DIMENSONIAL INSTABILITY OF CEMENT-BONDED PARTICLEBOARD: BEHAVIOR OF CEMENT PASTE AND ITS CONTRIBUTION TO THE COMPOSITE

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ABSTRACT

This paper examines the behavior of cement paste under constant and changing relative humidity (RH) conditions to evaluate the contribution of cement paste to the dimensional instability of cement-bonded particleboard (CBPB). It was found that the trend of changes in cement paste was very similar to, but the degree of changes was different from, that of CBPB at various exposures. The comparison of the results of cement paste with those of CBPB indicated that the inclusion of wood chips accelerated the carbonation reaction, and that carbonation of the cement paste exerted additional stresses on the wood chips in CBPB; this resulted in a slightly higher increase in mass but an appreciably greater decrease in the dimension of CBPB under constant 20°C/65% RH. The cement paste had considerably lower changes in mass and dimension with a single change in RH between 35 and 90% RH (except for the increase in mass on adsorption at 90% RH) compared to CBPB. The inflection in the relationship between mass and dimensional changes of cement paste was more distinct than that of CBPB with the change of mass per unit length change after the "inflection point" being about eight times higher than that of CBPB on desorption. Under cyclic RH, the response to the level of RH and the history of sorption was different between cement paste and CBPB, with the difference in dimensional change between adsorption and desorption being more significant, while the adsorption at 90% RH for the cement paste was considerably higher. Fitting of models previously developed to the data permitted the prediction of accumulated change of the cement paste with a good degree of fit and established the suitability of using these formulae for modelling CBPB as a composite to be described in a further paper in this series.

Keywords: Cement-bonded particleboard, cement paste, relative humidity, cycle, hysteresis, adsorption and desorption, mass and dimensional changes.

INTRODUCTION

The behavior observed for CBPB has given an indication of a possible relationship between CBPB and the sum of its components (Fan et al. 1999a, b). The study of the behavior of dissected chips under various environmental conditions (Fan et al. 1999c) has provided valuable information on the behavior of one of these components, namely the wood chips. This paper sets out results of an investigation on the behavior of cement paste.

There are two main limitations of the results recorded in literature for sorption and length change measurements on hydrated cement—water system (e.g., Powers and Brownyard 1948; Feldman and Sereda 1963, 1964; Sereda and Feldman 1963; Helmuth and Turk 1967). First, where length change measurements were carried out, these usually involved only the initial drying from the saturated state and seldom included the complete range of RHs for the adsorption and desorption cycle, let alone the conditions used to study CBPB (constant, single and cyclic changes in RH) (Fan, et al. 1999a, b). Second, nearly all available data were affected by extraneous complicating effects such as raw materials, manufacturing variables, after-curing and exposure conditions. It, therefore, appeared essential to undertake experimental research into the behavior of cement paste of the type found in CBPB.

The present paper examines and predicts the behavior of this cement paste. Cement paste was prepared in a manner simulating that in the manufacture of CBPB and was then subjected to the same exposure conditions as those for CBPB (Fan et al. 1999a, b). Cement paste particle (cement paste from CBPB boards) was used to test whether the laboratory-made cement paste (cement paste having the same production parameters as those for commercial manufacture of CBPB) was representative of commercial production.

MATERIALS AND PROCEDURES

Manufacture of cement paste

Cement paste was molded, 300 mm in length, 52 mm in width, and 5 mm in thickness. The ratio of water to cement was 0.35, being based on the formula used in the manufacture of CBPB, namely,

Water requirement = $0.35 \, Wc + (0.3 - Mc)Ww$

where Wc is the mass of cement paste, Mc is the moisture content in wood chips (based on absolutely dry chips), and Ww is the mass of absolutely dry chips. For the neat cement paste manufacture, water requirement = 0.35 Wc.

The cement paste was prepared by measuring accurately sufficient ordinary Portland cement, aluminum sulphate (3%), sodium silicate (3%), and water in the desired ratio, to yield the same formulation of cement paste as it is in CBPB. Mixing in a large aluminum open-topped container was initiated immediately on the addition of additive and continued until an even distribution of the cement paste, chemicals, and water was produced (about a 7-min mixing period).

