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Dimensional instability of cement bonded particleboard: SEM and image analysis

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Scanning electron microscope (SEM) and image analysis were applied to quantify the structure of commercial cement bonded particleboard (CBPB) to obtain a more fundamental understanding of the instability of CBPB and to provide a basis of information for modelling the stress–strain behaviour of CBPB. Surfaces through the thickness of the board and vertically within the board were analysed mainly with respect to the distribution, size, shape and percent area occupied by individual components (void, cement paste and wood chips). Results showed that the area occupied by wood chips 1) increased from the surface to the core layer (from 34 to 49%), 2) was 5% higher for vertical surfaces than for horizontal surfaces, 3) but was in total only about 40%; this is much lower than the volume fraction (about 75%) of raw materials used in the manufacture of CBPB. This confirms the mechanism/organisation of mat formation, showing the more significant effect of wood chips on thickness than on length changes with changing moisture content and indicating that the wood chips are compressed in CBPB. The wood chips nearly all lie flat in the horizontal planes throughout the board thickness and were randomly distributed on the horizontal plane. The mean angle was about 10.7° between wood chips and the horizontal surface and about 44.7° between wood chips and the longitudinal direction within a horizontal plane, verifying that the change in thickness should be much higher than that in length or width, and the change in length and width should be similar. The size and shape of the wood chips were very different among six horizontal layers and between the horizontal and the vertical layers.

1. Introduction

The properties of CBPB are dependent on the network of wood chips, cement paste and void spaces resulting from the interaction of the raw materials and fabrication process parameters. The nature of the voids, cement paste and wood chips in the mat will significantly affect mass transfer and result in different amount of movement of CBPB in the different directions.

Very little work has been done on wood composites to characterise the network structure of the mat. Suchsland [1] was perhaps the first to investigate a related topic, namely the horizontal density distribution in wood composites. This investigation was continued in order to develop a model for the simulation of the horizontal density distribution in flake board [2] and to examine its relationship with various properties of the product. More recently a micromechanical model has been tried to optimize the structural properties of heterogeneous wood composites [3–5]. It was concluded that the microstructural details can have an important effect on the engineering properties of wood composites and the expected structural properties can be adequately modelled from average flake length and width, total flake number and total layer area. The feature of voids in flakeboard was also found to be related to the method of mat formation and the direction of flake orientation [6].

The purpose of the current programme of research is to characterise the structure of commercial CBPB with the objective of modelling the dimensional changes using the law of mixtures. A method for observing the gross structure of CBPB was developed using computer image analysis techniques to quantify the parameters necessary to define the structure and this is reported on in this paper. The result of this research will be used specifically to support information when modelling the stress–strain behaviour of CBPB, including the development of internal stresses, and this will be discussed in a subsequent paper on "Modelling CBPB as a composite." However, the information provided should have very valuable implications for other areas of wood–based composite research.

2. Preparation of SEM samples

In the preparation of 18 mm thick CBPB samples for SEM, two factors were considered. Firstly, the samples should be of sufficient size and of a form to enable the full size of particles to be included, the chip orientation to be identified and the distribution of wood cement interfaces to be viewed. Secondly, various sizes of wood particles have to be included in one sample to ensure that a true random distribution is represented. Consequently, in order to satisfy these two constraints, a form of CBPB specimens was chosen as the best means of investigating orientation and distribution within a bulk system. Samples with a cross-section of 50×50 mm were cut vertically from the CBPB. The samples were then sanded from one top surface to produce surfaces at various depths across the thickness of the boards. Samples with horizontal faces were prepared with a thickness of 18, 17, 15, 13, 11 and 9 mm (Fig. 1A) and the faces were designated as L0, L1, L2, L3, L4 and L5 respectively from surface to core.

To assess the distribution of wood particles and cement paste on side faces (within the thickness of the board), three matched samples, of dimensions 50×18 (board thickness) $\times$ 10 mm, were also prepared (Fig. 1B) and designated as T1, T2 and T3.

3. Image processing and measurement

The schematic diagram and corresponding flowchart (Fig. 2) describe the procedures for image processing

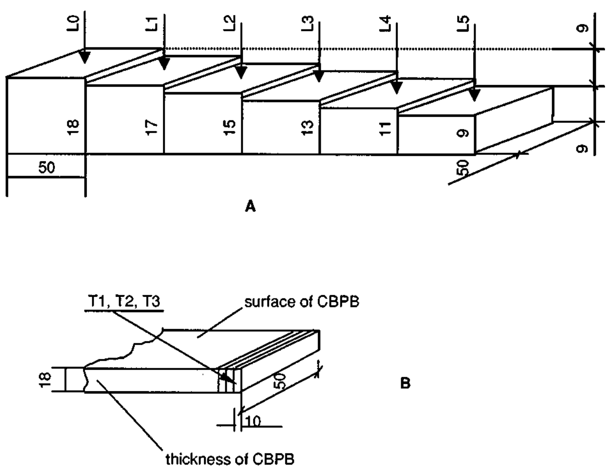

Figure 1 Surface preparation of CBPB through the thickness of the board (A) and on its edge (B) (side faces).

