J Mater Sci (2006) 41:5666–5678
DOI 10.1007/s10853-006-0286-2

Nature and behaviour of cement bonded particleboard: structure, physical property and movement

Mizi Fan · Peter Bonfield · John Dinwoodie

Received: 27 June 2005 / Accepted: 13 October 2005 / Published online: 20 June 2006

Abstract The paper records work carried out to analyse the structure and determine the behaviour of cement bonded particleboard (CBPB). The structure was quantified with respect to the structural parameters (distribution, size, shape and occupied area) of and interaction between individual components (pore, wood particle and cement paste), and the movement was analysed with respect to the structure of CBPB and the nature of the cement paste and wood particles. The results showed that: (1) The volume of CBPB occupied by the detectable pores is less than 1%, the areas occupied by wood particles are about 42% and 38% in vertical and horizontal surfaces respectively, and those by cement paste about 58% and 62%. (2) Orientation, size and shape of wood particles are very different between across the thickness and along the transverse directions of CBPB. (3) Equilibrium moisture content (EMC) and density have been complicated by the penetration of cement paste into wood particles and interfacial region between wood and cement paste. (4) CBPB was unstable under both constant and changing environmental conditions: exposure to a constant environmental condition resulted in an increase in mass and decrease in dimensions. Under a single change in relative humidity, the changes both in mass and dimensions on both adsorption and desorption consisted of two distinct stages: a significant change in the early stage of exposure and a gradual change in the later stage. Cycling under changing environmental regimes resulted in corresponding changes in mass and dimensions, and both reversible and irreversible behaviour occurred, giving rise to a series of displaced hysteresis loops which are very dissimilar to those for other materials. (5) The movement of CBPB has been attributed to the combined effects of moisture reaction, carbonation and degradation of CBPB, and all of these parameters gave rise to the development of incompatible stresses, which aggravated the above effects. Both mass and dimensional changes were essentially Fickian and non-Fickian. Models have been developed and able to predict both mass and dimensional changes effectively and efficiently. (6) The change of CBPB also reflected the change of wood particles and cement paste, and the strain and sorption of the CBPB have been successfully quantified in terms of moduli and volume/mass concentration of the wood particles and cement paste (the rule of mixtures).

M. Fan (✉)
Department of Architecture and Civil Engineering,
University of Bath, BA2 7AY, Bath, UK
e-mail: m.fan@bath.ac.uk

P. Bonfield · J. Dinwoodie
Building Research Establishment, Watford, Hertfordshire
WD25 9XX, UK

Introduction

Since a product with smooth, fine-grained, cement enriched surface, characteristic of the present day cement bonded particleboard (CBPB) was first commercially produced in Switzerland in 1973, the potential of cement wood composites (CBPB) in building construction and refurbishment was quickly realised, and CBPB is today becoming significantly important in modern methods of construction (MMC) (i.e. SIPs = structurally insulated panels).

Over the years a considerable amount of research and development has been carried out. Research on CBPB falls conveniently into two aspects: the first relates to the compatibility between cement and the species of wood, much of the information obtained is subsequently used in monitoring the quality of manufacturing CBPB. The second aspect relates to the properties and performance of CBPB, and understanding the basic mechanisms underlying these performances. This leads naturally to the development of methods for the improvement of the strength and stabilisation of products.

Research into the structure and properties of cement and timber has been well recorded and it is well known that they can in some aspects be completely different [1–2]. A combination of cement and wood has given rise to further complexity of CBPB as a whole. The Building Research Establishment, UK (BRE) may have been the first institute interested in the structure and properties of CBPB over since 1973 when it was provided with a small sample of CBPB from the Durisol plant, at that time the only producer in the world. Since that time BRE has also carried out both short and long-term evaluation of a range of boards currently produced throughout the world. Information on the product derived from these evaluations was published as early as 1978 [3]. Following an extensive investigation recently, further series of papers have been published [4–9], and this paper summarises part of the most recent findings on structure and physical properties of CBPB.

Materials and methods

Wood cement composite panels were taken from a production line. Wood particles were dissected from the panels and cement paste was fabricated using the same production parameters as those for commercial manufacture of the wood cement panels. Experimental materials and procedure are summarised in Table 1. All test pieces were initially conditioned to equilibrium moisture content (EMC) at 20 °C and 65% relative humidity in a controlled environment.

Structure analysis of CBPB

Samples of CBPB were impregnated with resin to increase their rigidity and to fill any pores with an electron-opaque medium. After polished, backscattered electron images were made. The images then were processed, 'stretched' and rendered to a standard contrast range. These images were then analysed and classified as pore, pores inside wood chips and wood chips based on grey levels. Parameters for each object in each image were measured to an accuracy of two decimal points (e.g. 0.01 mm) and logged on a data file, and further processed, including area, feature length, feature breadth, orientation, perimeter, aspect ratio, form factor, filed area and class name. Five image fields of view were taken for each of nine different viewing surfaces and the mean values are calculated and expressed to two decimal points.

EMC and density measurement

Mass and dimensions of the test pieces were measured, with mass to an accuracy of 0.01 g and dimension to 0.01 mm. The moisture content (expressed to 0.01%) and density were then calculated in accordance with EN322 and EN323 [10–11]. Density profile was generated by using a RAYTEST-PROFILE which monitored the

Table 1 Experimental materials and procedures

Aspect of work	Material and size (mm)	Experiment	Measurement
Structure of CBPB	Layered CBPB: (i) Across thickness: six horizontal layers: L0–L5, Size: 100 × 100 × t (ii) Along transverse: three vertical layers: T1–T3, size: 5 × 50 × 18	SEM and image analysis	Microstructure, orientation and area occupied by components
EMC, density and density profile	CBPB: 50 × 50 × 18, cement paste: 50 × 14 × 5, Wood particles: 300 g	(i) EMC and density: Exposed to 35, 65 and 90%RH (ii) Density profile: Raytest-PROFILE	(i) Mass, volume (ii) Intensity of the radiation
Movement due to carbonation	CBPB: 600 × 300 × 18	(i) 65%RH normal air (ii) 65%RH air devoid of CO_2	Mass, length, thickness
Movement due to moisture sorption	CBPB: 600 × 300 × 18 individual wood chips: various sizes, cement paste: 140 × 14 × 5	(i) Single change in RH: 35 → 90%; 65 → 90%; 90 → 35% and 65 → 35% (ii) Cyclic RH: 90 → 65 → 35 → 65 → 90% (iii) Water ↔oven dry: water soak → 65%RH → oven dry → 65%RH → water soak	Mass, length, thickness
Modelling	Data from the above	(i) Fickian, non-Fickian (ii) The rule of mixtures	Mass, length, thickness

t = 18, 17, 15, 13, 11, 9 mm, with 0, 1, 3, 5, 7, 9 mm being planed off from the top surface of CBPB, respectively

RH = relative humidity

intensity of the radiation travelling through the test pieces. Three replicates were carried out.

