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Effect of particle shape on linear expansion of particleboard

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Abstract Hinoki (Japanese cypress) strand with 0.6 mm thickness was hammer-milled to prepare three types of particles that had the same thickness but different lengths and widths. Screen analysis and image analysis were conducted to evaluate the shape and distribution of the particle dimensions. Laboratory-scale particleboards were fabricated at three density levels using these particles. To determine the true effect of particle shape on the linear expansion (LE) of the board, these boards exhibited almost the same temperature behavior during pressing, the same density profile, and the same bending properties at each board density level. LE at 40°C and 90% relative humidity of the board was found to be affected by the particle shape. The board composed of small particles showed a larger LE at the same density level. It was considered that the out-of-plane orientation angle of the particles affected the LE of the boards. Thickness swelling and internal bond strength were also affected by the particle shape.

Key words Linear expansion · Particleboard · Particle shape · Out-of-plane orientation of particle

Introduction

Linear expansion (LE) is one of the most important properties of mat-formed panel products used as structural material. LE is known to be affected by various manufacturing parameters and the ambient moisture condition. The literature on LE of wood-based panels can be classified into several groups[1]: the effect of board density,[2,3] resin content,[4,5] species of raw material,[6,7] orientation of elements,[8,9] press conditions,[10,11] and chemical modification.[12,13] Among these manufacturing parameters, we reviewed the research on the effect of the geometry of furnish on the LE of the board.

Suchsland[14] investigated the LE of commercial boards, but the dimensions of the element were not closely evaluated. Post[15] and Lehmann[16] reported that the LE of flakeboard decreased with increasing flake length. Work by Suda et al.[17] showed that the LE of particleboard increased with decreasing particle length and with increasing particle thickness. Shuler and Kelly[18] reported that no significant difference in LE of flakeboard was found between flake lengths of 1 and 3 inches. Sekino et al.[19] suggested that LE was related to the modulus of elasticity (MOE) of the board. Although some research has measured and discussed the effect of geometry on LE as noted above, the primary objectives of these studies were the effect of manufacturing parameters on the mechanical properties of the boards or on the dimensional stability in the thickness direction. There was a possibility that the boards had different structures, such as vertical density profiles, when the experimental boards were fabricated because the elements had widely different shapes and sizes. Because the behavior of LE was affected by many factors that related to each other, evaluating the effect of the geometry on LE was sometimes difficult.

In this study, we tried to prepare laboratory-scale boards with comparable structures and bending properties at the same density level so effects other than particle geometry could be eliminated when evaluating LE behavior. The objective of this study was to evaluate the effect of the shape of particles on LE of laboratory-made particleboards that had comparable bending properties and vertical density profiles.

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Materials and methods

Particle preparation and measurement of particle sizes

Wood particles were prepared by hammer-milling hinoki (*Chamaecyparis obtusa* Endl.; air-dried density of

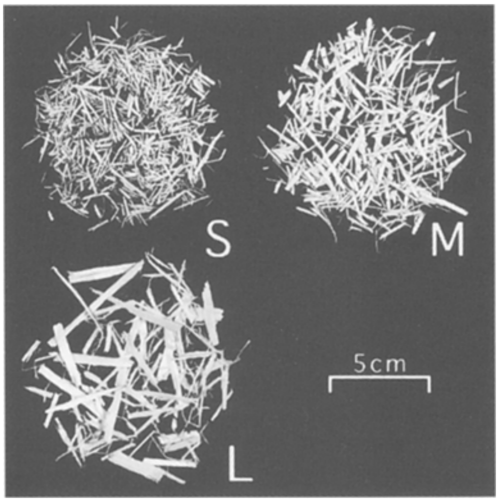

Fig. 1. Three types of particles prepared by hammer-milling hinoki strands. *S*, +6.5 mesh; *M*, −6.5 + 10.0 mesh; *L*, −10 mesh

0.38 g/cm^3) strands of 0.6 mm thickness. Three types of furnish were obtained by screening with removing dust: S, +6.5; M, −6.5 + 10; L, −10 mesh. Figure 1 shows the particles used for this research. A mixture of S, M, and L was also prepared (F). Screen analysis was conducted on each particle type using five different sieves.