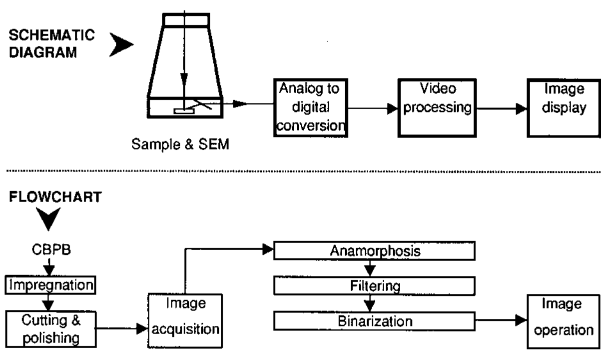

Figure 2 Schematic diagram and flowchart for image processing and measurement.

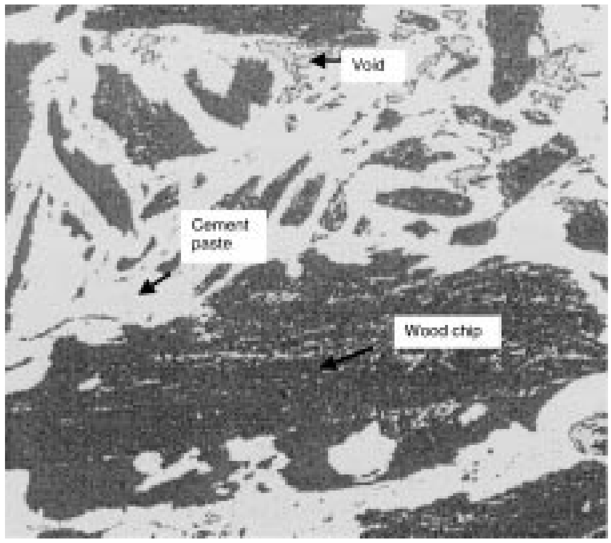

Figure 3 Micrograph showing void space (yellow region), wood chip (dark region) and cement paste (pale region) (Sample L3, field number 2).

and measurement. Samples of CBPB were impregnated with resin to increase sample rigidity and to fill any air pores with an electron-opaque medium so that they could be polished. Backscattered electron images were made at the minimum magnification ($\times 9$) with the sample normal to the electron beam (i.e. there is no distortion due to foreshortening).

A typical image is given in Fig. 3 (sample L3, field number 2). The images were processed by smoothing with a 4 : 2 : 1 filter. This was done in order to remove any spurious high and low brightness pixels that would otherwise make image stretching inconsistent. After this the images were "stretched" so that the lowest grey level corresponded to a pixel brightness of 0 and the highest grey level corresponded to 255. This ensures that as far as possible all the images are rendered to a standard contrast range. These processed images were than analyzed in terms of their greyscale.

Two grey levels were used in this analysis. The lowest grey level, g_1, corresponds to regions that contain only the encapsulating resin used in the preparation of the thin samples; the upper grey level, g_2, corresponds to the wood particles. Since the wood particles can absorb varying amounts of the resin and the resin density and thickness can vary, g_1 and g_2 each span a range of grey levels, Fig. 3. The picture is further complicated by the fact that the wood particles can be so heavily impregnated with resin that they are imaged at the same grey scale as true voids. To avoid incorrect identification of these regions by the software as air voids, regions are only labelled as air voids if they contain less than one region with a grey level greater than g_1, Fig. 3. These criteria (grey level, pore numbers) were arrived at by using two independent assessors examining a number of images.

The classification used is thus:

Void: Region of grey level g_1 with less than 1 included hole. This is the area of voids in the cement paste;

Dark wood: Region of grey level g_1 with greater than 1 included hole. This is the area of the voids inside wood chips;

Wood: Region of grey level g_2 (hole size immaterial).

These regions are further classified according to their sizes (area): size 0 being an area from 0 to 1 mm^2, size 1 being from 1 to 2 mm^2 and so on, up to size 10 which are those having an area greater than 10 mm^2. For each object in each image the following parameters of interest were logged on a data file for each of the objects measured: feature number, area, position (using x and y coordinates), threshold number, number of pixels (pix), feature length, feature breadth, orientation, perimeter, area (no holes), number of holes, ellipse minor, elongation 1, elongation 2, aspect ratio, convex circularity, circularity, form factor, hole area, convexity, field area, number detected, number of interest, field number and class name. According to the feature of interest on the image analysis, the specific parameters measured were further processed. These included: area, feature length, feature breadth, orientation, perimeter, aspect ratio, form factor, field area and class name, and are discussed and presented in the present paper.

