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Dimensional instability of cement bonded particleboard: stabilisation treatments

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Abstract As part of an extensive programme of research aimed at a better understanding of the dimensional instability of cement bonded particleboard (CBPB) and establishing methods of improving its stability, this paper discusses the treatment processes for stabilisation of CBPB. CBPB as a composite of wood chips and reacted Portland cement is unstable in service. One solution to this deficiency is to treat the CBPB product to reduce its magnitude. Three treatment processes, namely, storage of, pre-drying and application of surface coatings on CBPB, were investigated. The results indicated that all three treatments were able to reduce both dimensional and mass change of CBPB, but the efficacy of the treatments was closely related to their schedules. Prolonged storage resulted in a stabilisation of CBPB due to further hydration and carbonation of CBPB. Mass change of CBPB with 12 month storage was only about 2/3–3/4 that with 2 month storage under changing relative humidity (RH). A pre-drying process resulted in a structure alternation of CBPB and stabilised it permanently. A considerably irreversible mass decrease and dimensional shrinkage occurred when re-wetting at 65%RH: about 0.7% and 3% for mass, 0.02% and 0.12% for length, and 0.08% and 0.19% for thickness, respectively for 35%RH and 105°C pre-drying CBPB. However, mass change was independent of the pre-drying schedules after exposure at 90%RH, while irreversible dimensional shrinkage remained. Surface coating had a significant influence on the behaviour of CBPB due to physical and chemical reaction. The ranking in effectiveness of sealers was: proprietary system greater than model systems, and solvent-borne sealers greater than water-borne sealers. Compared with uncoated CBPB, that which is coated with the most effective sealer showed 70–90% reduction in both mass and dimensions over the whole range of RH exposure with the exception of the range from 65–90%RH. All coatings also showed a strong resistance to carbonation of CBPB.

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Introduction

Cement bonded particleboard (CBPB) exhibits the characteristic of mass and dimensional change under both constant and changing relative humidity (RH) (Fan et al. 2002; 2004a). The contributions to the behaviour of CBPB have been reported in this author's previous paper (Fan et al. 2004b). The present paper presents the treatment processes in order to reduce CBPB's magnitude.

It has been found that the behaviour of CBPB is attributable to (1) the behaviour of its components—wood chips and cement paste, (2) the carbonation and carbonation-induced shrinkage of CBPB, (3) the structure of CBPB in which the orientation of wood chips determines the different movement between the length, width and thickness of CBPB, and (4) the internal stresses developed during the manufacture of CBPB (Fan et al. 2004c). Accordingly, there are at least three possible ways in which the dimensional movement of CBPB in the presence of changing RH could be reduced:

- Modification of the chips to reduce their hygroscopicity
- Modification of cement paste to reduce its permeability
- Treatment for the CBPB product

This paper presents the treatment processes for the CBPB product to reduce its dimensional instability. The treatment processes include:

- Determining the effect of storage time prior to exposure of CBPB
- Determining the effect of pre-drying
- Evaluating the efficacy of surface coating

Materials and procedure

Samples were removed from panels taken from the production lines. All samples were exposed to normal environmental conditions of 20°C at 65%RH for about 2 months before testing. The details of samples used are presented in Table 1. Further information can be found in a previous publication (Fan 1997).

Mass, thickness and length of the CBPB were monitored at 24 h, 48 h, and 72 h, then at 72 h intervals thereafter until constant dimensions had been reached. Dimensional changes were read to 0.001 mm using a dial gauge. The mass was measured to 0.01 g. The results were expressed as a percentage change of initial values.

Results and discussion

Effect of storage period on the behaviour of CBPB

This work was intended to detect changes in the internal structure of CBPB and consequential effects on their dimensional stabilisation when CBPB was exposed before service. Conditioned CBPB was stored at 20°C and 65%RH for 2, 4, 8 and 12 months prior to cyclic exposure, and then conditioned at 20°C and 90%RH.