To measure the actual length and width of particles, an image analysis was conducted using particles deposited on the face of the scanner. The images of the particles were transferred to the computer and were binarized using a commercial application for image analysis (NIH Image, free software). Dimensions of each particle in the image were determined by approximating the shape of the particle to an ellipse. The major and minor axes of the ellipse were regarded as the actual length and width of the particle.

Board fabrication

The particles were dried to about 2.3% moisture content before the glue spreading. Homogeneous boards were manufactured from four particle types at three board density levels: 0.48, 0.60, and 0.72 g/cm^3. Four replicate boards were made at each condition. Specifications of the board manufacturing were as follows.

Board size: 340 mm long ×320 mm wide ×10 mm thick
Resin type: commercial liquid phenol-formaldehyde resin
Resin content: 9% (solid basis)
Wax: not applied
Press temperature: 180°C
Press pressure: 3.0 MPa
Total press time: 7.5 min

Distance bars were used to control the final thickness of the board. The mat moisture content before pressing was about 13.5%. After pressing, the boards were conditioned at 25°C and 65% relative humidity (RH).

To measure the temperature change with time inside the mat during hot pressing, two thermocouples were inserted into the mat. One was placed at the middle of the central layer of the mat and the other at the middle of the top surface of the mat.

LE measurement

Specimens of 50 × 300 mm were conditioned for pretreatment in an air-circulation chamber at 60°C for 24 h to reach a constant weight. The moisture content was approximately 2.0% after the drying treatment. The specimens were exposed at 40°C and 90% RH until practical equilibrium was reached. Three specimens were used for each condition. After reaching saturation in weight, specimens were successively dried at 60°C in the air-circulation dryer to reach equilibrium. In this study, the practical equilibrium was defined as the state of time change in weight, neither gaining nor losing moisture of more than 0.1 wt% in a 24-h period. The length of the specimens was measured at certain intervals using the equipment specified in the ASTM standard.[20] LE was calculated on the basis of the initial measurements dried at 60°C before the exposure.

Mechanical properties and TS measurement

The MOE and modulus of rupture (MOR) in bending and the internal bond strength (IB) were obtained according to the JIS standard.[21] Five samples for the bending test and ten samples for the IB test were prepared.

A vacuum-pressure soak plus oven-drying (VPSD) was conducted to determine the thickness swelling (TS) of the boards. The VPSD treatment consisted of the vacuum for 30 min, pressure soak for 1 h, and oven-drying at 60°C for 22 h. This treatment was repeated 10 times successively. Ten 50 × 50 mm specimens were prepared for each condition. TS was measured after the 10-cycle treatment.

Density profile

Two 50 × 50 mm specimens were prepared for each level. The vertical density profile of the board was measured using a commercial density profiler with gamma ray densitometry.

Results and discussion

Particle shape

Table 1 shows the distribution of particle size determined by the screen analysis. The largest weight fraction was seen in fractions +20, +10, and +5 for particle types S, M, and L, respectively. Particle type S had the smallest dimension of the three types of particle shown in Fig. 1; about 85% of these particles passed through the 10 mesh sieve. It was seen that more than 90% of M particles remained on the 10 mesh sieve, and about 65% of L particles were on the 5 mesh sieve.

Table 1. Screen analysis for four particle types

Particle type	Weight ratio (%)					
	+5[a]	+10	+20	+30	+40	−40
S	0	14.2	67.7	11.2	5.5	1.4
M	1.8	92.1	5.8	0.2	0	0
L	64.2	33.9	1.8	0.1	0	0
F	11.2	55.7	26.5	4.3	1.8	0.6