For each of the 9 different viewing surfaces, the results are the sum of the examinations of five image fields of view for each sample, with each view having an area of 82.64 mm^2, i.e. $5 \times 82.64\ mm^2 = 4413.2\ mm^2$.

4. Results and discussion

4.1. Percent mat area occupied by components

The percent area of a mat occupied by the components is an indication of the volume of wood chips, cement paste and voids in a panel product. The percentage of components on the horizontal surface will characterize the change in length and width of CBPB under moisture change, while that on the vertical, side faces will contribute a different effect on the thickness and length (width) directions. In this investigation, both vertical and horizontal surfaces were examined. The results (mean values) are presented in Table I.

Vertical surface. In each of the three vertical surfaces with an area of 413.2 mm^2, on average about 42% is occupied by wood chips and 58% is occupied by cement paste. The detectable voids, due to air embedded during manufacture, is less than 1%.

In Table I it appears that the total area occupied by the three components (wood chips, voids and cement paste) are similar between three samples. The one way analysis of variance (ANOVA) statistical procedure determined that no significant difference existed between the three side faces for all the items evaluated. This fact (which actually covers all parameters measured) also verified the accuracy of sampling and view selection for image processing.

Horizontal surface. Regarding the horizontal surfaces, the features of the wood chips are different between different layers, and this will be discussed in a following section. Looking first at the mean values of the six surfaces related to the three components, it was calculated that about 62% area of the horizontal surface is occupied by cement paste and about 38% occupied by wood chips. Less than 1% area is occupied by voids, a value similar to that for the vertical surface.

However, the total percent area occupied by the three components is different between the different layers. The area occupied by voids is largest in the horizontal layer L3. Lower values were detected in the layers near the surface and at the core of the CBPB. In layer L1, detectable pore was not found in all five views. This suggests that certain sizes of wood chips, together with a certain ratio of wood chips to cement paste, may produce a most compacted CBPB.

The area occupied by wood chips increased from the surface layer to the core layer, with an exception of layer L2. About 34% of the area are occupied by wood chips in layer L0 compared to about 49% in layer L5. This result is in agreement with the mechanism of mat formation used in the manufacture of CBPB.

A comparison of values between the vertical and horizontal surfaces shows that the mean percent area of wood chips is higher in the vertical than that in the horizontal faces though the horizontal surfaces near the core contain the highest percentage area of wood chips; the mean percent area of cement paste is lower in the vertical than in the horizontal surface. The high value of the mean percent area occupied by wood chips in the vertical surface may be partly responsible for the greater change in thickness than in length of CBPB under changing RH.

TABLE I Total/mean area occupied by components of CBPB on vertical and horizontal surfaces*

Surface	T1	T2	T3	T-mean	L0	L1	L2	L3	L4	L5	L-mean
					Voids						
Number of object	51	20	55	42	6		47	44	29	31	26
Area (mm^2)	2.90	0.96	3.99	2.62	0.29		2.99	3.85	2.10	1.86	1.85
% of total area	0.70	0.23	0.97	0.63	0.07		0.72	0.93	0.51	0.45	0.45
					Wood chips**						
Number of object	465	548	567	527	353	335	298	349	329	424	348
Area (mm^2)	163.58	183.39	170.67	172.55	141.61	144.34	122.02	162.18	168.23	203.56	156.99
% of total area	39.59	44.38	41.30	41.76	34.27	34.93	29.53	39.25	40.71	49.26	37.99
					Cement paste						
Area (mm^2)	246.72	228.85	238.54	238.04	271.30	268.86	288.19	247.17	242.87	207.78	254.36
% of total area	59.71	55.38	57.73	57.61	65.66	65.07	69.75	59.82	58.78	50.29	61.56

*Number of view for each surface is 5; total area observed is 413.2 mm^2.

**Total area and number of wood chips = those of wood and dark wood.

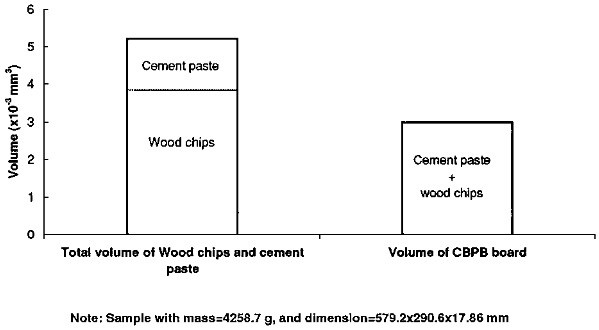

Figure 4 Volume of uncompressed and compressed CBPB.