Table 1 Experimental materials and procedure

Treatment process	Materials (mm)	Test condition	Replicate
Storage prior to exposure	Edge sealed CBPB: 600×300×18 1)	Stored at 20°C, 65%RH, then	
		2 months,	3
		4 months,	3
		8 months, or	3
		12 months,	3
		and then cyclic RH 2)	
Pre-drying CBPB	600×300×18 1)	Exposed at:	
	Edge sealed CBPB:	20°C, 65%RH,	3
		20°C, 35%RH, or	3
		oven dry (105°C),	3
		and then cyclic RH 2)	
Application of surface coating 3)	Unsealed CBPB: 100×100×12	20°C, 90%RH	3
	Edge sealed CBPB: 600×600×12 1)	Cyclic RH 2)	3

1) The edges of these samples were coated with 2 coats of epoxy resin. 2) The cyclic RH range was selected to embrace the extremes of RH likely to be encountered in service, that is, the cycling regimes were:

$$\begin{tikzcd} 20^\circ C,\ 90\% RH \arrow[r] & 20^\circ C,\ 65\% RH \arrow[r] & 20^\circ C,\ 35\% RH \arrow[dl] \\ & 20^\circ C,\ 65\% RH \arrow[ul] & \end{tikzcd}$$

, and repeated. 3) Based on the chemical and physical characteristics of CBPB, material availability, cost and previous experience, four model and three proprietary sealers were selected for small scale trials. Three sealers, namely acrylic, styrene butadiene and CPB sealers were further applied to large-size samples of 600 mm×600 mm×12 mm. After three cycles, only the uncoated control CBPB and the CBPB with two coats of CPB sealer (with the best performance) were continued through ten cycles.

Change in mass and dimension of CBPB with different storage periods under cyclic RH (adsorption and desorption) are given in Table 2. It appears that the storage time had a significant influence on the magnitude of mass change under cyclic changing RH. With increasing period of storage from 2–12 months, there was a progressive reduction in the magnitude of the changes. Comparison of 2 months with 12 months storage shows that the total change in mass both under adsorption and desorption is about 1/4–1/3 higher for the 2 months period. Two main reasons were thought to be related to this reduced susceptibility to moisture.

CBPB undergoes a consistent carbonation, resulting in a reduction in permeability (Fan 1997). This carbonation-induced reduction in permeability is probably caused by the precipitation of calcite and other carbonation products

Table 2 The effect of storage time on movement of CBPB subjected to cyclic RH (values represent the maximum change for the change in RH; values of change for RH from 90–65–35% are negative, and those for RH from 35–65–90% are positive). **m = months

RH (%)	Mass change (%)				Length change (%)				Thickness change (%)			
From-to	2m**	4m	8m	12m	2m	4m	8m	12m	2m	4m	8m	12m
90–65–35	4.21	3.77	3.24	3.25	0.20	0.17	0.15	0.15	0.51	0.44	0.45	0.41
35–65–90	4.62	3.43	3.23	3.50	0.19	0.16	0.15	0.17	0.47	0.43	0.42	0.46
90–65–35	4.12	3.21	3.27	2.95	0.17	0.16	0.16	0.16	0.45	0.40	0.46	0.46
35–65–90	3.65	3.17	3.17	2.56	0.16	0.16	0.16	0.15	0.42	0.37	0.48	0.41

on the surfaces and in the cavities of the chips in contact with CO_2-charged solutions, thereby effectively reducing the effective radius of the cavity. This has been recorded for grout by Reardon and Abouchar (1989).

Further hydration of cement paste increased the solid content of the paste, and the cavities may also have become blocked by gel (Powers and Brownyard 1959). It is well known that porosity decreases with age, and irreversible shrinkage decreases with increasing porosity. However, if the degree of hydration of cement paste in CBPB is greater in the longer storage period then the volume of gel pores and the resulting water content in the low pressure range should be greater. This is because in this case only smaller pores (gel pores) remain filled with water whereas the larger ones (capillary pores) are empty. The results for CBPB seem contrary to this, but under 90%RH this characteristic results. The reason for this contrasting result under low RH range may be attributable to the change in the features of capillary pores (sizes and numbers) as it has been mixed with the large volumetric content of chips; bearing in mind the result from cement paste excluded the carbonation effect. In fact, the calcium carbonate crystallised out in the pores during carbonation and consequently changed the radius of the pores and the amount of water held in the gel pores. Prolonged storage at intermediate RH reduces the ultimate shrinkage during drying and results in slow changes in the structure of the hydrated cement paste (Helmuth and Turk 1967), and an increase in the strength and stiffness of CBPB under a long term exposure to actual weather conditions was also recorded (Dinwoodie and Paxton 1990). The overall changes were balanced by the increases and decreases of change which are associated with the degree of un-hydrated cement in the CBPB.

The effect of storage time on the dimensional changes of CBPB was less significant compared to that on the mass change, and the effect on the length change was greater than on the thickness change. This reflected the combined effect of wood chips and cement paste on the behaviour of CBPB.