The wet cement paste was then immediately formed by evenly spreading a small quantity (approximately 20%) of the paste into a mold. A top plate was then placed directly above the mattress, and a load was applied to meet the required pressure, 2.8 N/mm^2 as used in the manufacture of CBPB.

After 6 to 8 min pressing, the mattress was clamped and the filled mold was transferred to an oven, at about 70°C, to precure the mixture for 7 to 8 h, after which the constraint was released.

Further curing was carried out in two consecutive stages: 1) Immediately after precuring, the cement paste was removed from the mold and transferred to a conditioning room at 20°C/65% RH for 7 to 8 days; 2) then the cement paste was returned to the oven at 110 ± 5°C for about 3 h, thus ensuring that sufficient hardening had taken place and the desired strength and moisture content (about 9%) of cement paste had been produced.

Sampling and examination

Samples for testing were prepared by two different methods:

TABLE 1.   *Types of cement paste and exposure conditions.** *

Test	Exposure condition (RH)	Type of cement paste	Measurement
Constant RH	Normal air**: 65%	Laboratory-made cement paste	Mass, dimension
Constant RH	CO_2-free air***: 65%	Laboratory-made cement paste	Mass, dimension
Single change in RH	Normal air: 35-90%; 90-35%	Cement paste particle from CBPB	Mass
Single change in RH	Normal air: 35-90%; 90-35%	Laboratory-made cement paste	Mass, dimension
Single change in RH	CO_2-free air: 35-90%; 90-35%	Laboratory-made cement paste	Mass, dimension
Cyclic RHs	Normal air: 90-65-35-65-90%	Cement paste particle from CBPB	Mass
Cyclic RHs	Normal air: 90-65-35-65-90%	Laboratory-made cement paste	Mass, dimension

 * All tests were carried out at 20°C.
 ** Normal air = indoor environmental air.
 *** CO_2-free air = indoor environmental air with CO_2 trapped by carbosorb (Fan 1997).

1) *From the laboratory-made cement paste.* Samples were sawn into dimensions 140 × 14 × 5 mm and visually assessed for quality; those with an absence of small cracks and possessing a uniform surface were selected for exposure.

2) *From panels of CBPB.* This sample was employed to examine the similarity in the property between the cement paste particle and laboratory-made cement paste. Small samples of board were broken into fine particles and the wood chips were separated. This sample of the cement paste should be representative of the nature of cement paste in CBPB, but it inevitably includes small amounts of wood powder. Moreover, this type of sample can be used only to examine the change in the mass of cement paste during RH exposure.

The two sets of samples of hydrated cement paste were divided into seven groups and subjected to the same environmental conditions (Table 1) that were employed for the CBPB exposure investigations (Fan 1997; Fan, et al. 1999a, b).

It should be noted that the duration of exposure of the cement paste samples as determined by the time to reach constant dimension varied from that used on CBPB. This action control was thought to be important due to the

time-dependence of carbonation of cement paste on CO_2 level. To enable the small change of the cement paste to be assessed, a unique measuring equipment was constructed to suit the samples tested (Fan 1997).

Three replicates were produced. The changing values in mass and length were converted into percentage changes with respect to the original values. The mean percentage change of the three replicates was used.