S, +6.5 mesh; M, −6.5 + 10.0 mesh; L, −10 mesh; F, mixture of S, M, and L

[a] +, on the sieve; −, passes the sieve

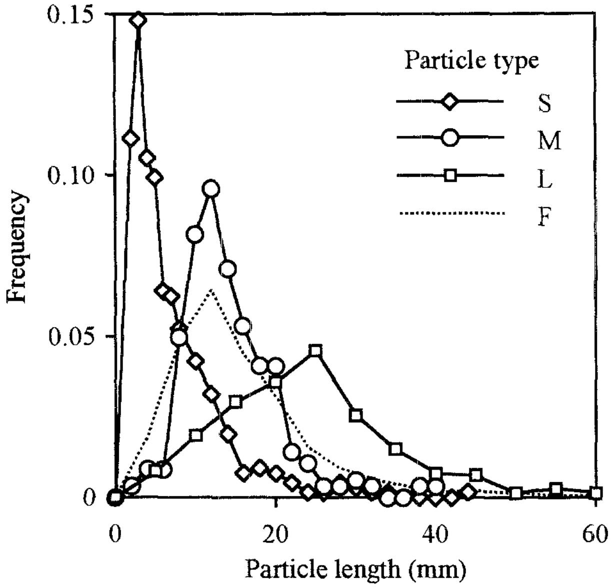

Fig. 2. Distribution of particle length as determined by the image analysis. *F*, mixture of S, M, and L mesh

An image analysis procedure was introduced to determine the actual dimensions of the particles. The distributions for four types of furnish are shown in Fig. 2. It was found that the peak and the shape of the distribution are quite different for these particles. The peaks were found at 3.0, 12, and 25 mm for S, M, and L, respectively. The peak of F was equal to that of M. The range of the distribution increased with increasing particle size.

The means and standard deviations of the length and width of the particles are listed in Table 2 for each particle type, as are the mat heights. The mat height, which provides information on particle characteristics, increased with increasing particle size. The mean values for length were 5.8, 13.3, and 21.4 mm for S, M, and L, respectively. The mixed particle type (F) had a value similar to that of M, but the standard deviation of F was larger. The thickness of these particles was considered to be a constant of 0.6 mm because they were prepared from strands with uniform thickness. Figure 2 also gives information on the distribution of the slenderness ratio, as the thickness was constant. Whereas the length strongly depended on the particle type, the differences in width were rather small. There were about 400 measurements, while was a large enough sample to obtain

Table 2. Length and width of particles as determined by image analysis

Particle type	Length (mm)	Width (mm)	Mat height[a] (mm)
S	5.8 ± 5.1	1.29 ± 0.74	94
M	13.3 ± 5.9	2.05 ± 0.71	109
L	21.4 ± 10.9	2.13 ± 1.03	149
F	13.8 ± 9.2	2.16 ± 1.23	126

Lengths and widths are the mean ± SD

[a] Height was measured using air-dried particles without gluing

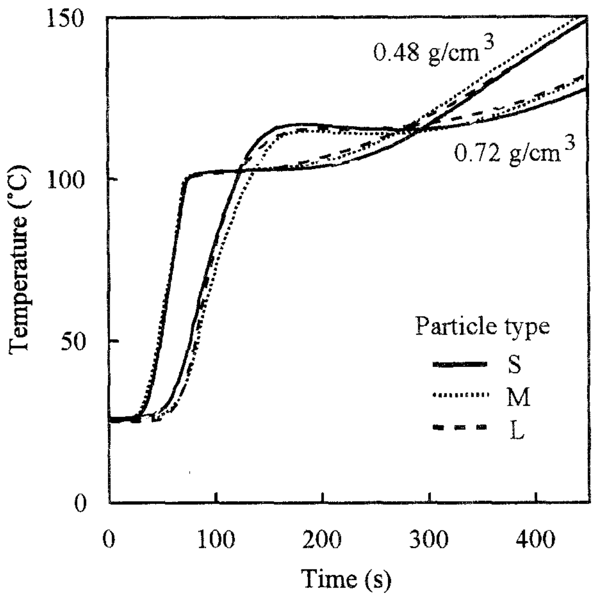

Fig. 3. Temperature behavior at the center of the mat with time after press closure

results with certain accuracy. It was further revealed that the image analysis used in this study was a practical method for obtaining the dimensions of particles under the assumption that the particles were almost of the same thickness.