Measurement of movement

The test pieces were conditioned and exposed in various exposure regimes (Table 1). The conditions of the exposing chambers were continuously monitored. The behaviour of the test pieces was recorded through the whole testing period. The mass was measured to 0.01 g, and length and thickness to 0.01 mm. The recorded changes in mass, length and thickness were converted into percentage values with respected to the originally conditioned values, expressed to 0.01%. All measurements were replicated three times and the mean values were used.

Results and discussion

Structure of CBPB

The details of scanning electron microscope (SEM) processing, image analysis and the test results for the structure of CBPB have already been recorded [6]. The grand summarised results are discussed below.

CBPB is comprised of cement paste, pores and wood particles. The structure of both cement paste and wood particles under the microscope is very complex (Fig. 1): Both microcrystalline and colloidal materials occur in cement paste, and pores in the cement paste include both gel pores and capillary pores. The structure of wood particles is comprised of cells, which for softwood, consist of both tracheids and parenchyma. Overall 90–95% of cells are aligned in the vertical axis (the tracheids), whilst the remaining percentage (the parenchyma) is present in transverse radial bands. The cells are hollow and the lumens (cell cavities) are interconnected by pores (pits) of different kinds. The interface between the cement paste and the wood particles of CBPB consists of a transition zone, which does not develop the dense microstructure typical of the bulk matrix. Generally, there is very close contact between the cement paste and the surface of the lumens of those open or fractured cells, where fracture has permitted easy access, or the actual surface of wood particles. Sufficient cement paste enters the fractured cell lumens after mixing. However, hydrated or unhydrated cement constituents cannot be observed in non-fractured cell lumen within the wood substrate. Those complete cells adjacent to the particle surface were generally deformed and nearly flattened. Performance of CBPB is complicated by the interfacial region.

Percentage area occupied by components

The percent area of a mat occupied by the components is an indication of the volume of wood particles, cement paste and pores in panel products. The percentage of components on the horizontal or vertical surfaces will characterise certain performance parameters of CBPB. Only recently, this investigation has been carried out, the results (mean values) are summarised in Table 2.

SEM and image analysis show that on average, about 42% area of the vertical surface is occupied by wood particles and 58% is occupied by cement paste, Table 2. The detectable pores, due to air embedded during manufacture, is less than 1%. On the horizontal surface, about 62% area

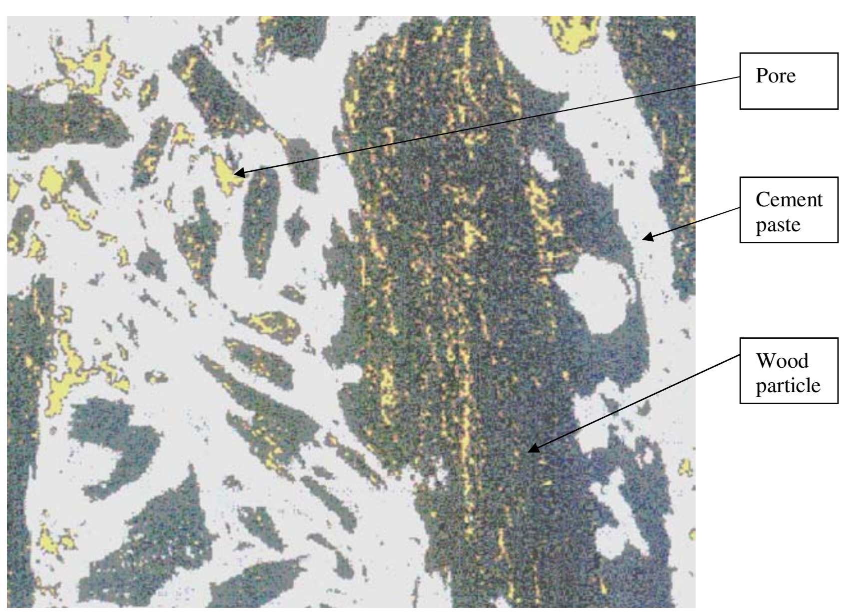


Fig. 1 Structure of wood–cement composite

Table 2 Mean area (%) occupied by components of CBPB on vertical and horizontal surfaces[a]

	T	L0	L1	L2	L3	L4	L5	*L* mean
Pore	0.63	0.07	0	0.72	0.93	0.51	0.45	0.45
Wood particle	41.76	34.27	34.93	29.53	39.25	40.71	49.26	37.99
Cement paste	57.61	65.66	65.07	69.75	59.82	58.78	50.29	61.56

[a] *T* = mean value observed on three vertical surfaces of CBPB panels, *L* = value observed on the horizontal surface of CBPB panels, 0–5 denote the layers from surface to the centre of the board across thickness, i.e. layers at 0, 1, 3, 5, 7, 9 mm to the top surface of CBPB, respectively

is occupied by cement paste and about 38% occupied by wood particles. Less than 1% area is occupied by pores.

However, the total percent area occupied by the three components is different between the different layers across the thickness of board. The area occupied by pores 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. The area occupied by wood particles increased from the surface layer to the core layer, with an exception of layer L2. About 34% of the area is occupied by wood particles 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.

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 particles. This greatly deviates from the proportions of raw materials used in the manufacture of CBPB (which is about 75% by volume of wood particles and 25% of cement paste). This means that the wood particles in CBPB are highly compressed, which could give rise to internal stresses within CBPB.

Orientation of components

The orientation of wood particles is a vital factor affecting the performance of CBPB due to the anisotropic nature of wood. SEM and image analysis show that as expected, almost all particles lie flat in CBPB, Fig. 2a, 48% of the total wood particles lie at an angle of 0–20°, 40% of them at an angle of 161–180° and only 6% of them at an angle of 31–150° with respect to the horizontal surface. It should be noted that the raw data for the orientation give the angle over a range of 2π radians. On the graphs this had been expressed in degrees over the range of 0–180°.