From the mean percent areas in both the vertical and horizontal surfaces it appears that only about 40% of the surface area is occupied by wood chips. This greatly deviates from the proportions of raw materials used in the manufacture of CBPB (which is about 75% by volume of wood chips and 25% of cement paste). The result may be attributable to the significant difference in the stiffness of cement paste and wood chips, resulting in compression in wood chips in CBPB. The fact that compression of wood chips occurs in CBPB can also be verified by analysing the commercial CBPB products. For example, with a sample of 4258.7 g, and dimensions of $579.2 \times 290.6 \times 17.86$ mm, the volumes of cement paste and wood chips used are 1.42×10^{-3} and 3.81×10^{-3} mm^3 respectively. The total uncompressed volumes of cement paste and wood chips, and actual volume of CBPB board are presented in Fig. 4. The ratio of the uncompressed to compressed volume of CBPB is 1.75.

This result confirms that the large change in the length of chips following dissection was due to stress relief [7].

4.2. Orientation of components and voids

Resulting from the anisotropic nature of wood, it is considered that the orientation of wood chips is a vital factor affecting the dimensional change of CBPB. This investigation examines whether the change in dimensions of CBPB between length and width is identical, and whether changes between thickness and width is significantly different. It should be noted that the raw data for the orientation give the angle over a range of 2π radians. On the graphs in the following discussion this had been expressed in degrees over the range of 0–180°.

Vertical surface. Very similar results were obtained for all 3 side faces of CBPB (Fig. 5). As expected, almost all chips lie flat in CBPB, 36–45% of the total wood chips lie at an angle of 0–10°, and 20–22% of them at an angle of 171–180° with respect to the horizontal surface.

In considering the effect of the orientation of wood chips on the thickness and length changes due to moisture, chips with the same complementary angle (effective angle) were taken together. It was found that about 90% of wood chips lie with an angle 0–20° to the horizontal. Very few wood chips (only about 2%) are present with an angle of 41–90°.

The mean angle was calculated based on the fractional occupied area of wood chip. This was 10.82°, 11.21° and 9.95° respectively for samples T1, T2 and T3. Therefore the mean angle for the three samples is approximately 10.7° to the horizontal surface. This result clearly verified the significantly different contributions of wood chips to CBPB between the thickness and length or width changes [8, 9], because the longitudinal movement of wood (length of wood chip) is less than 10% that of the transverse (width or thickness of wood chip). The numerical modelling is reported on in a separate paper [10].

Horizontal surface. Unlike the orientation on the side faces, the wood chips are distributed randomly on the horizontal surfaces (Fig. 6), whether in total area or frequency. The mean angles (based on the fractional area for each chip) were calculated, Table II.

From Table II, the effective mean angles for 5 layers are seen to range from 41 to 51°. The total mean angle is approximately 44.7°. This indicates that the effect of orientation of wood chip in the length and width directions is similar and is in line with the

TABLE II Mean effective angles of wood chips on the horizontal surfaces (°)

Layer	L0	L1	L2	L3	L4	L5
Effective angle	45.86	40.59	51.41	47.08	42.79	43.51

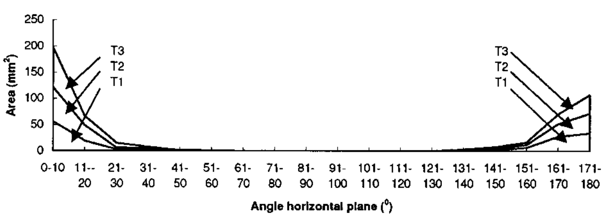

Figure 5 Area occupied by wood chips having various orientations in vertical layers.

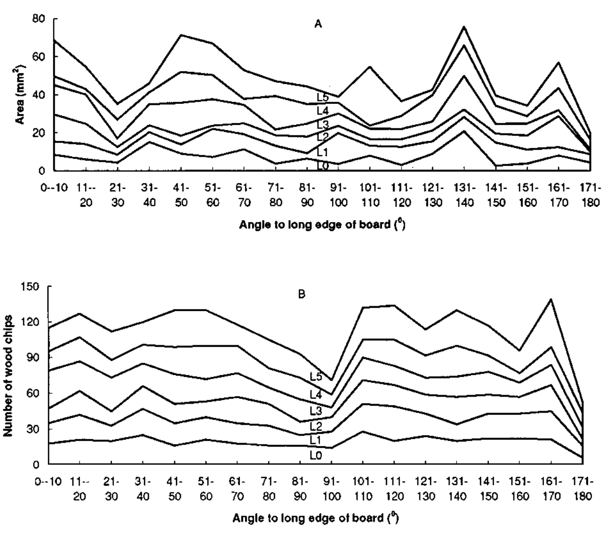

Figure 6 Area occupied by wood chips (A) and number of wood chips (B) having various orientations in horizontal layers.