Comparison of temperature behavior, density profile, and bending properties of the fabricated boards

Figure 3 shows the behavior of temperature during hot pressing at the middle of the central layer of the mat. Board density was found to affect the temperature behavior. The temperature at the central layer of the mat began to rise at about 40 s of pressing time for 0.48 g/cm^3 board and at 70 s for 0.72 g/cm^3 board. The rate of the temperature rise of 0.48 g/cm^3 board was slightly larger than that of 0.72 g/cm^3 board. After the rapid temperature rise, the rate of temperature rise decreased, and the temperature became almost constant at 100°C for 0.48 g/cm^3 board and 115°C for 0.72 g/cm^3 board. Bolton et al.[22] reported similar results. In regard to the effect of element size on temperature behavior, it was reported that larger elements such as flakes obstructed the flow of moisture inside the mat compared to smaller element such as particles.[23] However, the particle size employed in this study had little effect on the temperature behavior, as shown in Fig. 3.

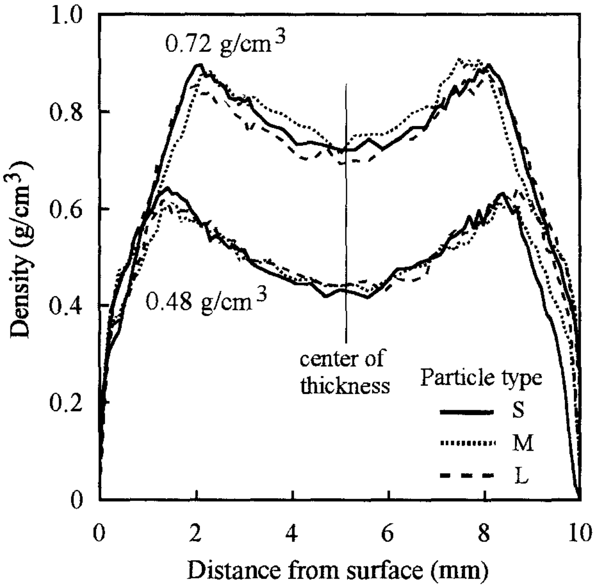

Fig. 4. Density profile of the particleboards

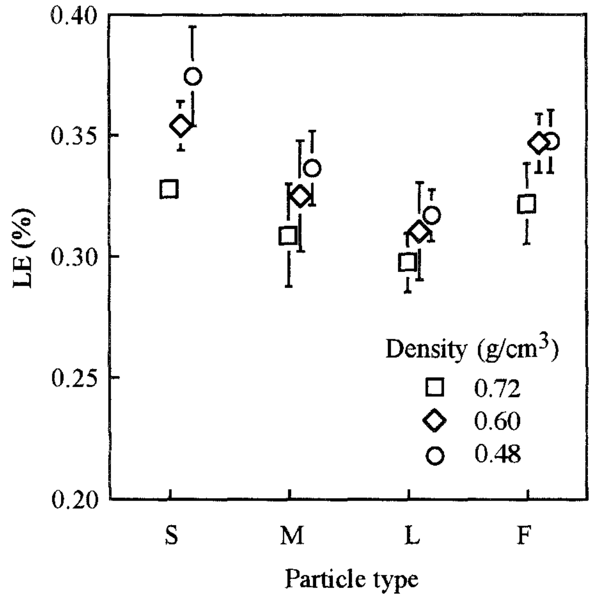

Fig. 5. Effect of particle shape on linear expansion (*LE*) of particleboard at 40°C and 90% relative humidity

Table 3. MOE and MOR in bending of particleboard

Density (g/cm^3)	Particle type	MOR (MPa)	MOE (GPa)
0.48	S	18.3 ± 2.1	1.9 ± 0.2
	M	16.9 ± 1.6	1.8 ± 0.2
	L	17.8 ± 0.3	1.9 ± 0.2
	F	17.3 ± 1.5	1.7 ± 0.1
0.60	S	26.1 ± 3.0	2.5 ± 0.2
	M	24.6 ± 2.3	2.4 ± 0.2
	L	25.9 ± 2.9	2.6 ± 0.2
	F	22.6 ± 8.4	2.7 ± 0.3
0.72	S	37.3 ± 5.0	3.4 ± 0.4
	M	30.5 ± 2.4	2.8 ± 0.3
	L	35.2 ± 2.3	3.2 ± 0.2
	F	36.4 ± 4.7	3.4 ± 0.4

MOE, modulus of elasticity; MOR, modulus of rupture
Results are the mean ± SD

Figure 4 shows the density gradient across the board thickness. Despite the difference in particle sizes, no differences in the density profiles were seen at the same density level. The MOE and MOR in bending are shown on Table 3. Except for the M board of 0.72 g/cm^3, these mechanical properties were almost equal at same density level. Based on these results it was concluded that the boards fabricated in this study had almost the same temperature history during pressing, layer structure, and bending properties.