Effect of pre-drying on the behaviour of CBPB

This schedule provided for both slow and rapid removal of evaporable water, so as to examine the initial drying effect on CBPB. The CBPB after 2 months storage under a normal environment (conditioned at 20°C and 65%RH) was subjected to different drying regimes: 35%RH, 65%RH and oven drying. After initial drying treatments, the CBPB was reconditioned at 20°C and 65%RH, and then subjected to 20°C and 90%RH before cycling.

Effect on the behaviour under first adsorption at 90%RH

Figure 1 shows the mass and dimensional changes of CBPB subjected to re-wetting from the original condition (20°C, 65%RH) and further high RH wetting (20°C, 90%RH) after three different pre-drying regimes. The ultimate values and final rate of change are provided in Table 3.

As shown in Fig. 1, CBPB dried under 35%RH or 105°C showed a considerable irreversible mass change after re-wetting; about 0.7% mass decrease was recorded to be irrecoverable under 35%RH drying and about 3% with 105°C drying. However, the ultimate values of mass increase after further high

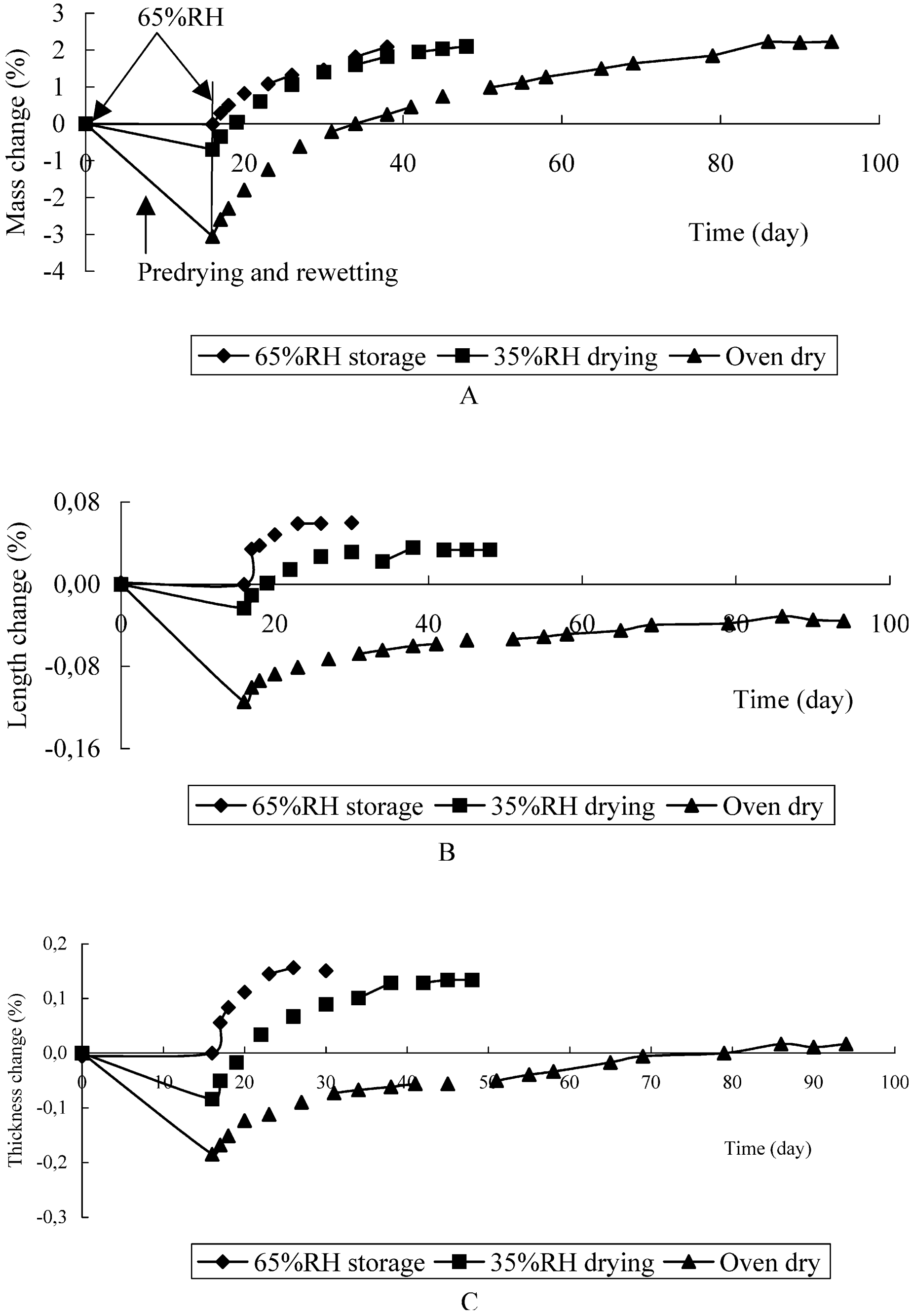

Fig. 1A–C Mass (**A**), length (**B**) and thickness (**C**) change of pre-drying CBPB under the first 90%RH exposure