Unlike the orientation on the side faces, the wood particles are distributed randomly on the horizontal surfaces (Fig. 2b). In considering the effect of the orientation of wood particles on length and width directions, particles with the same complementary angle (effective angle) were taken together, then the mean angles (based on the fractional area for each particle) were calculated, with the effective mean angles for six layers ranging from 41 to 51° (L0 = 45.86°, L1 = 40.59°, L2 = 51.41°, L3 = 47.08°, L4 = 42.79°, L5 = 43.51°). The total mean angle is approximately 44.7°. This indicates that the effect of orientation of wood particle on the properties in the length and width directions is similar. On assumption that cement paste in CBPB is isotropic, CBPB products would have 2D uniform characteristics (Transverse).

Size of components

It was found that the size of components varies considerably from one place to another within board. The length and width of pores measured in the horizontal surfaces range from 0.52 to 0.69 mm and from 0.23 to 0.29 mm, respectively, with larger in layer L3 and smaller in both surface and core layers.

Wood particles measured on the horizontal surfaces showed that the percent area occupied is fairly evenly distributed among the different layers for the size class 1–4 mm^2. However, for the largest (≥4 mm^2) and smallest (0–1 mm^2) size of wood particles there were very marked

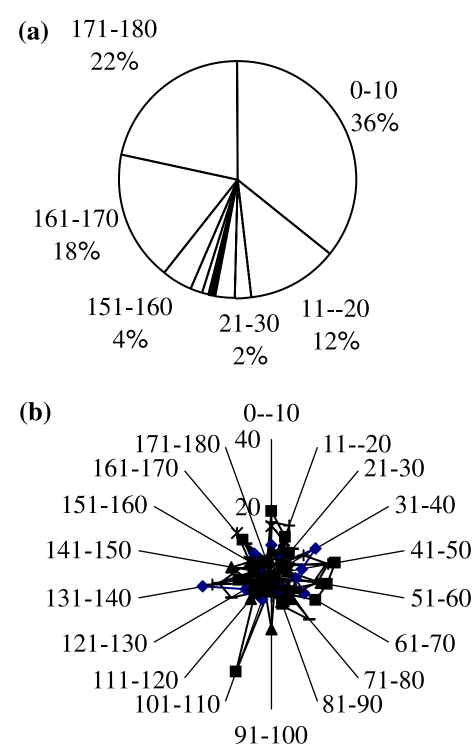


Fig. 2 Area occupied by wood chips having various orientations

differences of percent area occupied between the layers L0, L1, L2 and L3, L4, L5. The size class of 0–1 mm^2 comprised about 45% of the total area of 34% (Table 2) of wood particles in the horizontal surface for layer L0 compared to 35% of the total area of 49% of wood particles for the layer L5, while the size class of ≥4 mm^2 only occupied 14% for L0 compared to 32% for L5. This visually confirms the general concept that wood particle size gradually increases from the surface to core layer in CBPB.

It is interesting that the total area occupied by smaller size class of wood particles (i.e. 0–2 mm^2) is much higher observed from the vertical surface than horizontal surface, while that occupied by larger size of wood particles (i.e. >2 mm^2) is much lower observed from the vertical surface than horizontal surface (Table 3). The mean length was very similar for the wood particles in the horizontal and vertical surfaces, while the breadth is much greater for particles in the horizontal surfaces than in the vertical surfaces. These results agree with the general concept of the alignment of wood particles within CBPB.

Note that the size of wood particles prior to mixing with cement is: thickness × width × length = 0.35 × 1.61 × 35 mm, wood particles have further been broken down during CBPB production (Table 3). The breadth measured included both thickness and width directions of wood particles in CBPB products.

Equilibrium moisture content (EMC) of CBPB

CBPB is a combination of wood particles and cement paste. The structure is complicated by the penetration of cement paste into cell wall and lumens, and interfacial region. The EMC may not be equal to an arithmetical sum of cement paste and wood particles. To determine the EMC of CBPB, both CBPB and its components were exposed to various conditions and their EMCs were measured. The summarised results are given in Table 4.

Note that the CBPB tested consists of 68% cement and 32% wood particles by weight, it can be found that the EMCs of CBPB is lower than the weighted arithmetical sums of wood particles and cement paste under both 35% and 65% relative humidity, while higher under 90% relative humidity (Table 4). This means that both the penetration of cement paste into wood particles and the interfacial region have given rise to an unique characteristic of water sorption for CBPB, and the cement paste and wood particles within CBPB may have played different roles in EMCs of CBPB under different relative humidity.

Density and density profile of CBPB

As the EMC of CBPB, density of CBPB is complicated by the interfacial region between cement paste and wood particles, the mean density is not equal to the calculated arithmetical sum of the densities of the components (Table 5). The density of CBPB lies between that of cement paste and wood particles. The fact of the lower densities of CBPB than the arithmetical sums of those of the cement paste and wood particles under both 65% and 90% relative humidity reflects an influence of the penetration of cement paste into wood particles.

Across the thickness of board, CBPB has high face densities and low core densities, Fig. 3. However, although this profile coincides with the density profile of other particleboard, the resulting properties are very unlikely to be the same. Unlike the other particleboards, in which the layering effect is caused by the distribution of the particle size, resin, moisture, and especially by the parameters applied during hot pressing, the layer densities of CBPB are thought mostly to be controlled by the parameters in mat forming, producing a significant gradient of cement and wood particle content from face to core of CBPB, i.e. the fine particles (most of cement) are laid on the top or bottom faces with the coarse particles (most of wood particles) on the deeper layers. Such high percentage of cement paste on both faces makes up the higher density of face layers while the higher percentage of wood particles in the core makes up the lower density in the core layer.

Table 3 Parameter of wood particles in horizontal and vertical surfaces (mean)

Wood area (mm^2)	Area occupied (%)		Length (mm)		Breadth (mm)		Perimeter (mm)	
	H[a]	V	H	V	H	V	H	V
0–1	37.78	57.19	0.89	1.13	0.39	0.33	2.93	2.99
1–2	14.63	22.81	2.84	4.11	1.07	1.04	9.93	13.58
2–3	10.11	7.95	3.68	5.74	1.48	1.36	14.80	20.16
3–4	8.67	5.91	4.25	6.80	1.69	1.36	16.33	22.92
>4	22.53	4.77	5.81	8.16	2.44	2.32	24.58	48.50
Mean	–	–	2.80	2.83	1.15	0.73	11.01	10.08

[a]H = horizontal layers; V = vertical layers

Table 4 EMC of CBPB and its components (%)