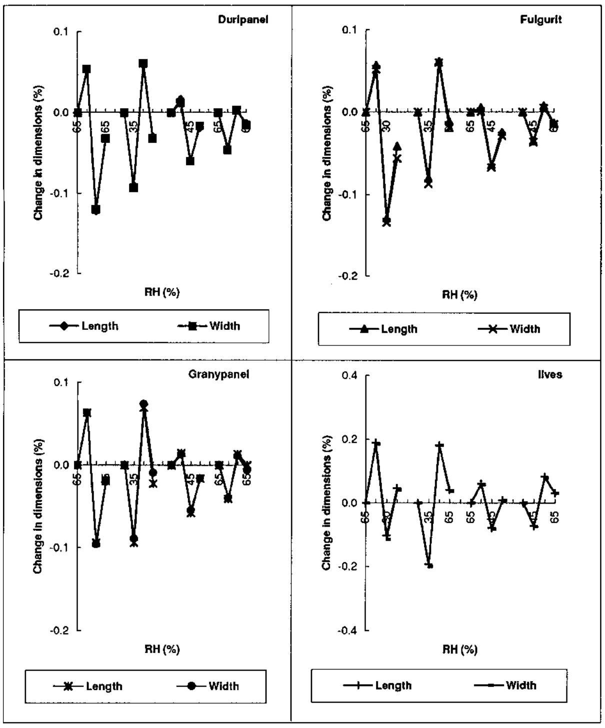

Figure 7 Change in length and width of four brands of CBPB boards under various cyclic RH.

intention of manufacturing an isotropic board. The experimental results have also confirmed this (Fig. 7). Fig. 7 illustrates the change in length and width of four brands of CBPB. Four different cyclic conditions, 20°C/65% → 20°C/90% → 20°C/30% → 20°C/65% relative humidity (RH), 20°C/65% → 20°C/35% → 20°C/90% → 20°C/65%RH, 20°C/65% → 20°C/75% → 20°C/45% → 20°C/65%RH, 20°C/65% → 20°C/45% → 20°C/75% → 20°C/65%RH, were used. It is apparent that under various RH conditions the changes in length and width of various CBPB are very similar.

4.3. The size and shape of components in CBPB

The structure of CBPB and hence its behaviour depends principally on the components (including voids) and their size embracing their length, width, perimeter and shape. The total area occupied by each component and the orientation of the wood chips has been discussed in previous sections. Further evaluation was carried out in order to obtain a better concept of the structure of commercial CBPB. The summaries of statistics for the dimensions, area and shape factors of individual components have already been recorded [11]. The grand mean values are presented in Tables III and IV, and Figs. 8 and 9.

Size of components

Void. Table III shows extreme variability in the length, width, perimeter and area of void within individual layers tested, with the greatest variability being for the area. However, the degree of variability for all parameters was very similar for various layers.

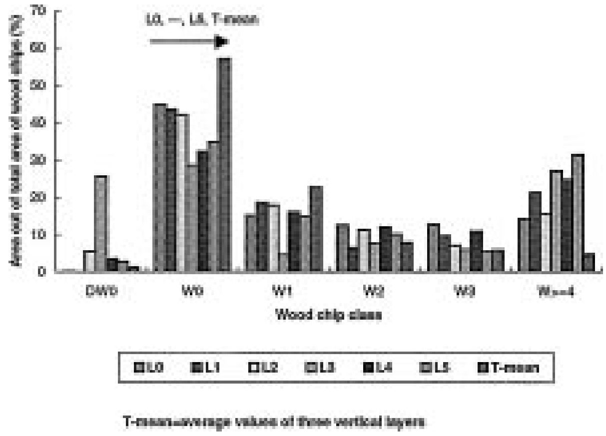

Figure 8 Distribution of various size classes of wood chips in vertical and horizontal surfaces.

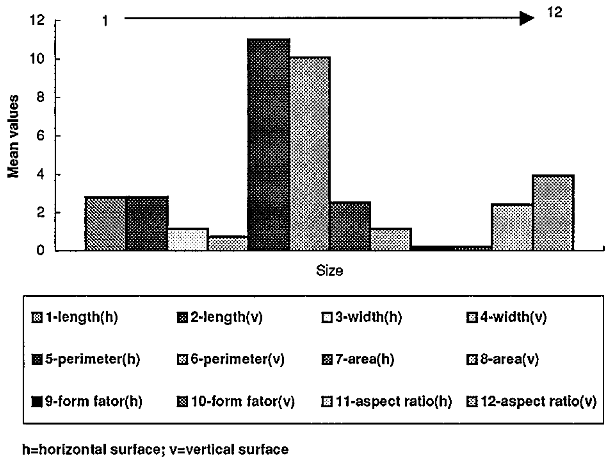

Figure 9 A comparison of size of wood chip on horizontal surface with that on vertical surface.

The mean values of the parameters measured are similar between layers. In horizontal surfaces, the length of the voids varies from 0.52 to 0.69 mm and from 0.23 to 0.29 mm for the width. The perimeter is always the same except for layer L2. As for the area of the void, it seems to be larger in layer L3, and both surface and core layers have a lower percent area of void. A one way ANOVA test determined that no significance existed between layers. This indicates that the detectable voids in CBPB are relatively randomly distributed.