RH wetting were found to be independent of pre-drying, although they somewhat depend upon the time to reach the constant. After further high RH wetting, all samples reached a similar level of mass change, increased by about

Table 3 Final rate and ultimate values of change of CBPB after re-wetting and further high RH wetting. Values without ( ) = final rate in %/day; values inside ( ) = ultimate change in %

Schedule	Mass		Length		Thickness	
	65%RH	90%RH	65%RH	90%RH	65%RH	90%RH
65%RH exposure	2.1×10^{-3}(0.01)	4.3×10^{-3}(2.09)	2.5×10^{-4}(0.00)	2.5×10^{-4}(0.06)	1.25x10^{-3}(-0.01)	1.25x10^{-3}(0.15)
35%RH drying	2.8×10^{-3}(-0.69)	3.8×10^{-3}(2.10)	2.5×10^{-4}(-0.02)	2.5×10^{-4}(0.03)	1.25x10^{-3}(-0.08)	1.26x10^{-3}(0.13)
105°C drying	2.2×10^{-3}(-3.06)	4.2×10^{-3}(2.15)	2.6×10^{-4}(-0.11)	2.6×10^{-4}(-0.04)	1.39x10^{-3}(-0.19)	1.28x10^{-3}(0.02)

2.1%. The end points of mass gain lay on a straight line which are nearly parallel to the *x* axis.

Unlike the behaviour for mass, CBPB shows very different behaviour regarding changes in dimensions depending on the drying schedules used. There existed considerable irreversible dimensional shrinkage after re-wetting (Fig. 1B, C). About 0.023% of the length and 0.085% of the thickness shrinkage of CBPB with 35%RH drying remained irreversible, and 0.115% length and 0.185% thickness remained with 105°C drying. Moreover, further high RH wetting resulted in different dimensional changes. CBPB with drying pre-treatment showed lack of recoverability in dimensions. The degree of irreversibility strongly depended on the degree of drying. Even after 90%RH exposure, the length of CBPB after 105°C pre-drying did not expand to its original value at 65%RH pre-conditioning. But with 65%RH prolonged exposure it had 0.06% expansion and with 35%RH drying 0.03% expansion. A similar situation was seen in thickness changes though with higher magnitude. However, the difference in ultimate changing values between three pre-dryings was reduced (Table 3). These results indicate that a stabilisation process occurs in CBPB during pre-drying. There existed a structural change for cement paste in CBPB during drying, and the wood chips played a certain role in the dimensional change in terms of its isotropicity or their distribution within CBPB. A portion of the pores of the cement paste in CBPB may be enlarged and thus unable to produce the capillary effect under low RH (65%).

Both the mass and dimensions are irreversible under re-wetting, but further high RH wetting resulted in a compensation of the mass decrease, while the dimensions remained irreversible. Thus, it became very important to find out whether and/or why these changes were really irreversible, or if the recovery was merely very slow. To answer this question, the final changing rate of CBPB was evaluated (Table 3). According to the cementitious work (eg. Helmuth and Turk 1967), it was stated that cement paste may continue to expand throughout the re-wetting period, but the prolonged expansion of these wet specimens are not believed to be slow recovery following drying shrinkage. Re-wetting may be considered complete when the normal expansion rate for the paste during moist exposure is observed, although the time required to re-wet depends upon the drying history. In terms of the changing rates of CBPB tested (Table 3), it was concluded that the procedure of drying or wetting was complete and there did exist permanently irreversible changes in both length and thickness, and whatever the drying histories are, the mass can recover to its original values under high RH wetting. In addition to the aforementioned reasons, this is partly attributable to (1) the irreversible behaviour of chips which has been described in terms of differences in contact angle of the advancing and receding water front within the cell cavities, or in terms of the behaviour of the hydroxyl groups, some of which in both the cellulose and lignin permanently satisfy each other on drying, and some of which have irreversible inelastic exchange between neighbouring cellulose molecules (Skaar 1988), and (2) the behaviour of cement paste: drying results in the closing of gaps between gel particles and between inter-crystal layers of cement paste following expulsion of water confined between adjacent surfaces. The contraction of such small inter-solid gaps is accompanied by a steep increase in Van der Waals binding forces and by the formation of new chemical or physical bonds. Raising the RH at the lower level would not result in full recovery of these gaps owing to the inability of water molecules to reoccupy the newly closed original spaces, which leads to (3) the change in the structure of CBPB: the heating treatment affects the structure of the paste and its composition. Generally speaking, heating results in a considerable reduction in shrinkage (Powers and Brownyard 1959). No pores the size of gel pores in normally cured paste are present in paste treated in an autoclave, so during 65%RH exposure a number of larger pores in dried CBPB were not filled with water, and the mass change of corresponding dried CBPB did not recover to its original values; whilst at 90%RH exposure most of pores left were refilled with water, the mass of CBPB recovered and compensated the previous change (Fig. 1). This also suggested that condensation plays an important role in the mass change of CBPB under high RH which, inversely, had much less effect on dimensional change.