Regime[a]	CBPB	Arithmetical sum	Cement paste	Wood particle
20°C/35% RH	4.24	5.33	3.83	8.53
20°C/65% RH	8.10	8.19	5.27	14.39
20°C/90% RH	12.68	11.30	7.40	19.59

[a]RH = relative humidity

Table 5 Density of CBPB and its components (kg/m^3)

Regime[a]	CBPB	Arithmetical sum	Cement paste	Wood particle
20 °C/35% RH	1342	1145	1507	377
20 °C/65% RH	1366	1455	1956	391
20 °C/90% RH	1430	1580	2123	425

[a]RH, relative humidity

Mass change of CBPB

Under a constant environmental condition

The implication of the results of a comprehensive study on both mass and dimensional changes of CBPB under various service conditions [6] is that even under constant relative humidity, CBPB undergoes mass change and dimensional movement (Section ''Dimensional change of CBPB) and even normal air has a significant effect on the behaviour of CBPB. The explanation of the pronounced effect of normal air on the mass change of CBPB can be discussed primarily in terms of chemical activity of calcium hydroxide in the boards. Very dilute carbonic acid, resulting from the low concentration of carbon dioxide in the atmosphere, can significantly attack most of the components of the hardened cement paste in CBPB: $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$. Thus water is released and there is an increase in mass of the CBPB (Fig. 4a). It should be noted that the further hydration of cement paste in CBPB may also have a subtle effect on mass change of CBPB. However, the effect of a hydrated cement paste on the wood particles would probably bring about the mass decrease of CBPB in contrast to an increase in mass if the alkali soluble products were removed.

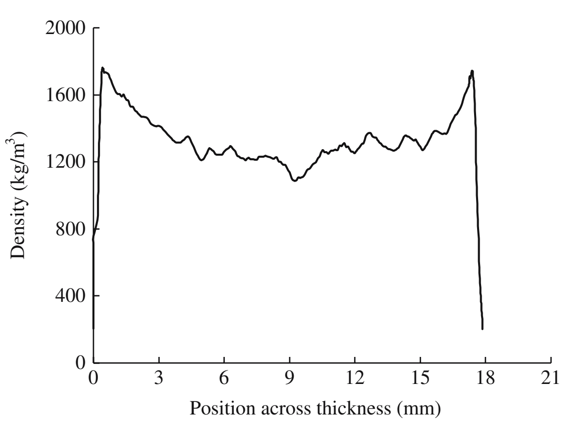


Fig. 3 Density profile of CBPB

Under a single change in relative humidity

The changes in mass of the CBPB under a single change in relative humidity are obviously not of the type usually observed in wood or other particleboard, Fig. 4b. Rather these changes comprise not only substantial change in the early stages, but also a consistent change at the later stages of exposure. The substantial change in the early stage of exposure is dominated by the moisture sorption, and a consistent change at the later stage of exposure is due possibly to condensation, whereby the number of ''mini pores'' which exist in the cement paste could be filled with water due to the high surrounding relative humidity, or carbonation which, as in parallel with that occurring under constant relative humidity, could contribute an increase in the mass of the CBPB.

Under successive cycles between 35% and 90% relative humidity

Most interesting results were obtained from a set of cycles. With increasing number of cycles, there was an accumulated increase in mass, Fig. 4c. This means that the CBPB in service is getting heavier with time. This is very important finding and should be taken into account for structure design of the material. It should be noted that the values are expressed in terms of the original values at 90% relative humidity. Total recovery did not take place during cyclic relative humidity; the degree of irrecovery was very high in the first cycle, but decreased over successive cycles. Reversible behaviour is well known in terms of wood and cement paste, and the mechanisms of these have been well interpreted [12–13]. Irreversible behaviour of CBPB has been related, first, to

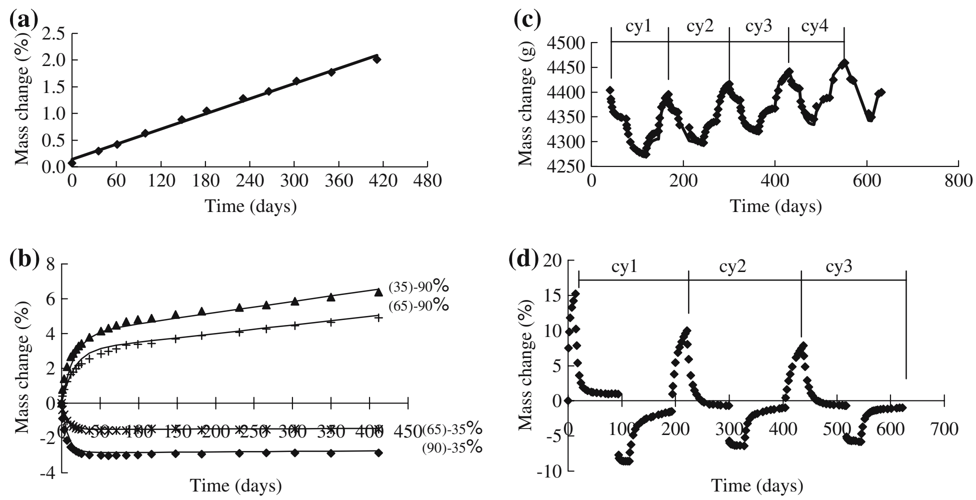


Fig. 4 Experimental (dot) and fitted curves (solid line) of mass change

the carbonation of cement paste in the CBPB which not only increased the mass of the cement paste, but was also accompanied by irreversible carbonation shrinkage, and, second, to the alkali degradation of the wood particles which resulted in mass loss and a consequent volumetric decrease (Section ''Results and discussion'').

Under water soaking and oven drying

Figure 4d shows the change in mass of CBPB cycling in water soaking-65% relative humidity-oven drying. Not only occurred a marked increase in mass of CBPB under water soaking, but also a consistent increase in mass even after the dimension reached equilibrium (Fig. 5d). This indicates that the water probably was firstly absorbed by the wood cell wall and the gel pores of cement paste, and above the fiber saturation point of the wood particles, moisture increase will not bring about dimensional change. Hence, at this time the location of water in the cement paste is mostly in the capillary pores; this in turn results in less expansion compared to the removal of gel pore water.

Oven drying resulted in rapid decrease in mass initially, but thereafter slowing down rapidly to an almost constant level. Free water was firstly released, this water being present in the cell lumens of wood particles or some large cavities in the cement paste and the interfacial area. This results in a considerable mass decrease. Drying absorbed or bound water from CBPB at the later stage of oven drying only brought about a slight change in the mass of CBPB, Fig. 4d. The process of movement of free water out of CBPB may continue for a certain period depending on the thickness and density of the CBPB, receding further from the surface into the centre of the CBPB. However, at the beginning of the exposure period the absorbed or bound water near the surface of the CBPB starts evaporating.