RESULTS AND DISCUSSION

Behavior under a constant RH

Under a constant RH, there was a consistent increase in mass but decrease in length of the laboratory-made cement paste (Fig. 1). The plots of the changes in both mass and dimension with time are polynomial, while the plot of relationship between mass and dimensional changes is approximately linear (Fig. 1C). These findings are different from those recorded for the change of wood chips, but in agreement with the change of CBPB under constant RH, though with a difference in magnitude due to the effect of the inclusion of wood chips in CBPB (Fan, et al. 1999a, c). It is evident that the result above was attributable to the carbonation of the cement paste. The accumulated changes in both mass and dimen-
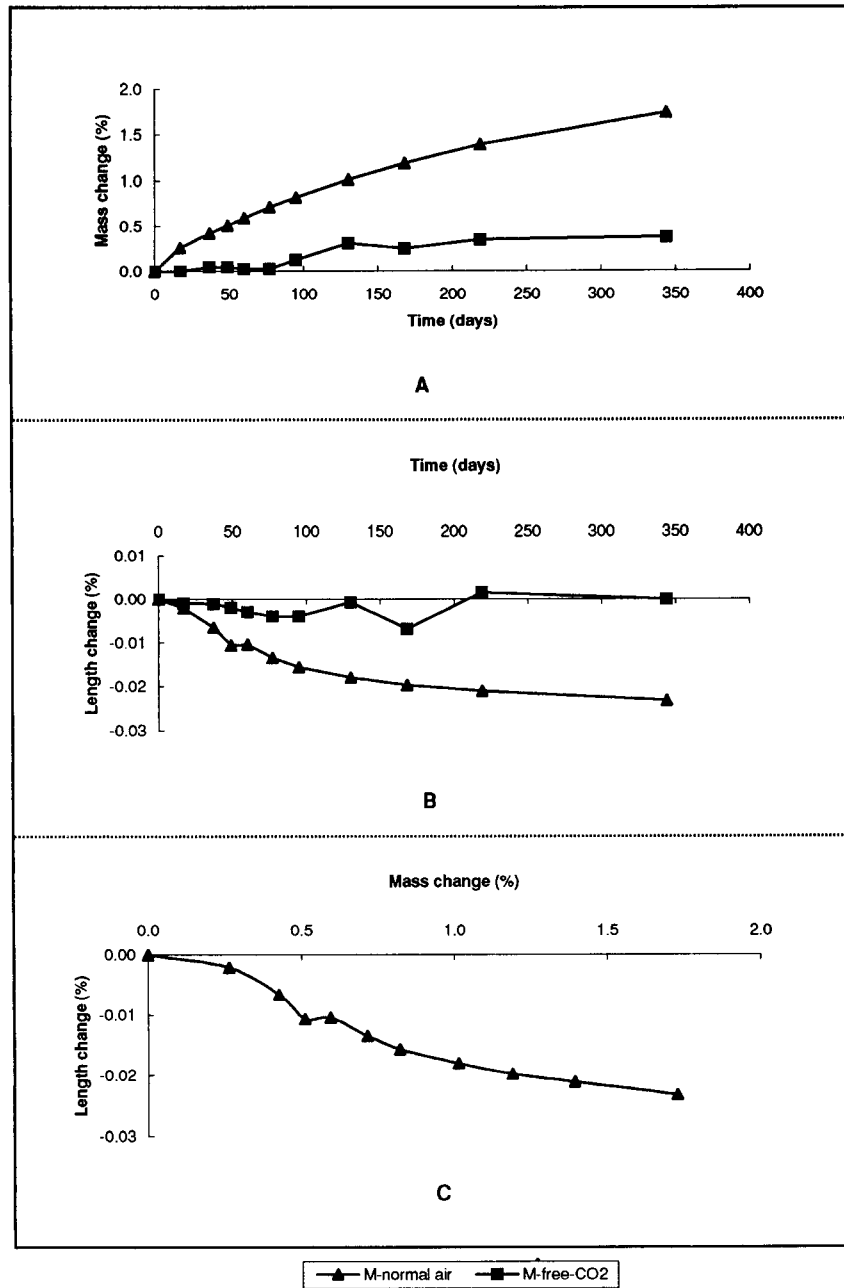
FIG. 1.   Change in mass (A) and length (B) of laboratory-made cement paste under constant normal air and air free of CO_2 and relationship (C) between mass and length change under normal air.

sions did not occur in the cement paste subjected to the CO_2-free air (Figs. 1A and 1B). The slight increase in mass and decrease in length of cement paste at early stage of exposure were due possibly to further hydration by virtue of the long period required for the complete hydration of the cement paste.

A comparison of the results above with those of CBPB under the same conditions shows that after 350 days' exposure at 20 °C/65% RH, the change in mass of cement paste was about 1.73% (Fig. 1A) and that of CBPB about 1.45% (Fan et al. 1999a). It appears to be less for CBPB than for cement paste. However, account should be taken of the volume percentage occupied by each of the constituents in CBPB. Assuming that the mass of wood chips remains constant under constant environment, it can be calculated that:

for "neat" cement paste, final mass

= 1.014 × initial mass;

for the cement paste in the CBPB, final mass

= 1.018 × initial mass.

Obviously the change of cement paste in CBPB was more significant than that of laboratory-made cement paste due to the compactness of CBPB and porosity of wood chips that may provide a pathway for sufficient carbon dioxide to enter the carbonate cement paste. This was in agreement with the study of concrete in which there is fairly good inverse correlation between density of aggregate and depth of carbonation, and between compressive strength of composite and depth of carbonation (Collins 1986; Lesage 1985; Nagataki et al. 1986).