Effect on the behaviour under cyclic RH

After exposing at 90%RH, CBPB were subjected to cyclic RH. The mass and dimensional changes are shown in Fig. 2. Although the time dependence of the irreversible change will not be dealt with extensively in this paper, two effects must be noted. Overall, for all samples, with an increase in exposing time/cycle numbers, the mass consistently increased but the dimensions decreased.

Figure 2 shows that the values of each change in the CBPB under a certain period of RH exposure decreased under 35%RH or 105°C drying. The order of changes is (whether mass or length or thickness): changes of CBPB with 65%RH exposure greater than that of CBPB with 35%RH drying which is greater than that of CBPB with 105°C drying. Oven drying reduced the adsorption of the CBPB by about 10–30% for all stages of exposure, but this decreased to only about 5–10% reduction for 35%RH pre-drying. A similar percentage reduction occurred for length change and a few percent greater reduction was produced for thickness change. It is apparent that drying resulted in the permanent stabilisation of CBPB. The stabilisation was reflected more significantly in the dimensions than in the mass. The deduction of maximum change values in each stage of consequential cyclic RH exposure may be attributable to the fundamental structural change, inactivated ions or the precipitation of the carbonated products on the surface or in the cavities of cement paste and wood chips.

Application of surface coating

This work was carried out to detect the applicability and efficacy of surface coating to reduce the dimensional instability of CBPB. Full details of the programme are reported on in a separate paper (Fan et al. 2004b), and therefore only a brief summary is given to illustrate the efficacy of this treatment process for stabilisation of CBPB.

The assessment of candidate sealers

All seven sealers were evaluated by applying them to the small-sized samples. The efficacy of sealers to reduce moisture uptake is shown in Table 4 and Fig. 3.

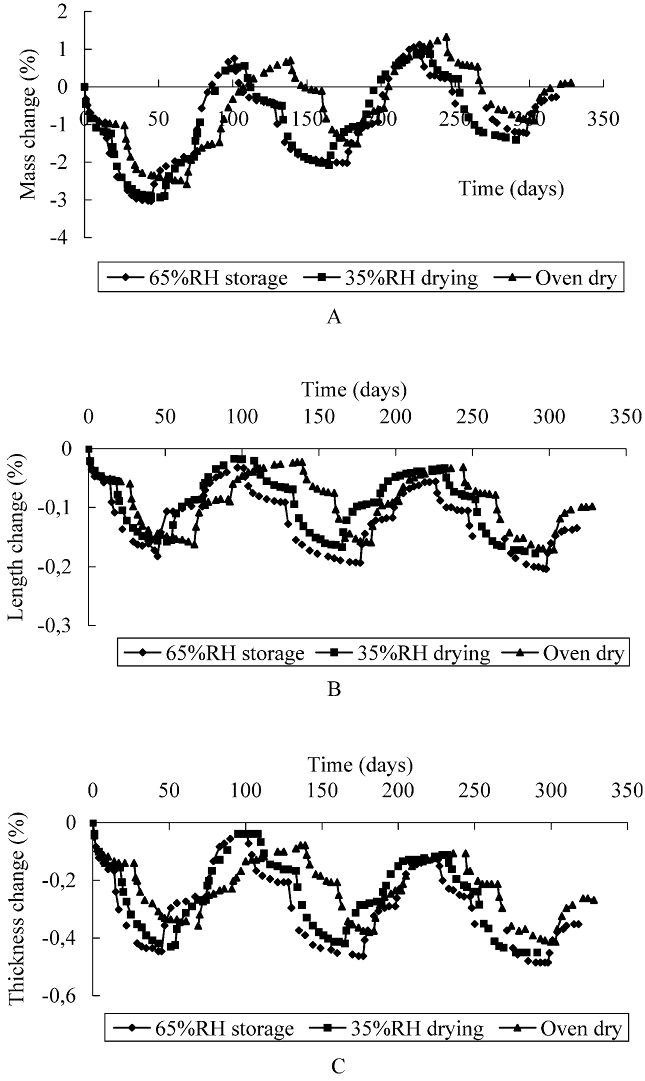

Fig. 2A–C Effect of pre-drying on mass (**A**), length (**B**) and thickness (**C**) change of CBPB under cyclic RH