Effect of particle shape on LE

Figure 5 shows the effect of particle shape on the LE at 40°C and 90% RH. From the results for S, M, and L type boards, it was found that the LE of particleboard decreases with increasing particle size for each density. This proved to be statistically significant. Comparing the mean values within the same density, LE at a density of 0.48, 0.60, and 0.72 g/cm^3 decreased from 0.38% to 0.33%, from 0.34% to 0.31%, and from 0.32% to 0.30%, respectively. For the particles used in this study with mean lengths ranging from 5.8 to 21.4 mm, as shown in Table 2, increasing the particle size from S to L reduced the LE of the board by about 10%–15%. Results of LEs obtained by the drying operation after the hygroscopic moisturing condition also showed a similar tendency for the effect of particle size on LE. The LE per unit of moisture change (LE/MC) slightly decreased with increasing particle size for each board density. For 0.60 g/cm^3 board, the values of LE/MC were 0.020, 0.018, and 0.017 (%/%) for S, M, and L boards, respectively.

Some different experimental results were reported concerning the effect of particle shape, and no clear conclusion has been drawn. Some research studies done on flakeboards did not agree about the effect of flake length,[24] but the length effect was shown to be less than 25 mm. Hiziroglu and Suchsland[25] reported that the effect of particle size by screen mesh on the LE of particleboard was insignificant. One of the reasons for the different views could be the difficulty evaluating LE, because LE has an extremely small dimensional change compared to TS. Many factors other than the particle shape could strongly affect the dimensional change of the board. The layer structure of the board or high thickness swelling can sometimes have a significant effect on LE measurements.[26]

As mentioned in the above sections, the particleboards tested in this work had almost the same vertical density profile and the same history of temperature behavior during pressing for the same density boards. Thus, it was experimentally confirmed that the particle shape affected the LE of the board.

It is thought that one of the reasons for these phenomena in LE is the out-of-plane orientation of a particle, which was defined by the angle of the longitudinal direction of a

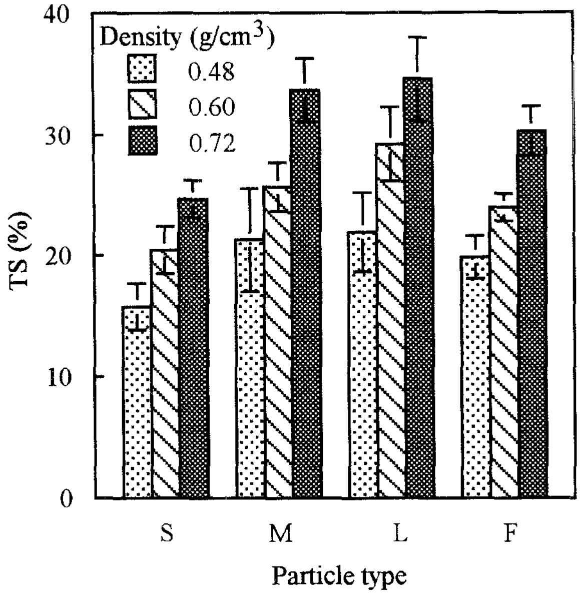

Fig. 6. Effect of particle shape on thickness swelling (*TS*) of the particleboard after vacuum-pressure soak and oven-dried exposure