Both the change in length (about 0.035%) and especially the change in thickness of the CBPB (about 0.18%) (Fan et al. 1999a) were higher than the change in length of the cement paste (about 0.023%) (Fig. 1B). It is apparent that the ratios of both length and thickness changes of CBPB to length change of cement paste are much higher than 1.018/1.014, indicating that the change of CBPB was not due

solely to the higher proportional change in the dimension of cement paste in CBPB as mass change. The change of cement paste may further cause a change in wood chips due to the effect of stresses during carbonation. The shrinkage of cement paste due to carbonation is attributed to the dissolution of the calcium hydroxide crystals while the crystals are under pressure (Powers 1962). Such dissolution temporarily increases stress in the remaining solids of the paste bringing about a corresponding volume decrease. This may, meanwhile, exert an extra compression on the wood chips.; thereby the volume of wood chips decreases, causing a higher gross shrinkage of CBPB.

Behavior on both adsorption (35–90% RH) and desorption (90–35% RH)

The changes in mass and length of laboratory-made cement paste in both normal and CO_2-free air on moving from 35 to 90% RH are shown in Figs. 2P and 2Q. Corresponding changes on moving samples from 90 to 35% RH are given in Figs. 2R and 2S.

It was found that the trend of changes in both mass and length was very similar to that of CBPB (Fan et al. 1999a). The curves for both mass and length changes, whether on adsorption or on desorption, between 35 and 90% RH, can be divided into two distinct stages:—OA and AB. The inflection points A for the materials tested are located at 27 days. A large proportion of the change occurred at the beginning of exposure. After the inflection points, the degree of changes slowed down considerably. However, the unique nature of change was illustrated more distinctly in cement paste than in CBPB (Fan et al. 1999a)—that is, the behavior of the cement paste was equally dominated by other effect(s) rather than solely general moisture reaction and was reflected as a mass increase on moving samples from 90 to 35% RH and slight decrease in length on moving samples from 35 to 90% RH. The degree of reverse change depends on the balance between two processes, which, at
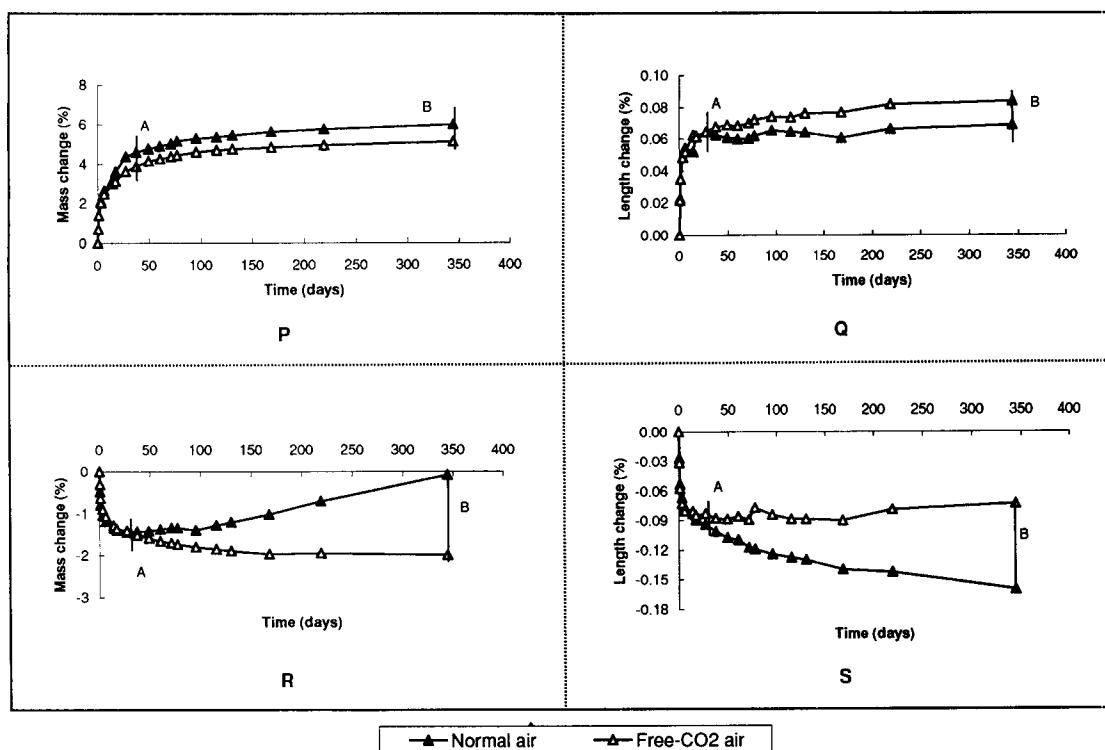
FIG. 2. Changes of laboratory-made cement paste under normal air and air free of CO_2: in mass (P) and length (Q) in moving from 35 to 90% RH and mass (R) and length (S) in moving from 90 to 35% RH.