It was found that there were wide differences in performance between sealers. The water-borne formulations (whether model or proprietary systems), were at best only about half as effective as the solvent-borne sealers in reducing moisture uptake. Nearly 1,000 days exposure showed that panels coated with model formulations exhibited similar mass gains to the uncoated CBPB panels. The effectiveness of water-borne acrylic in proprietary systems compared with the uncoated control panel reduced to about 24% over this period, while both solvent-borne systems retained an adsorption reduction of about 42% and 49% respectively. The results show that all the proprietary formulations are effective moisture barriers with the solvent-borne coatings being the more effective. The

Table 4 Moisture uptake of small size coated CBPB (expressed as a % of the control value of uncoated CBPB)

Time (day)	7	15	30	60	295	965
Model formulations						
Polyvinylidene chloride	91	96	95	91	97	100
Acrylic	87	91	90	90	101	103
Styrene acrylic	73	75	69	65	74	95
Vinyl chloride	68	74	73	73	91	99
Proprietary formulations						
Acrylic	75	71	62	57	59	76
Styrene butadiene	20	28	35	42	46	58
CBPB Sealer	23	29	37	43	44	51

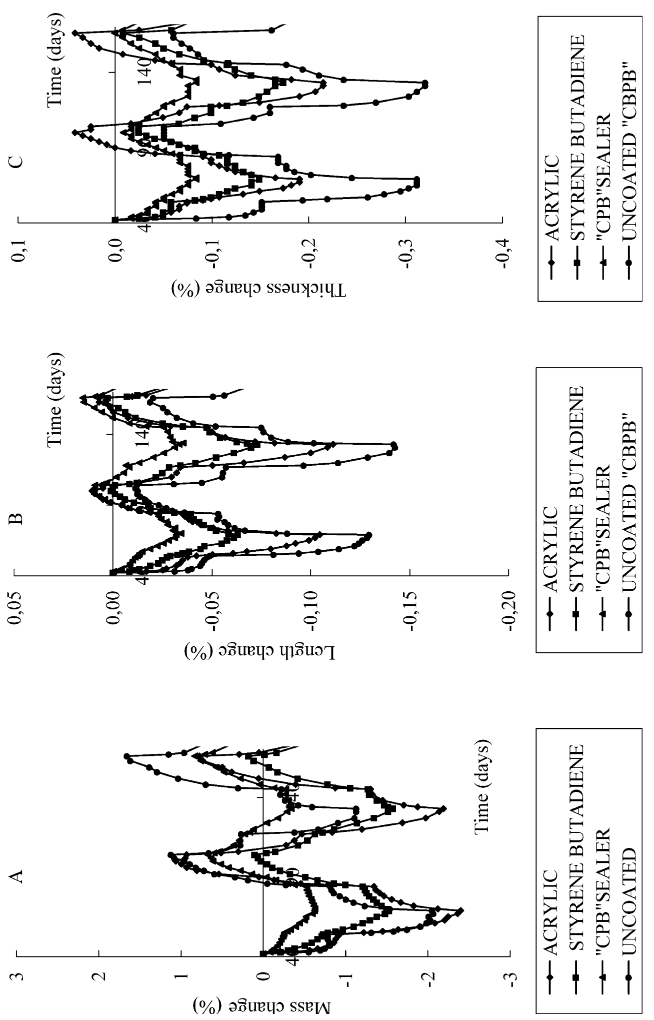

Fig. 3A–C Effect of various coatings on mass (**A**), length (**B**) and thickness (**C**) change of CBPB under cyclic RH

Table 5 Types of surface coatings

Model formulation	Polymer type	Proprietary formulations	Polymer type
1	Polyvinylidene chloride	1	Acrylic
2	Acrylic	2	Styrene butadiene
3	Styrene acrylic	3	CPB sealer
4	Vinyl chloride		

model formulations resulted in poor performance and were therefore eliminated from the large size tests.

Large-sized sample tests

Large size test pieces of CBPB were coated with three selected proprietary coatings (Table 5) and together with the uncoated control samples were subjected to cyclic RH regimes between 35–90%RH to represent severe service environments. The mass and dimensional changes with time are shown in Fig. 3.