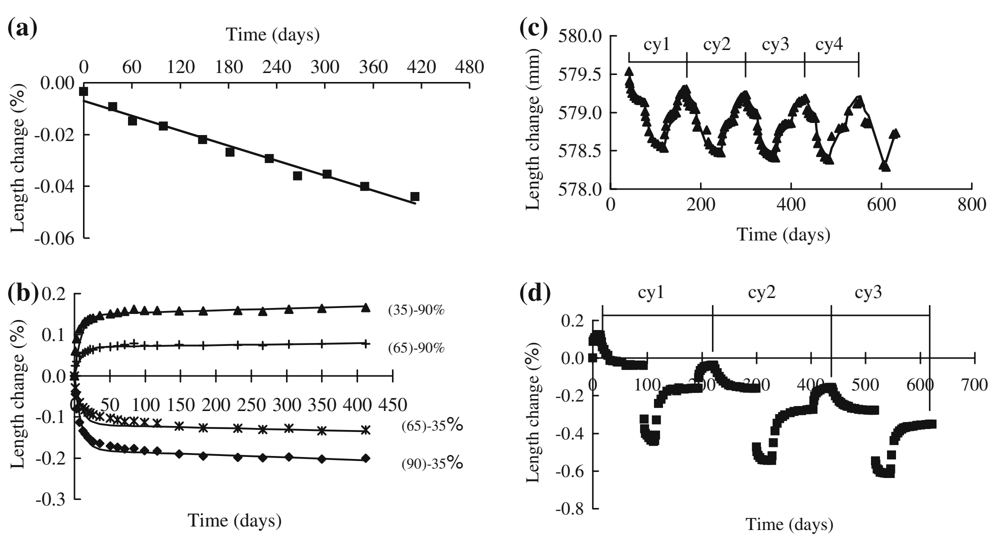
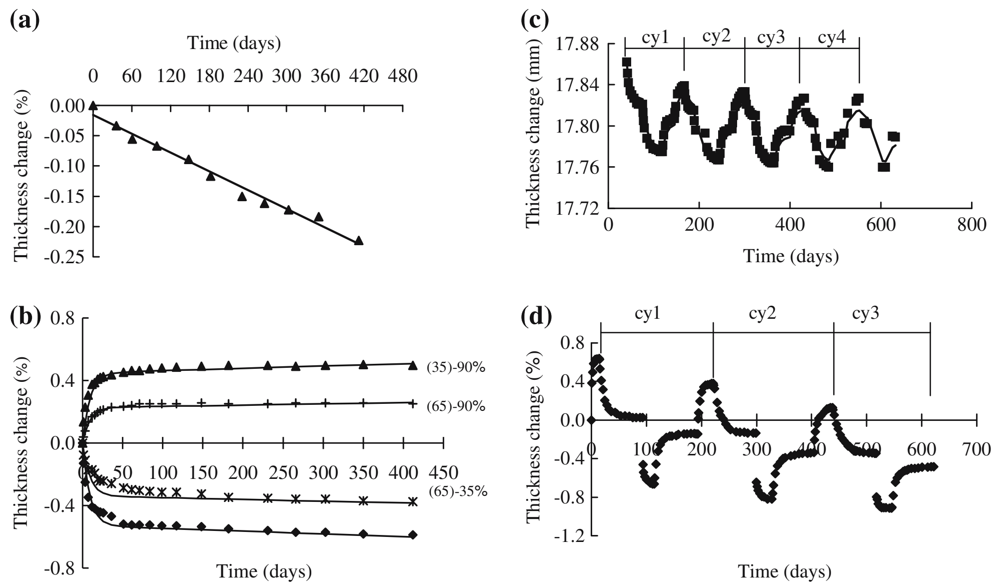


Fig. 5 Experimental (dot) and fitted curves (solid line) of length change

Fig. 6 Experimental (dot) and fitted curves (solid line) of thickness change



Dimensional change of CBPB

Under constant environmental conditions

Compared to the increase in the mass of CBPB under constant environmental condition, the mechanisms of changes in the dimensions of CBPB are more complex (Figs. 5a and 6a). The decrease in the dimensions is attributable to several factors. Movement of the particles in CBPB, possibly due to the high alkalinity present as mentioned above, resulted in the movement of CBPB. When considerable quantities of the hemicelluloses and some of lignin are dissolved, the soluble substances may migrate from the CBPB and if the stiffness of the particles is not enough to withstand the internal stresses which normally exist in materials, substantial changes will take place in the structure of CBPB.

Irreversible shrinkage of cement paste also occurs as a result of the dissolution of the calcium hydroxide crystals from the more highly stressed regions, temporarily increasing stress in the remaining solid part of the paste and resulting in a corresponding volumetric decrease. As $CaCO_3$ crystallizes out in the pores, so a reduction in this restraint occurs. Thus, there is a progressive decrease in dimensions with increase in exposure period.

Thirdly, when cement paste shrinks, incompatible strains probably appear and produce residual stresses. These stresses are of long duration, and consequently result in the creep of material elements, which could be reflected in further dimensional decrease of CBPB.

Under a single change in relative humidity

As mass change, dimensional changes comprise not only substantial movement in the early stages, but also a consistent change at the later stages of exposure, Figs. 5b and 6b. These results confirm that the physical properties of CBPB are closely related to the combined properties of both wood particles and cement paste. The dimensional change of CBPB was due primarily to the interaction between the movement of moisture into or out of the wood particles, the cement paste, and the solid skeletal structure of the material. Internal volumetric stress varied in sympathy with the changes in moisture state, consequently causing volume change. A significant movement of the wood particles, resulting from the moisture change, could induce a simultaneous deformation in the CBPB at the early stages of exposure.

While the cement paste shrank or swelled around the wood particles to a much higher degree, compensating either tensile (in the cement paste) and compressive (in the wood particles) or compressive (in the cement paste) and tensile (in the wood particles) stresses are generated. This results in the overall volumetric strain of CBPB lying between that of the cement paste and the wood particles [6].

As in parallel with that occurring under constant relative humidity, carbonation of CBPB could contribute a reduction in the dimension of the CBPB.