A comparison of the mean values in the horizontal face with that in the vertical surface shows that the mean values of all parameters measured in the vertical surface were similar to those in the horizontal surfaces, Tables III and IV.

Wood chips. As for the size of voids, the variabilities in the sizes of wood chips within individual layers tested is significant, especially for the wood chips with areas ranging between 0–1 mm^2. Hence, for the same size class of wood chips, the mean values were different within the six layers. There was a tendency for the lower mean values to be in the surface and core layers. For the same class of wood chips, a one way ANOVA model determined that significant differences existed only for the perimeter of wood chips with an area of 0–1 mm^2, 1–2 mm^2 and 3–4 mm^2. There was no significance for all other parameters measured among

TABLE III Mean size and shape of pores and wood chips in six horizontal layers across the thickness of CBPB

Layer	Number of objects	Length (mm)		Breadth (mm)		Perimeter (mm)		Area (mm^2)		Form factor		Aspect ratio	
		Mean	COV(%)	Mean	COV(%)	Mean	COV (%)	Mean	COV(%)	Mean	COV(%)	Mean	COV(%)
						Void (0–1 mm^2 in area)							
L0	6	0.62	24.46	0.23	37.77	2.04	27.83	0.05	35.64	0.16	37.13	3.00	41.94
L2	47	0.52	31.87	0.27	31.84	1.75	40.23	0.06	57.75	0.30	47.17	2.01	33.33
L3	44	0.69	49.61	0.27	42.68	1.99	46.91	0.09	82.35	0.29	44.40	2.80	46.02
L4	29	0.57	38.83	0.29	36.85	1.95	58.80	0.07	80.50	0.26	41.13	2.06	30.85
L5	31	0.60	32.09	0.25	46.05	1.92	36.12	0.06	63.90	0.21	38.98	2.65	46.07
p*		>0.05		>0.05		>0.05		>0.05		>0.01		<0.01	
						Wood (0–1 mm^2 in area)							
L0	318	0.89	59.64	0.38	56.06	2.74	70.15	0.20	106.44	0.32	40.43	2.50	40.65
L1	303	0.85	57.17	0.40	55.09	2.59	62.08	0.21	104.60	0.37	37.64	2.28	37.74
L2	236	0.93	61.18	0.41	61.73	3.42	80.30	0.22	111.99	0.24	48.49	2.50	42.19
L3	271	0.92	55.62	0.37	55.42	3.03	59.82	0.17	110.25	0.23	56.58	2.64	41.37
L4	264	0.90	58.08	0.40	55.93	2.98	66.37	0.21	105.40	0.28	46.91	2.41	50.78
L5	351	0.87	63.05	0.39	58.52	2.79	72.47	0.20	115.07	0.32	45.63	2.38	45.67
p		>0.05		>0.05		<0.01		>0.05		<0.01		<0.01	
						Wood (1–2 mm^2 in area)							
L0	16	2.66	26.20	1.13	26.66	9.70	31.15	1.35	20.45	0.21	50.84	2.58	44.88
L1	20	2.63	32.01	1.02	23.59	8.19	24.91	1.35	18.92	0.28	37.64	2.81	49.24
L2	14	3.26	27.80	1.03	18.07	12.50	23.06	1.57	25.58	0.13	43.42	3.30	34.75
L3	5	3.06	33.42	0.91	30.14	9.42	29.23	1.49	25.02	0.23	45.22	3.58	41.90
L4	18	2.66	23.91	1.22	27.00	10.67	31.97	1.51	18.43	0.21	57.02	2.40	44.14
L5	21	2.76	26.20	1.08	23.47	9.10	28.46	1.46	20.40	0.25	41.38	2.77	44.75
p		>0.05		>0.05		<0.01		>0.05		<0.01		>0.05	
						Wood (2–3 mm^2 in area)							
L0	7	3.62	20.26	1.53	18.97	13.24	20.88	2.56	12.62	0.19	35.39	2.47	32.53
L1	4	3.92	17.92	1.46	16.84	14.52	15.46	2.37	14.87	0.15	31.10	2.75	25.05
L2	5	3.25	10.25	1.58	9.50	17.28	25.90	2.77	21.21	0.11	35.42	2.06	5.20
L3	5	3.84	32.92	1.41	28.43	14.54	39.43	2.52	11.38	0.18	53.59	3.12	63.20
L4	8	3.71	26.45	1.41	35.68	12.36	24.92	2.55	18.42	0.22	39.78	3.10	55.43
L5	8	3.74	27.91	1.52	35.61	16.85	41.77	2.59	11.95	0.15	54.83	2.87	51.16
p		>0.05		>0.05		>0.05		>0.05		>0.05		>0.05	
						Wood (3–4 mm^2 in area)							
L0	5	3.66	17.13	1.96	22.43	14.89	23.36	3.62	10.89	0.21	36.45	1.93	24.88
L1	4	3.97	32.93	1.57	23.44	14.87	22.46	3.52	11.46	0.22	34.89	2.85	65.90
L2	2	5.94	19.42	1.43	16.38	25.92	10.20	4.37	17.66	0.07	0.00	4.29	35.15
L3	3	3.78	13.32	1.64	3.98	12.83	9.76	3.22	7.29	0.25	18.35	2.31	15.82
L4	5	4.26	38.36	1.78	26.75	14.78	25.57	3.67	12.45	0.23	41.34	2.74	69.58
L5	3	3.91	6.98	1.77	26.93	14.68	23.73	3.72	13.48	0.22	41.67	2.30	22.61
p		>0.05		>0.05		<0.01		>0.05		>0.05		>0.05	
						Wood (>=4 mm^2 in area)							
L0	3	4.80	30.91	2.37	15.41	18.70	9.87	6.73	35.58	0.23	21.57	2.10	43.53
L1	4	5.94	32.26	2.86	22.59	28.30	39.55	7.73	53.80	0.13	37.16	2.12	32.84
L2	3	5.76	12.20	2.38	22.41	28.41	26.73	6.40	23.53	0.09	26.96	2.47	16.63
L3	6	5.90	13.95	2.31	43.81	23.01	30.95	7.36	60.70	0.16	37.86	2.86	32.96
L4	7	5.67	23.92	2.12	6.02	22.53	17.37	5.98	24.62	0.14	18.12	2.70	29.05
L5	6	6.80	29.51	2.61	38.83	26.56	37.63	10.70	76.52	0.19	46.32	2.75	25.47
p		>0.05		>0.05		>0.05		>0.05		>0.05		>0.05	