90% RH (long-term exposure), are between the shrinkage due to carbonation, and swelling because prolonged immersion induces tensile stresses in inter-solid bonds, disrupting some of weak links and causing further adsorption (Fig. 2Q). At 35% RH (long-term exposure), the balance is between the increase in the mass due to carbonation and decrease in the mass due to the evaporation of water from two distinct sources–that present in the pores of the paste and that released during the carbonation process (Fig. 2R). The increase in the rate of mass increase of cement paste on adsorption and length decrease on desorption also indicated the effect of above reactions (Figs. 2P and 2S). From "A" to "B" (27 to 344 days), on a prolonged adsorption at 90% RH, mass increased by 1.65%, while change in length was only about 0.004%. On a prolonged desorption at 35% RH, the increase rather than decrease in mass of cement paste was about

1.366%, while the decrease in length was 0.066%. It can be concluded that both mass and dimensional changes are associated with the moisture in the cement paste, but are not due solely to the movement of water into or out of the cement paste. The changes at a prolonged exposure at 90% RH are thought to be dominated by the condensation of moisture and at 35% RH by the carbonation of the cement paste.

The most interesting result (which not only interprets the mechanisms of movement of cement paste but also shows good agreement with the results arising from CBPB) is the relationship between mass and dimensional changes of cement paste, Fig. 3. O, A, and B represent the same points as on Fig. 2. On moving samples from 35 to 90% RH, the relationship (Fig. 3P) of mass to dimensional change is linear at the beginning of adsorption (up to about first 3-day exposure), after which
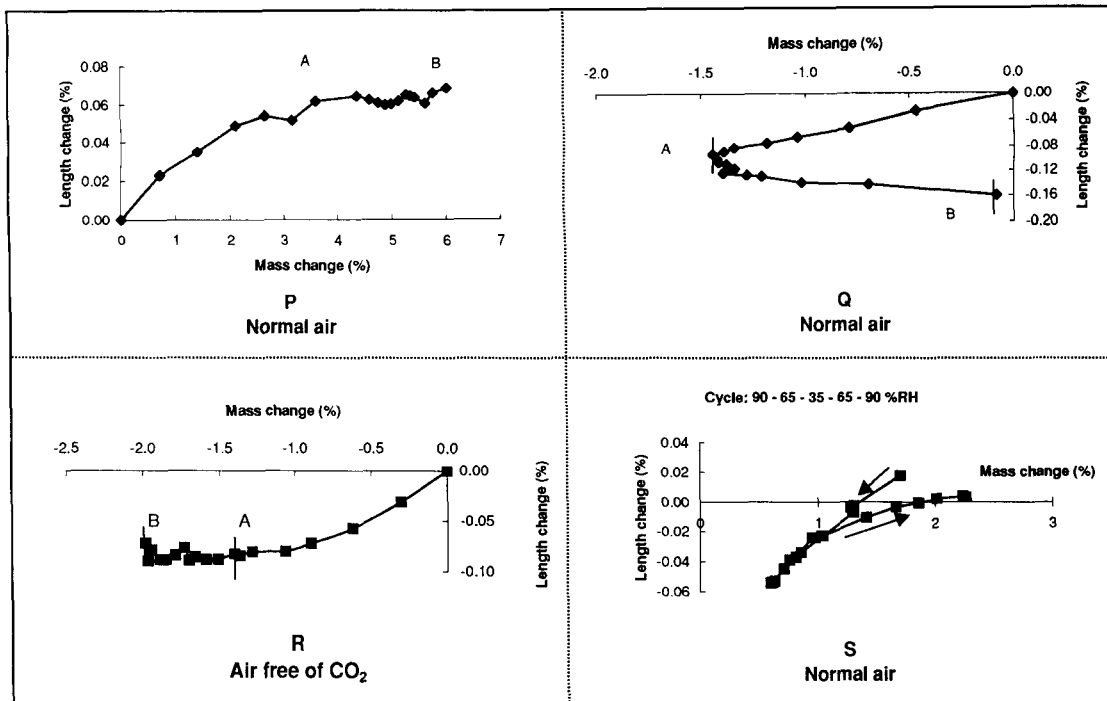
FIG. 3.   Relationships between mass and dimensional change of laboratory-made cement paste: P-in moving from 35 to 90% RH; Q and R-in moving from 90 to 35% RH; S-under cyclic RH.