Under successive cycles between 35% and 90% relative humidity

By contrast to mass change, with increasing number of cycles, there was an accumulated decrease in dimensions of CBPB under sets of relative humidity cycles, Figs. 5c and 6c. As discussed before, irreversible shrinkage of CBPB has been related, first, to the carbonation of cement paste in the CBPB, which was accompanied by irreversible carbonation shrinkage, and, second, to the alkali degradation of the wood particles, which resulted in mass loss and a consequent volumetric decrease. Another significant factor in determining irreversible change is the restraint (stress) each other (between the cement paste and the wood particles). There are, at least, two types of stress (and resulting strains) in CBPB subjected to cyclic relative humidity, one of which results from moisture gradients and the other from the different chemical composition and anatomical structure of the cement paste and the wood particles [6].

The thickness change arising from a set of cycles followed the trend of length change of CBPB. However, the degree of the changes at various stages of the relative humidity cycle was different. This difference is related to the structure of CBPB [6]. Additionally, the moisture gradients due to the cyclic relative humidity changes may bring about an adverse effect on the different change between thickness and length (or width).

Under water soaking and oven drying

Unlike mass change, the dimensional changes of CBPB under water soaking reached constant after about 2 weeks. Water entered the cell lumens of wood particles or some large cavities in the cement paste and the interfacial region may not bring about dimensional change. Oven drying resulted in rapid decrease in the dimension of CBPB due to the removal of mainly absorbed or bound water. However, as mass change, the magnitude of dimensional change decreased with the number of cycles increased, suggesting a structural change during soaking and drying CBPB (Figs. 5d and 6d).

Comparison of values in thickness change with those in length change indicates the significant effects of stresses generated by moisture gradient, the difference in structure along length and thickness directions, and the different nature of wood particles and cement paste.

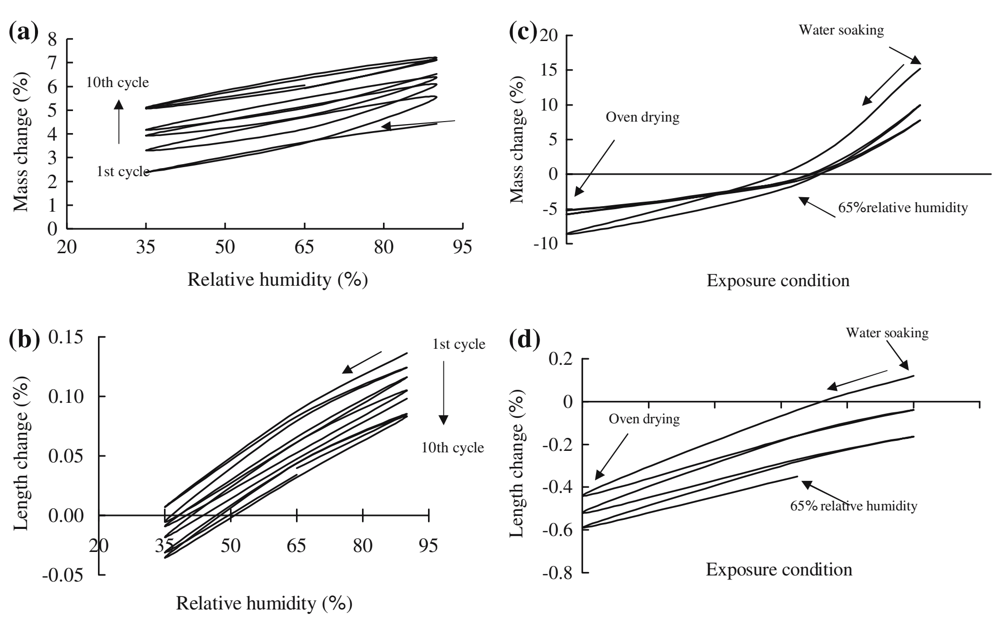
Sorption and dimensional change isotherms (hysteresis loops)

Like other porous materials, there existed hysteresis loops for both mass and dimension change of CBPB, Fig. 7. However, the hysteresis loop of CBPB is not of the type usually found for other materials: the maximum width of the hysteresis loop does not occur in the middle stage, but could be located anywhere depending on the changing range of exposing conditions. When cycling in 35–90% relative humidity, there exists an intersection between the adsorption and desorption curves of mass change which lies between 65% and 90% relative humidity, and moves nearer the point of 90% relative humidity with increasing number of cycles, Fig. 7a. In other words the loops do not close at the top relative humidity, but the intersection divides the loops into two parts, one closed and the other open. In contrast, in the hysteresis loops arising from the length changes, Fig. 7b, the adsorption curves are not able to reach the desorption curves within one complete cycle, forming an open loop.

In the hysteresis loops arising from both mass and length change of CBPB cycling in oven drying and water soaking, Fig. 7c and d, the adsorption curves are not able to reach the desorption curves after completing individual cycles, forming open loops for both mass and dimensional changes.

Unlike those of other materials, as the number of cycle increases, the hysteresis loop for mass change moved upward. The vertical movement of the loop clearly indicates

Fig. 7 Sorption isotherm for mass and length change



an appreciable increase in mass, which suggests that the mass of CBPB increased with each successive cycle. In contrast to mass change, as the number of cycles increased, the hysteresis loop for length moved lower and length gradually decreased. Thus, the degree of movement of each loop for both mass and length was reduced with increasing number of cycles [6]. It should be noted that all loops arising from thickness change are similar to the corresponding loops arising from length change. The implication behind the results is in particular of importance in practice: the self-weight of the materials in situ may be increasing and the joints between panels enlarging with the duration of service increases.

Behaviour prediction (numerical modelling)

Consequent upon understanding the structure and movement of CBPB, it is possible to model individual change and hence to predict its behaviour, and much effort has been put into this [6].