*Level of significance.

TABLE IV Values of size and shape of void and wood chips averaged over the three vertical surfaces

Object	Number of objects	Length (mm)		Breadth (mm)		Perimeter (mm)		Area (mm^2)		Form factor		Aspect ratio	
		Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
Pore0*	126	0.54	35.07	0.26	38.09	1.76	47.89	0.07	98.31	0.28	44.10	2.29	43.41
Darkwood0	29	1.00	62.74	0.42	49.68	4.04	80.19	0.19	137.54	0.21	50.59	2.37	34.77
Wood0	1444	1.13	66.25	0.33	56.20	2.99	71.39	0.21	103.70	0.31	48.09	3.59	47.82
Wood1	78	4.11	30.96	1.04	32.60	13.58	39.01	1.49	20.08	0.13	61.89	4.41	46.46
Wood2	16	5.74	32.78	1.36	22.81	20.16	36.24	2.59	12.46	0.11	81.56	4.41	39.17
Wood3	9	6.80	23.90	1.36	41.60	22.92	29.05	3.42	10.04	0.10	53.13	5.75	43.03
Wood>=4	4	8.16	14.32	2.32	40.76	48.50	20.08	6.35	17.52	0.03	29.46	4.04	43.98

*The number, 0, 1, 2, 3 and 4, after pore and wood = the area of 0–1, 1–2, 2–3, 3–4 and >= $4mm^2$ respectively.

the different layers. It should be noted that the results for the three vertical surfaces are very close, the ANOVA test confirming no significant differences.

In addition to the different sizes within the various layers, the percent area represented by the various size classes of wood chips change with layers due to different number of objects. A typical histogram (Fig. 8), produced to illustrate the distribution of the area of wood chips as a function of wood size for the six layers examined and a comparison of the values for the horizontal and vertical surfaces, shows that the percent area is fairly evenly distributed among the different layers for the size class 1–4 mm^2, with an exception of layers L3, which may be due to the wood being incorrectly detected as "dark wood," resulting in a high percent value of the area occupied by the dark wood. For the largest (≥ 5 mm^2) and smallest (0–1 mm^2) size of wood chips there were very marked differences of percent area occupied between the layers L0, L1, L2 and L3, L4, L5. This visually confirms the general concept that wood chip size gradually increases from the surface to core layer in graded density particleboard. The size class of 0–1 mm^2 comprised about 45% of the total area of 34% of wood chips in the horizontal surface for layer L0 compared to 35% of the total area of 49% of wood chips for the layer L5, while the size class of ≥ 5 mm^2 only occupied 14% for L0 compared to 32% for L5.

Size distribution of wood chips in the horizontal surfaces was very different from that in the vertical surfaces (Fig. 8), with the total area occupied by the size class 0–1 mm^2 being much higher and that by the size class ≥ 5 mm^2 being much lower in the vertical than in the horizontal surfaces. It is interesting that the mean length was very similar for the wood chips in the horizontal and vertical surfaces, while the breadth and perimeter are greater for chips in the horizontal surfaces than in the vertical surfaces (Fig. 9). These results agree with the general concept of the alignment of wood chips within CBPB.