the slope of the curves consistently decreases until point "A," but the increase in mass is not associated with an increase in length between "A" and "B." It is apparent that an increase in length of cement paste on adsorption was due first to an increase of bound (adsorbed) water as soon as it was exposed; further exposure increased the capillary water content, reducing the rate of length change compared to adsorption of gel water. At the later stages of exposure, condensation produced an unobservable change in length, but a considerable increase in the mass of the cement paste.

A very distinct relationship between mass and dimensional changes of the cement paste occurred on desorption (Fig. 3Q). Both curves before and after "inflection point A" are linear, but the slopes of the lines in the two stages are completely different—one is positive and the other negative. The relationship over the whole duration of exposure plotted as a hori-

zontal "V." In the region OA', mass decrease occurs somewhat gradually with length decrease, showing a dominant effect of the movement of adsorbed water, which imposed a compressive stress on the cement paste, causing a commensurate shrinkage in the cement paste. The region A'B' shows a very high gain in mass per unit length change, with the ratio of mass to length changes of the cement paste (20.5) being about 8 times that of CBPB (ratios of 2.6 for thickness and 2.8 for length). This result deviates considerably from that occurring in a CO_2-free air exposure (Fig. 3R). This shows evidence of carbonation of cement paste, which resulted in an increase in mass and decrease in dimension.

The differences in the changes between cement paste and CBPB on adsorption were not equal to those on desorption, reflecting the nature of both the cement paste and the wood, which made different contributions to the changes with changing RH. On adsorption, the
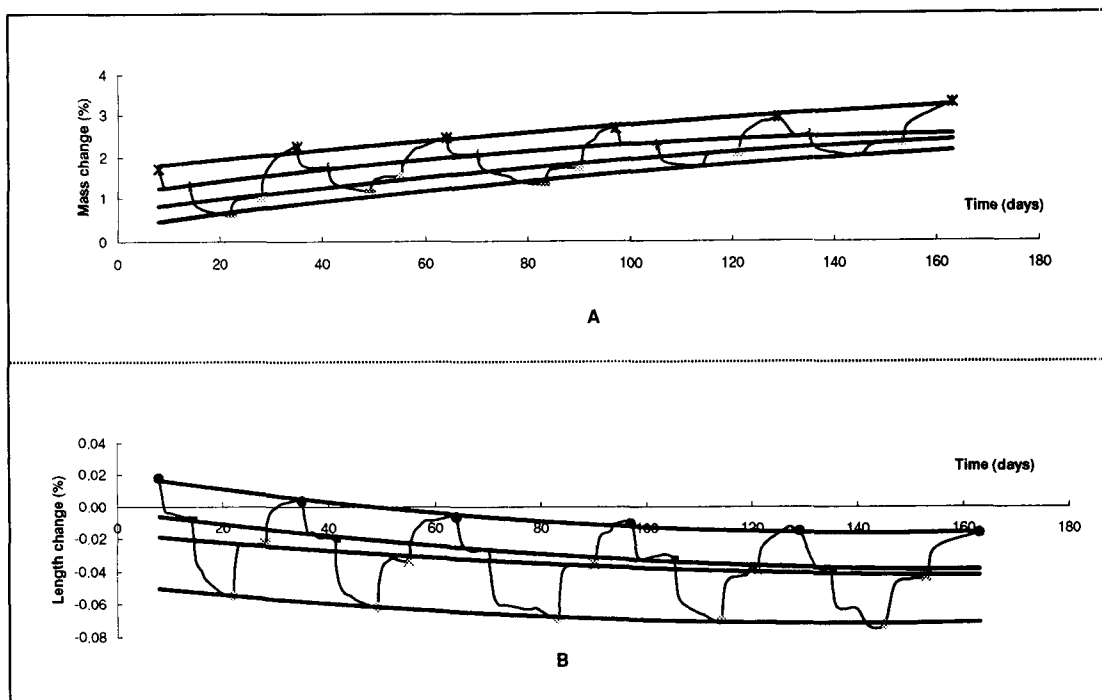
FIG. 4. Change in mass (A) and length (B) of laboratory-made cement paste under cyclic RH: 90-65-35-65-90% RH.