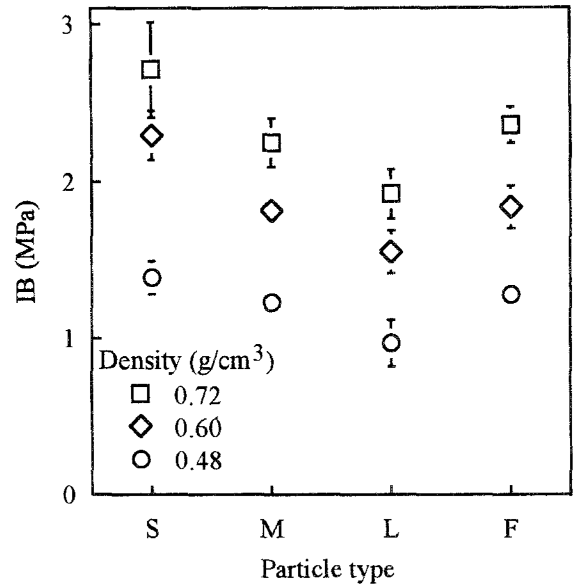

Fig. 7. Effect of particle shape on the internal bond (*IB*) strength of the particleboard

particle and its in-plane projection. Because the particles are not always deposited perfectly parallel to the plane of the board, particles inside the mat have a certain angle to the board plane. The effect of the out-of-plane orientation of particles on the LE of particleboard was evaluated by both theoretical and simulation analysis.[27] The similar consideration employing the out-of-plane orientation angle can be applied to explain the results obtained in this research. Assuming that the grain direction of wood coincides with the largest dimension of the particles, when the particles in the board have a larger out-of-plane orientation angle, the LE of the board is larger because the contribution of the transverse swelling component of wood increases along the plane direction. The larger the out-of-plane orientation angle becomes, the more the LE of particleboard increases.

The particles M and F had almost the same mean length and width, as shown in Table 2, and the distribution ranges for these parameters of F were larger than those of M. The distribution of the element length might affect the out-of-plane orientation angle distribution, but the difference in LE for M and F particles was not clear from this experiment. Further discussion is necessary on how the distribution of the particle size affects the board properties.

Properties in thickness direction of the boards

The TS and IB strength were measured to evaluate the properties in the thickness direction of the boards. Figure 6 shows the effects of particle shape on the TS of the board after VPSD treatment. The VPSD treatment consisted of 10-cycle repetitions of water soaking and drying. This treatment would give information on the dimensional stability in the thickness direction that is inherent in mat-formed panel products.[28] TS after the treatment was affected by both density and particle type. It was found that TS increases with increasing particle size for each board density level. There is a significant difference among particle types at each density level. For $0.6\,g/cm^3$ boards, the TS values for the board after treatment were 21%, 26%, and 30%, for S, M, and L, respectively. This result was contrary to the effect of the particle size on LE. The out-of-plane orientation angle of particles could explain this contrast. It was thought that particles with a larger out-of-plane orientation angle may contribute to reducing the TS of the board because of less dimensional change in the longitudinal direction of wood. Another factors, such as bonding efficiency, entanglement, and total surface area of particles, must be considered for further discussion.

Figure 7 shows the effect of particle shape on IB strength of particleboards at the different board density levels. The IB values ranged from 1.0 to 3.0 MPa when the boards were made with a resin content of 9%. These values seemed to be high enough compared with the JIS requirement of 0.3 MPa.[21] Figure 7 also shows that IB strength decreased with increasing particle size for each density level. For example, at the density level $0.60\,g/cm^3$ the mean IB value of the S board was 2.3 MPa, whereas that of L board was 1.6 MPa. It is known that, in general, IB of particleboard composed of small particles is higher than that made with long or flat particle elements.[15] It was also thought that the out-of-plane orientation angle of the particles was one of the factors affecting the mechanical property perpendicular to the board surface. The results of TS and IB, which reflected the properties in the thickness direction, corresponded to the LE behavior when the out-of-plane orientation angle of the particles was used in consideration for the effect of particle shape and size.

Conclusions

Using hinoki particles, particleboards were fabricated to evaluate the effect of the geometry on the LE of the boards. Particle shapes, LE, TS, and IB were determined. The results obtained can be summarized as follows.

1. The actual dimensions of the particles were measured by image analysis. The image analysis used in this study enabled us to determine the distribution of particle sizes under the assumption of constant thickness.

2. The laboratory-scale boards were made to have almost the same temperature behavior during pressing and the same vertical density profile for evaluating the LE. It was revealed that the LE increased with decreasing particle size under the moisturing condition at 40°C and 90% RH. Properties in the thickness direction, TS and IB, were also affected by particle size.

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