, respectively
m = number of replications per treatment combinations
* significant; ** highly significant; ^{NS} not significant

producing strands that have more bundle sheaths per unit square than the bigger strands. As a result, they have an irregular network with long, stiff, strong fiber. Kim et al.[6] indicated that zephyr strands make strong bending material because the hot pressing pressure during board production is done mainly to obtain better gluing contact between the strands.

Results of statistical analysis (Table 3) show that the level of target density and the size of the zephyr strands had a significant effect on MOE and MOR. The effect of board density is apparent; that is, increasing the density improved this property remarkably. The MOR and MOE values reach 900 kgf/cm^2 and 90 $\times$ 10^3 kgf/cm^2, respectively, at a density of 0.80 g/cm^3.

As for the bending test, the boards were tested parallel and perpendicular to the length. The BZB samples (with 2.8 mm strands) tested in longitudinal orientation showed values approximately three to six times higher than those of cross-grain-oriented samples at the same target density (Figs. 3, 4). The superior MOR and MOE values of BZB might be due to the nature of the bamboo itself or to the utilization of E-MDI resins, which produce high-quality bonding strength.

Notably, when specimens using the large zephyr strands (9.5 mm) was subjected to a load in the bending test, delaminating fracture occurred owing to the high content of wax and silica on the outer bark of the zephyr strand, which can seriously affect the bonding strength of the glue line. On the other hand, all BZB specimens using small zephyr strands showed the true bending fracture that is observed due to the greater surface area available in contact with adhesive.[4]

A comparison of MOE and MOR values between the BZB and several commercial products is summarized in Table 4. The average MOE of BZB is slightly lower, but comparable to, that of LVL, glulam, and solid wood such as Japanese cypress (hinoki) and Japanese cedar (sugi). The MOE of BZB is also higher than that of plywood, OSB, particleboard, MDF, and hardboard. Moreover, it was found that the average MOR of BZB (especially BZB using 1.5 mm zephyr strands) is greater than those of all other commercial products. These results are consistent with those of Lee et al.[14] Although BZB was found to be slightly less rigid, it exhibited superior strength properties, as indicated by its higher MOR. This means that the BZB is also reliable material for structural purposes.

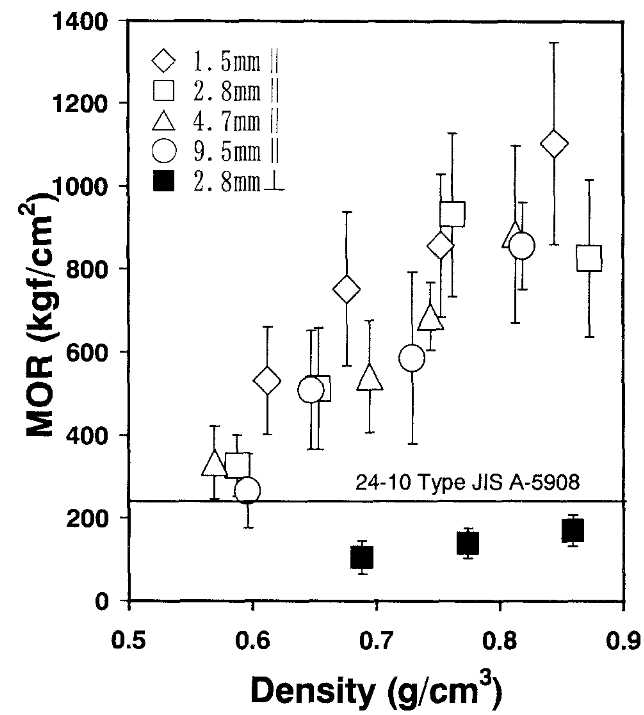

Fig. 3. Modulus of rupture (*MOR*) of BZB at different densities and diameters of zephyr strand. *Diamonds*, BZB 1.5 mm; *squares*, BZB 2.8 mm; *triangles*, BZB 4.7 mm; *circles*, BZB 9.5 mm. *Open and filled symbols* indicate that the fiber direction of the face layer is parallel or perpendicular to the span direction in the bending test, respectively. Symbols and vertical bars denote average values and standard deviations, respectively

From Table 3 it can be seen that both the target density and the size of zephyr strand had a significant effect on IB strength. The IB strength of BZB improves with increasing density. The highest values were obtained from small zephyr strands. The effect of BZB and bamboo density on IB strength may best be expressed by the relation of the compactness in the board. Figure 5 shows that IB strength increased proportionately with the compaction ratio. These findings indicate that a high compaction ratio is a necessity