Shape of components

The shape of components was characterized with respect to the form factor and aspect ratio. The form factor is a function of area to perimeter which allows objects to be classified by the degree of their roundness; a form factor of 1 represents a perfect circle, a form factor of 0 represents an infinitely thin object and 0.785 represents a square object. An object form factor is defined as the area of the object divided by the area of a circle having a diameter equal to the perimeter of the object divided by π, i.e.

$$\text{Formfactor} = \frac{4\pi\,\text{area}}{\text{perimeter}^2}$$

Another important factor is the aspect ratio:

$$\text{Aspectratio} = \frac{\text{length}}{\text{breadth}}$$

The form factor distinguishes the more angular shapes from those with smoother edges but appears insensitive to degree of elongation. The aspect ratio, however, distinguishes between the degree of elongation rather than indentations and angularity.

In Table III, the one way ANOVA statistical procedure was carried out to compare the average shape factors for the six layers. The results show that there were significant differences in the average shapes factors of voids among horizontal surfaces.

For wood chips, the degree of significance varied with the size class of wood chips. After an examination of a number of wood chips found in each horizontal surface, it can be concluded that there was a significant difference in the average shape factor of wood chips. The average form factors for both surface and core layers were greater than those for intermediate layer(s). For wood chips with an area of 0–1 mm^2, it was 0.32 for layers L0 and L5 compared to 0.23 and 0.24 for layers L3 and L2 respectively. Conversely for the aspect ratio, the higher values occurred in intermediate layers with lower values in the surface and core layers. The results indicate that relatively shorter and smoother edged wood chips were placed in the surface and core layers of CBPB.

A comparison of average form factors in the horizontal surfaces with those of the vertical surfaces shows that the form factors were similar between the two surfaces but the aspect ratios were very different (Table IV and Fig. 8). This illustrates that the shape of wood chips is long, wide and thin.

5. Conclusions

1) A technique for quantifying the structure of CBPB has been presented which has proved to be efficient and effective. Images of both vertical and horizontal surfaces were obtained and the structural parameters, including the distribution, size, shape and the percent area occupied by individual components, were quantified.

2) The percentage area occupied by voids was lower for surface and core layers than for intermediate layers. The total value of detectable voids was less than 1% of the total surface area for both the horizontal and vertical surfaces. However, the percentage area occupied by wood chips increased from surface to core layer (from 34 to 49%), except for layer L2. This result was in agreement with the mechanism of mat formation in the manufacture of CBPB.

3) The mean percent area occupied by wood chips was different between horizontal and vertical surfaces, being 5% higher for the vertical surface, suggesting a greater contribution to the change in thickness of CBPB compared to length. The mean percent area occupied by cement paste was higher in the horizontal surface than in the vertical surface.

4) Overall, the mean percent area occupied by wood chips is only about 40%, which is much lower than the volume fraction for raw materials in the manufacture of CBPB (about 75%). This indicated that the wood chips in CBPB are highly compressed. Obviously, the much higher change in the length of dissected chips discussed in previous paper of this series [7] was due to stress relief.

5) In the vertical surface, wood chips were nearly all flat. The distributions of orientation (separated into 18 classes) showed that an area of 36–45% of wood chips lie at an angle of 0–10° and 20–22% at an angle of 170–180° to the horizontal direction. The average orientation of wood chips, based on the area fraction of individual wood chips, was 10.7°, explaining the much higher change in thickness than in length or width of CBPB with changing moisture content. While in the horizontal surface, the wood chips were randomly distributed. The effective mean angle was about 44.7°, confirming that the effect of wood chip on the length and width change was the same.

6) The distribution of void size was fairly uniform, but the size of wood chips was different among the six horizontal layers and between horizontal and vertical layers. The percent area occupied by larger wood chips increased from surface to the core layer, with the most marked difference for the largest (≥ 5 mm^2) and smallest (0–1 mm^2) wood chips. The percent area occupied by the smallest wood chips was much higher, but that by the largest wood chips much lower, in the vertical compared with the horizontal surfaces. However, the mean length of wood chips for each size class was very close, but the width and perimeter are lower in the vertical surfaces for all corresponding size classes. This illustrated the placement of wood chip in CBPB.

7) The shape factors for wood chips were significantly different between the horizontal layers. The average form factors for both surface and core layers were greater than those for intermediate layer(s), and the inverse for the aspect ratio, indicating that relatively shorter and smoother (edged) wood chips were placed in the surface and core layers of CBPB. The fact that the mean form factors were similar but aspect ratios were much higher in vertical surfaces than in horizontal surfaces illustrated the feature of wood chips being long, wide and thin.

8) The findings of image analysis indicated that both sampling and view selection were representative and appropriate. The results numerically: -

i) confirmed the features of wood chips used in CBPB and determined the parameters of components to be in agreement with those theoretically controlled in the manufacture of CBPB;
ii) revealed the structure of CBPB which agrees with the general concept of the structure of particleboard and the distribution of wood chips;
iii) provided a basis of information for modelling the stress–strain behaviour of CBPB (to be carried out in subsequent investigations).

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