change in mass of both the cement paste and CBPB (Fan et al. 1999a) was about 5.52%, whereas the change in the length of cement paste was about 0.06%; this was much less than the change in length (about 0.16%) and in thickness (about 0.51%) of CBPB. However, on desorption, the changes in both mass and dimension of CBPB were higher than those of the cement paste. Hence, increases of about 0.82% in mass of cement paste occurred after the "inflection points", compared with only about 0.11% change in CBPB.

Behavior under cyclic RH conditions

Cyclic changes in one complete cycle.—The resulting change of laboratory-made cement paste under cyclic RHs is shown in Fig. 4 (cyclic curves). The relationship between mass and dimensional change in one complete cycle is presented in Fig. 3S. Like the cyclic behavior of CBPB, when cement paste was cycled between 35–65–90% RH, the mass and length

change not only reflected the change of RH but also reflected the effect of carbon dioxide in the air environment. Apparently the changes in both mass and length were not completely recoverable. The change of cement paste was also dependent on the level of RH to which it was exposed. The ranking of the degree of mass change for cement paste is: the change on moving from 65 to 90% > that from 65 to 35% > that from 90 to 65% $\cong$ that from 35 to 65% RH. Mass change was about 0.068: 0.024:0.015:0.015 (%/% RH) in the first cycle. For length, the change on transferring from 65 to 35% > that from 35 to 65% > that from 90 to 65% > that from 65 to 90% RH, and it was about 15.67:10.33:9.88:7.08 ($\times 10^{-4}$ %/% RH) in the first cycle. The difference in change of both mass and length between different ranges of RH is closely related to the movement of different types of moisture in the cement paste. The relationship between mass and dimensional changes is clearly illustrated

TABLE 2.   *The ratio of change over various stages of cycle: 90-65-35-65-90% RH.*

Measurement	Cement paste	CBPB
Mass	(−)1.0:(−)1.6:1.0:4.5*	(−)1.0:(−)1.3:1.3:2.5
Length	(−)1.4:(−)2.2:1.5:1.0	(−)1:(−)2:2:1
Thickness	—	(−)1.1:(−)1.4:1.3:1.0

*(−) = decrease in mass or dimensions.

in Fig. 3S, which is similar to that for CBPB (Fan et al. 1999b). It can be seen that under desorption from 90 to 65 and then to 35% RH, there was a steady decrease in length of laboratory-made cement paste as mass decreased. The movement of water in this range of RH included the movement of capillary water, gel pore water, and adsorbed water in the cement paste (Fan 1997). At the beginning of exposure from 90 to 65% RH, the dominant movement was in capillary water; this decrease of the meniscus radii in channels and capillary cavities due to reduction in RH increased the tensile forces in the water, causing corresponding contraction of the solid. At the late stage of 65% RH desorption and the early stage of 35% RH desorption, the dominant movement was that of water in gel pores, producing a corresponding increase in the tensile forces in the water and contraction in the cement paste. At the later stage of 35% RH exposure, strong tangential tensile forces might arise in the adsorbed water condensed on crystal surfaces, causing a rise in reactive compression in the solid. Abrupt-change at the end of 65% RH exposure was thought to be due to the carbonation of cement paste. The adsorption part of the curve is complicated by a significant change in the slope of the plot of length versus mass change with RH levels. This indicates that another process was taking place, producing a different relationship between length and mass change.

The sensitivity of cement paste to the level of RH was different from that of CBPB, Table 2 (Fan, et al. 1999b). There was a considerable increase in mass on adsorption at 90% RH due to the amount of mini pores in the cement paste holding a great quantity of water. The drying shrinkage of cement paste was more significant, but swelling on wetting was less significant than that of CBPB.