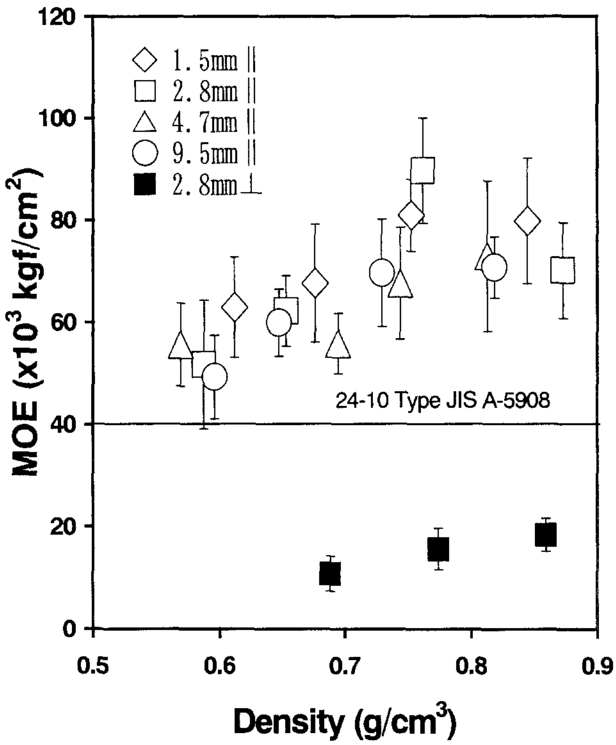

Fig. 4. Modulus of elasticity (*MOE*) of BZB at different densities and diameters of zephyr strand. All symbols are the same as those in Fig. 3

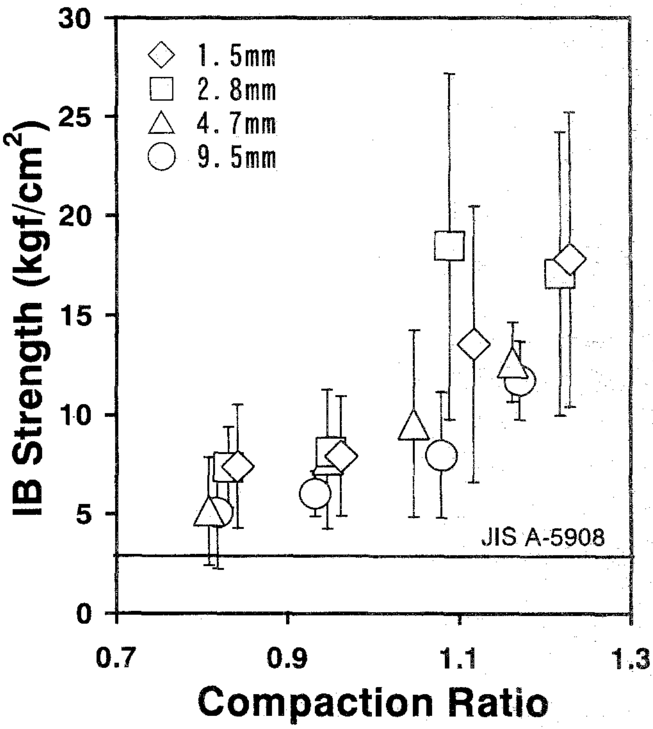

Fig. 5. Internal bond (*IB*) strength of BZB at different compaction ratios and diameters of zephyr strand. All symbols are the same as those in Fig. 3

Table 4. Comparison of BZB bending properties with several commercial products

Material	Specimen size (cm)	MOE ($\times 10^3$ kgf/cm^2)	MOR (kgf/cm^2)
Bamboo zephyr board (BZB) 1.8 × 5 × 32			
1.5 mm strand	1.8 × 5 × 32	72.9 (12.8)	806 (282)
2.8 mm strand		68.4 (17.5)	687 (274)
4.7 mm strand		63.0 (12.4)	613 (243)
9.5 mm strand		62.3 (11.5)	555 (232)
Commercial products			
Glulam (3 ply)	5 × 5 × 76	85.8 (16.4)	638 (119)
Laminated veneer lumber (12 ply)	3 × 3 × 50	91.8 (15.0)	576 (107)
Plywood (5 ply)	1.2 × 5 × 27	53.1 (8.1)	451 (85)
Oriented strand board	1.0 × 5 × 27	51.4 (10.4)	410 (89)
Particleboard	1.5 × 5 × 27	22.8 (4.3)	189 (43)
Medium density fiberboard	1.5 × 5 × 27	33.3 (4.7)	378 (58)
Hard board	0.6 × 5 × 27	55.9 (7.6)	515 (72)
Solid wood			
Hinoki (*Cupressus obtusa*)	1.2 × 5 × 27	88.2 (12.6)	740 (156)
Sugi (*Cryptomeria japonica*)	1.2 × 5 × 27	73.3 (11.1)	640 (123)

Numbers in parentheses are standard deviations from the sample mean
Number of specimens for BZB, commercial products, and ordinary wood are 64, 8, 8, respectively

in BZB with high density. This observed improvement on internal bonding with increase compaction ratio has been previously attributed to a large number of adhesive bond formations due to the greater coverage of the available surface area. Additionally, small zephyr strands were easily compacted and had a wider gluing area; therefore, the IB strength of BZB made with small zephyr strands is higher than that made with large strands. For IB strength, all of the boards exceeded the standard value established by JIS A-5908.