The results confirmed those from the tests on small-sized samples. That is, the water-borne coating was less effective compared to solvent-borne coatings. Moreover, the degree of stabilisation of the substrate strongly depended on the level of the changing RH. Among three sealers used, the CPB sealer is the most effective over the range of RH used, resulting in a reduction of 70–92% in mass and 75–83% in length of the test pieces, depending on the level of the changing RH. The change in thickness of coated CBPB was very similar to that in length, though by different amounts.

A comparison of the change of coated and uncoated CBPB subjected to ten cyclic RH cycles showed that the stabilisation of CBPB by surface coating was very durable under changing RH. There was no deduction of efficacy observable after ten cycles.

The resistance to carbon dioxide of coated CBPB

It was also found that the application of surface coating not only reduced the instability of CBPB, but also gave the potential resistance of coatings to carbon dioxide penetration. The coating acts as a barrier to the penetration of carbon dioxide, consequentially preventing or reducing the contact of $Ca(OH)_2$ with CO_2. The resistance to carbonation of every system tested is illustrated in Fig. 3. Due to the nature of carbonation, the mass of uncoated CBPB increased consistently with increasing number of cycles while the dimensions decreased (Fan et al. 2004a, b). However, these trends were considerably reduced for coated CBPB and even disappeared in some cases. It is of interest that the water-borne acrylic did not produce significant dimensional stabilisation but did show a considerable resistance to CO_2.

The benefit produced by the resistance of coatings to carbonation can be seen when considering long-term exposure (Fig. 4). There is a considerable increase in mass and decrease in dimensions after ten cycles of uncoated CBPB; however, only slight increases were found in both mass and dimen-

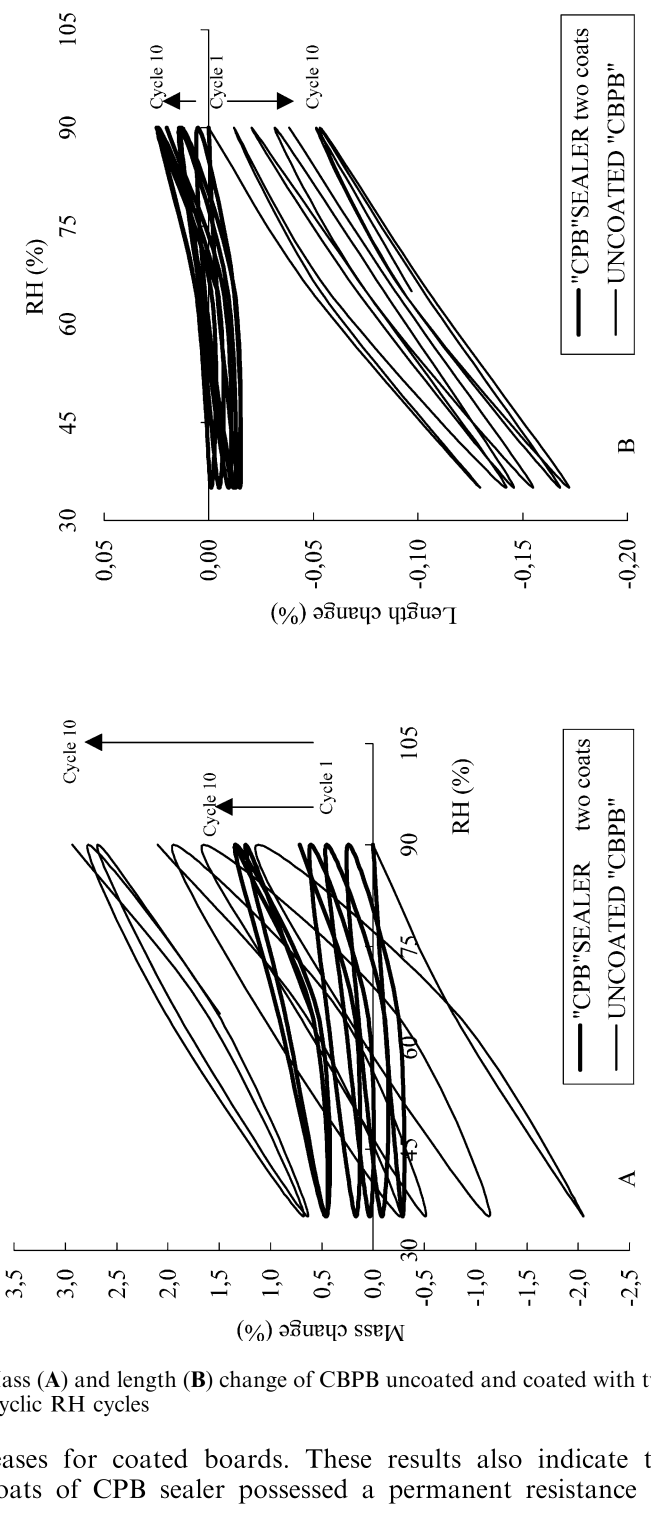

Fig. 4A–B Mass (**A**) and length (**B**) change of CBPB uncoated and coated with two coat CPB sealer in ten cyclic RH cycles