Fickian and non-Fictian processes

Sorption of CBPB has been found to be governed both by Fickian and non-Fickian processes. Under constant environmental condition, the changes have been thought to be due most likely to carbonation. Under both single change in and cyclic relative humidity, the change is dominated by both carbonation and moisture reaction. Fractional change of CBPB = Fickian part of the fractional change + non-Fickian part of fractional change. The mathematical models for these changes under various exposures have been developed. The details are given in previous publication [6]. The results can be summarised:

Under constant environmental condition,

$$\Delta M_{cp} = A_{m0}t^2 + B_{m0}t + C_{m0} \tag{1}$$

$$\Delta L_{cp} = A_{l0} + B_{l0}t + C_{l0} \tag{2}$$

$$\Delta T_{cp} = A_{t0}t^2 + B_{t0}t + C_{t0} \tag{3}$$

Under single change in or cyclic relative humidity,

$$\Delta M_{cp} = 100\left(\frac{M_f}{M_i} - 1\right)E_m \tag{4}$$

$$\Delta L_{cp} = 100\left(\frac{L_f}{L_i} - 1\right)E_d \tag{5}$$

$$\Delta T_{cp} = 100\left(\frac{T_f}{T_i} - 1\right)E_d \tag{6}$$

$$E_m = A_{m1} + B_{m1} - A_{m1}\exp(C_{m1}t) \tag{7}$$

$$E_d = A_{d1} + B_{d1}t - A_{d1}\exp(C_{d1}t) \tag{8}$$

Let $A_{m1} = A_2 + A_3$, then the term ''$A_2 - A_{m1}\exp(C_{m1}t)$'' is related to the Fickian effect, and the term ''$A_3 + B_{m1}t$'' represents the main non-Fickian effect. It should be noted that both mass and dimensional changes of CBPB under constant environmental condition were approximately linear, the part A_xt^2 in the Eqs. (1), (2) and (3) was negligible for theoretical consideration of modelling the changes under single change in and cyclic relative humidity [6], also see the Figs. 4a, 5a and 6a.

where E_d = fractional change in dimensions of CBPB over various relative humidity,
E_m = fractional change in the mass of CBPB over various relative humidity,
ΔL_{cp} = length change of CBPB,
L_f = final length of CBPB,
L_i = initial length of CBPB,
M_f = final mass of CBPB,
M_i = initial mass of CBPB,
ΔM_{cp} = mass change of CBPB,
t = duration of exposure,
ΔT_{cp} = thickness change of CBPB,
T_f = final thickness of CBPB,
T_i = initial thickness of CBPB,
A_x, B_x, and C_x = coefficients related to the feature of materials and environmental conditions.

Modelled curves for the changes under constant relative humidity are given in Figs. 4a, 5a and 6a (solid lines), those under a single change in relative humidity are given in Figs. 4b, 5b and 6b (solid lines). The coefficients and R^2 are given in Table 6. Using Eqs. 4–8 in conjunction with time constraint under cyclic regimes, the modelled curves for the changes under cyclic relative humidity can be plotted (Figs. 4c, 5c and 6c) (solid lines). Details can be found in previous papers [6]. Comparisons of the experimentally determined values (dots) with those produced using equations developed show an excellent correlation and these have verified that

(1) the behaviour of CBPB complies with the theory described (essentially Fickian and non-Fickian);
(2) the proposed models for both mass and dimensions are appropriate;
(3) condensation under high relative humidity did not affect the fractional change in dimension; the frac-

Table 6 R^2 and coefficients of model (20 °C)[a]

Change in	Regime (% RH)	F/I	A	B	C	R^2
$Y = At^2 + Bt + C$						
M	65	–	-3×0^{-6}	6×10^{-3}	0.08	1.00
L	65	–	1×10^{-7}	-1×10^{-4}	–0.01	0.99
T	65	–	4×10^{-7}	-7×10^{-4}	–0.01	0.99
$Y = (F/I - 1)(A + Bt - A\exp(Ct)$						
M	90 → 35	0.97	1.00	-1×10^{-4}	–0.13	0.97
	35 → 90	1.06	0.62	1×10^{-3}	–0.06	0.99
	65 → 35	0.99	1.00	-1×10^{-4}	–0.13	0.99
	65 → 90	1.05	0.62	1×10^{-3}	–0.06	0.99
L	90 → 35	1.00	0.90	3×10^{-4}	–0.11	0.97
	35 → 90	1.00				0.94
	65 → 35	1.00				0.94
	65 → 90	1.00				0.96
T	90 → 35	0.99				0.97
	35 → 90	1.01				0.97
	65 → 35	1.00				0.94
	65 → 90	1.00				0.99

[a] $F/I = M_f/M_i$, L_f/L_i or T_f/T_i

M = mass, L = length, T = thickness

tional changes in dimensions were very similar over various changes in relative humidity;

(4) the mass change of CBPB on adsorption under high relative humidity should be considered separately [6].

Rule of mixtures

By using the theory of mixtures, the strain and sorption of the CBPB can also be successfully quantified in terms of their moduli and volume/mass concentration of the wood particles and cement paste. The details are given in previous publication [6]. That is, the change in mass during sorption can be expressed as:

$$\Delta M_{\mathrm{cpj}} = \Delta M_{\mathrm{pj}} m_{\mathrm{pf}} + \Delta M_{\mathrm{wj}} m_{\mathrm{wf}} \tag{9}$$

and the changes of length and thickness of CBPB are expressed as:

$$\Delta L(T)_{\mathrm{cp}\alpha} = [V_{\mathrm{pf}} e_{\mathrm{p}} \Delta L(T)_{\mathrm{p}} + V_{\mathrm{wf}} \sigma_{\mathrm{w}\alpha}] \left[\frac{1 - \sqrt{V_{\mathrm{wf}}}}{e_{\mathrm{p}}} + \frac{1}{\left(\frac{1}{\sqrt{V_{\mathrm{wf}}}} - 1 \right) e_{\mathrm{p}} + e_{\mathrm{w}\alpha}} \right] \tag{10}$$

where ΔM_{cpj} = mass change of CBPB at the various conditions tested; ΔM_{pj} = mass change of cement paste at corresponding conditions; ΔM_{wj} = mass change of wood particles at corresponding conditions; m_{pf} = mass fraction of cement paste in unit mass of CBPB; m_{wf} = mass fraction of wood particles in unit mass of CBPB; $\Delta L(T)_{\mathrm{cp}\alpha}$ = length or thickness changes of CBPB; $\Delta L(T)_{\mathrm{p}}$ = length or thickness changes of cement paste at corresponding conditions; V_{pf} = volume fraction of cement paste in unit mass of CBPB; V_{wf} = volume fraction of wood particles in unit mass of CBPB; e_{p} = modulus of elasticity of cement paste; $e_{\mathrm{w}\alpha}$ = modulus of elasticity of wood particles at three principal directions of CBPB; $\sigma_{\mathrm{w}\alpha}$ = stress in the wood particles at three principal directions of CBPB.