Physical properties

The TS, WA, and LE values of BZB are summarized in Table 2. Results indicate that BZB exhibits lower WA and to a lesser extent TS compared to the bamboo strand board in a previous report.[3] The size of the zephyr strand and the target density had a significant effect on TS and WA, but there was no positive interaction between the two variables (Table 3). The TS values of BZB increased with the increase in board density. Our findings are in agreement with the study reported by Kawai and Sasaki[15] in which they indicated that TS has a tendency to increase with increasing board density because of the greater springback of the compacted particles in boards of high density. The results also shows that the small zephyr strands (1.5 and 2.8 mm) have a greater compaction ratio than the larger strands (4.7 and 9.5 mm), as shown in Fig. 5. Consequently, it is expected to have more swelling when exposed to water due to the release of stress developed during the pressing stage of board manufacture.

On the other hand, the WA of BZB decreases with increasing board density. The reduction in WA might be due to the following causes: There are fewer voids in high-density BZB than in low-density boards. As a result, less water was being absorbed. Higher IB strength may also contribute to the reduction in water penetration. At high density, the higher bonding strength may play a more dominant role where WA is concerned during water immersion. A similar trend was observed by Zhang et al.,[16] who indicated that the WA of high-density board is much smaller than that of low-density board.

It was also found that, unlike TS and WA, both the target density and the size of the zephyr strands had no significant effects on LE, although the magnitude of the expansion for BZB ranged from 0.18% to 0.58%. No apparent explanation can be offered in the case of this phenomenon. Further research is necessary in this area, especially the effects of the size of zephyr strands, void sizes, and the hygroscopicity of E-MDI resin cured in the board.

Figure 6 shows the TS of BZB under dry-wet conditioning cycles. All of the specimens followed the same pattern; that is, the utilization of small zephyr strands was expected to have slightly greater TS values than the large zephyr strands. As mentioned above, small zephyr strands have a greater compaction ratio than the large strands, so the BZB with small zephyr strands is highly compressed (densified) in the thickness direction during pressing, thereby inducing higher internal stress within and between the strands than that with large zephyr strands. However, the TS is less than 5% after soaking in 20°C water for 24 h and less than 12% even after boiling. It can be said that the dimensional stability of these products are sufficient. This result is far below the 20% maximum TS allowed under JIS A-5908.

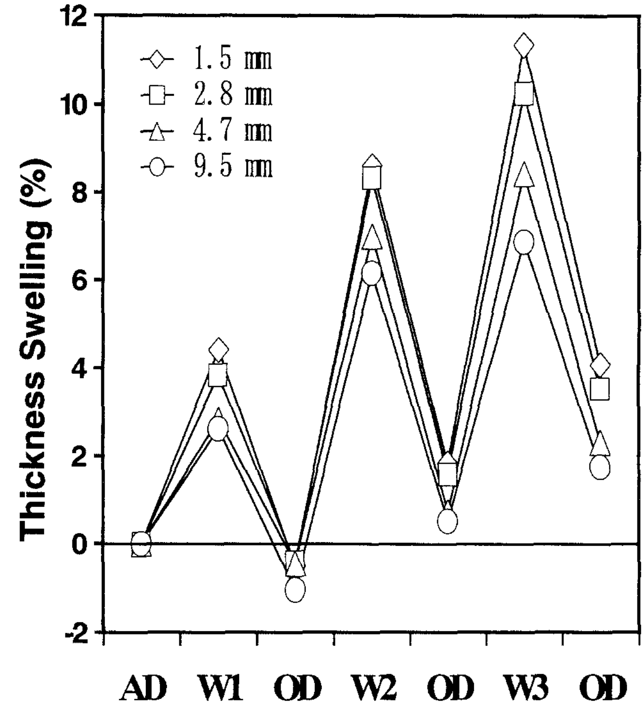

Fig. 6. Thickness swelling (*TS*) of BZB for the dry/wet cycle. *AD*, air-dried condition; *OD*, oven-dried condition at 60°C for 24 h; *W1*, water soaking at 20°C for 24 h; *W2*, water soaking at 70°C for 24 h; *W3*, boiling for 2 h and water soaking at 20°C for 1 h. Refer to Fig. 3 for explanation of the codes

Conclusions

The manufacture of BZB from zephyr strands of moso bamboo (*Pyllostachys pubescens* Mazel) appears to be technically feasible. Strength properties improve with increasing target density and decreasing zephyr strand size. Compared to the commercial products, BZB showed superior strength properties. Under dry-wet conditioning cycles, BZB also exhibited good dimensional stability. It is recommended that further research be done to investigate its other properties, such as biological resistance, weather-ability, finishing properties, and fastener-holding capacity.

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