sional increases for coated boards. These results also indicate that CBPB with two coats of CPB sealer possessed a permanent resistance to carbonation.

Conclusions

All three stabilisation processes were able to reduce both mass and dimensional changes of CBPB when subjected to changing RH. However, the efficacy of the treatments varied with the schedules of the treatments:

1. Storage time had a significant influence in sorption behaviour of CBPB due to further hydration, carbonation or both. With increased storage time, the mass and dimensional changes decreased. About 1/3 reduction in mass change was obtained for CBPB with 12 months 20°C and 65%RH exposure compared to that of 2 months under both adsorption and desorption.
2. Pre-drying resulted in an alternation of structure and permanent stabilisation of CBPB. The pre-drying mass decrease and dimensional shrinkage were irreversible—about 0.7% and 3% mass decrease for 35%RH and 105°C drying after re-wetting at 65%RH. The mass change of CBPB, however, was independent of the pre-drying schedules after exposure at 90%RH.
3. The ultimate irreversible values in dimensions after re-wetting at 65%RH was about 0.02% in length and four times higher in thickness for CBPB with 35%RH pre-drying, and 0.12% and 0.19% respectively for CBPB with 105°C drying. Further wetting at 90%RH did not make dimensional changes reproducible.
4. Pre-drying resulted in the permanent stabilisation of CBPB. The reduction in mass and dimensional change at each stage of consecutive cyclic RH was 105°C drying greater than that with 35%RH drying which was greater than that with 65%RH exposure pre-treatment.
5. Due to the high alkalinity of CBPB, there was a restricted number of sealers applicable to CBPB. Among the sealers tested, the ranking order of their effectiveness was: proprietary systems greater than model systems, and solvent-borne sealers greater than water-borne sealers. Of all the sealers tested, the CPB sealer was the most effective, with a reduction of 70–92% in mass change and 75–83% in length change over a range of RH.
6. CBPB coated with all sealers showed a strong resistance to carbonation, even with water-borne acrylic sealer, which was not very effective in reducing either mass or dimensional change under changing RH, being very efficacious. The resistance of coatings to carbonation was not affected by multiple-cycling under changing RH.

References

Dinwoodie JM, Paxton BH (1990) The long term performance of cement bonded particleboard. In: Moslemi AA (ed) Proceedings of the 2nd international conference on inorganic bonded wood and fiber composite materials. pp 45–55

Fan MZ, Dinwoodie JM, Bonfield PW, Breese MC (2002) Dimensional instability of cement bonded particleboard. Part 1: behaviour and modelling prediction under a constant and single change in RH. Wood Sci Technol 36:125–143

Fan MZ, Dinwoodie JM, Bonfield PW, Breese MC (2004a) Dimensional instability of cement bonded particleboard. Part 2: behaviour and its prediction under cyclic changes in RH. Wood Sci Technol 38:53–68

Fan MZ, Dinwoodie JM, Bonfield PW, Breese MC (2004b) Dimensional instability of cement bonded particleboard: the effect of surface coating. Cement and Concrete Research (in press)

Fan MZ, Dinwoodie JM, Bonfield PW, Breese MC (2004c) Dimensional instability of cement bonded particleboard: contributions to its occurrence. Wood Sci Technol (submitted)

Fan MZ (1997) Dimensional instability of cement bonded particleboard: understanding its occurrence and reducing its magnitude. PhD thesis, University of Wales

Helmuth RA, Turk D (1967) The reversible and irreversible drying shrinkage of hardened Portland cement and tricalcium silicate paste. J PCA Res Dev Lab May 1967

Powers TC, Brownyard TL (1959) Capillary continuing or discontinuing in cement paste. J PCA Res Dev Lab May 1967

Reardon EJ, Abouchar M (1989) High pressure carbonation of cementitious grouts. Cement Concrete Res 19:835–839

Skaar C (1988) Wood-water relations. Springer, Berlin Heidelberg New York