An example of the numerical results is presented in Fig. 8. The close agreement between the experimentally determined (dots) and theoretically predicted values (solid lines) further confirms the capability of the proposed models for modelling CBPB as a composite of two materials. It should be noted that the performance of CBPB is a function not only of the content but also the structure of CBPB. Thus, the behaviour of the product can be controlled not only by the percentage of components, but also by the placement of the wood particles. Therefore, $e_{\mathrm{w}\alpha}$ and $\sigma_{\mathrm{w}\alpha}$ should be calculated by transforming the stress or strains from the rotated to the principal axes [6]. In employing the values for the constituents, overlapping changes of phenomena should also be considered, such as, the condensation on the embedded cement paste in the wood particles at high relative humidity or the stress relief of wood particles dissected from CBPB due to high compression within the CBPB [6].

Conclusions

(1) A technique for effectively quantifying the structure of CBPB has been developed. The structural parameters, including the distribution, size and shape of, and the percent area occupied by individual components were successfully quantified through the images analysis of both vertical and horizontal layers: Image analysis numerically confirmed the features of wood

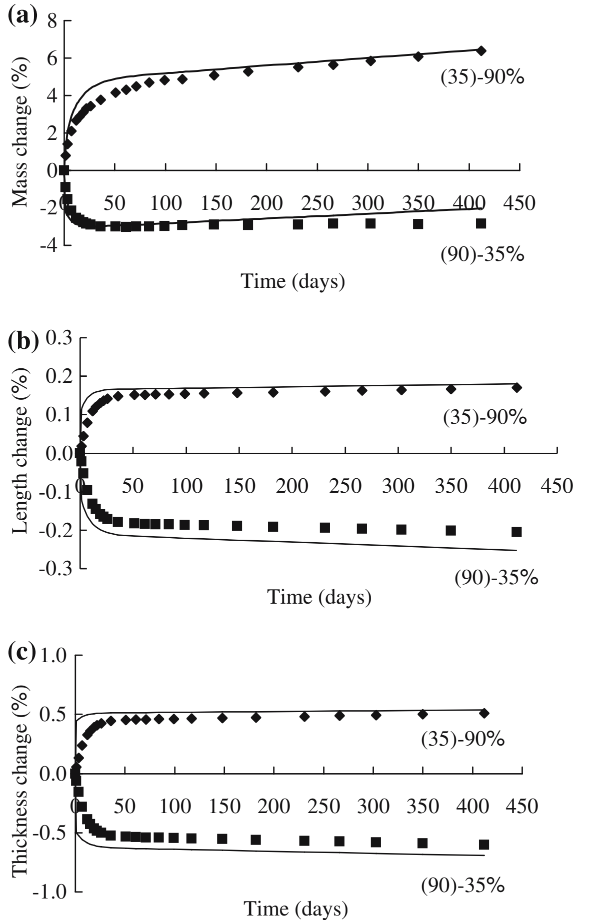


Fig. 8 Modelled (solid line) and experimental (dot) change in mass, length and thickness

particles used in CBPB and determined the parameters of components to be in agreement with those theoretically controlled in the manufacture of CBPB, and this has provided a basis of information for modelling the stress–strain behaviour of CBPB.

(2) Both EMCs and density of CBPB lay between those of the cement paste and wood particles. However, the values were not equal to the arithmetical sum of the components, suggesting an influence of the penetration of cement paste into wood particles and interfacial region between wood particles and cement paste.

(3) The shape of the density profile for CBPB was similar to that of other wood particleboard, however, it was due to different percentages of cement paste and wood particles across the thickness of CBPB rather than hot pressing parameters.

(4) CBPB was unstable under constant and changing relative humidity. Exposure of CBPB to a constant environmental condition resulted in consistent mass increase and dimensional decrease indicative of chemical or physical change in the CBPB. The change in mass and dimensions of CBPB relative to the change in relative humidity were different to those of other materials, rather it consisted of two distinct stages: a significant change at the early stage and a gradual change in the later stage, highlighting the existence of two dominant mechanisms, a general moisture reaction and a carbonation or condensation reaction. The changes in the mass and dimensions of CBPB reflected the changes in relative humidity during cycles.

(5) Both reversible and irreversible behaviour occurred in CBPB subjected to cyclic environmental conditions, giving rise to a series of displaced hysteresis loops for both mass and dimensions which were very disimilar to those for other materials. All hysteresis loops were incomplete in one complete cycle. There was an accumulated increase in mass and decrease in dimensions under a set of successive cycles. The hysteresis loops for mass change moved upward and those for dimensions moved downward. The shape and area of these loops changed with the number of cycles.

(6) Movement of CBPB can be attributed to the combined effects of moisture reaction, carbonation and degradation under changing relative humidity (carbonation and degradation under constant relative humidity). Both mass and dimensional changes have successfully been modelled. These models contained both Fickian and non-Fickian components. The former was controlled mainly by moisture sorption while the latter was affected mainly by carbonation or moisture condensation in the CBPB. The numerical tests demonstrated the excellent agreement of the predictions of the theory with the experimental data.

(7) The physical properties of CBPB are closely related to the properties of both the wood particles and the cement paste. The theory of mixtures can well be brought to bear on the constitutive behaviour of CBPB. The strain and sorption of the CBPB have been successfully quantified in terms of their moduli and volume or mass concentration of the wood particles and cement paste.

References

1. Powers TC, Brownyard TL (1948) Studies of the physical properties of hardened Portland cement paste, Res. Lab. Portland Cement Assoc. Chicago
2. Kollmann FP, Cote WA (1968) Principles of wood science and technology, Springer-Verlag, Berlin
3. Dinwoodie JM (1978) Wood cement particleboard, Building Res. Estab. Info. Sheet 2/78

4. Dinwoodie JM, Paxton BH (1988) In: Moslemi (ed) Inorganic-bonded wood and fibre composite materials, vol. 1 University of Idaho, pp 115–124
5. Fan MZ, Dinwoodie JM, Bonfield PW, Breese MC (1998) In: Moslemi A (ed) Inorganic-bonded wood and fibre composite materials, vol. 5, University of Idaho, 103 pp
6. Fan MZ (1997) Doctorate thesis, University of Wales
7. Fan MZ, Dinwoodie JM, Bonfield PW, Breese MC (1999) J Mater Sci 34:1729
8. Fan MZ, Dinwoodie JM, Bonfield PW, Breese MC (1999) Wood and Fibre Sci 33:306
9. Fan MZ, Dinwoodie JM, Bonfield PW, Breese MC (1999) Cement Concrete Res 29:923
10. EN322 (1992) Determination of moisture content. BSI, London
11. EN323 (1993) Determination of density. BSI, London
12. Scaar C (1988) Wood-water relation. Syracuse University Press, New York
13. Soroka I (1979) Portland cement paste and concrete. The Macmillan Press Ltd.102 pp