Sorption and dimensional change isotherms (hysteresis loop).—Figure 5 shows that the nature of hysteresis loops of cement paste is exactly the same as that produced from CBPB (Fan et al. 1999b), manifesting itself as making a dominant contribution to the behavior of CBPB. The hysteresis loop is dissimilar to that of wood chips. A gradual mass decrease on desorption reflects as nearly a straight line, while the mass change on adsorption is closely associated with the level of RH. The regain in mass under lower RH was less significant and the regain under higher RH more significant than the loss in mass under desorption, giving rise to an intersection between the desorption and adsorption curves, located between the 65% and 90% RH instead of at 90% RH. The maximum width of the hysteresis could be located anywhere depending on the changing range of RH.

As number of cycles increases, the hysteresis loop of mass moves upward. The vertical movement of the loop clearly indicates an appreciable increase in mass with each successive cycle.

Unlike the loop for mass change, in the loop of length change the curve of adsorption was unable to reach the curve of desorption (Fig. 5B). The values arising from desorption are higher than those arising from adsorption, with the result that the hysteresis loops move lower and lower and the length gradually decreases. The degree of moving of each loop reduced with increasing in the number of cycles.

A comparison of the loop arising from cement paste particle from CBPB and that arising from laboratory-made cement paste shows that a small amount of wood powder may be
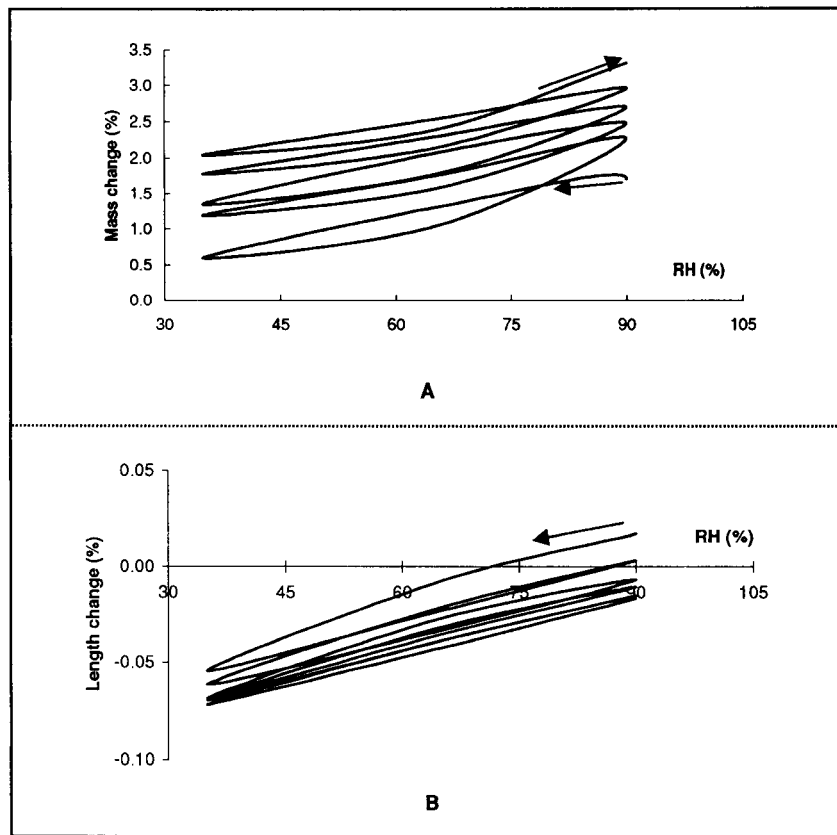
Fig. 5.   A set of hysteresis loops of mass (A) and length (B) changes of laboratory-made cement paste over series of cycles.

contained in the cement paste particle (Fig. 6A). The value arising from cement paste particle is slightly lower than that arising from laboratory-made cement paste at 35% RH, but is very close at 90% RH. This result also indicates a dominant change in mass of cement paste at high RH.

Accumulated change with time or number of cycles.—As occurs under a constant and a single change in RH, when cement paste is cycled between different RHs, the movement is also influenced by the effect of CO_2, resulting in an accumulative increase in mass and decrease in length of cement paste with increasing number of cycles (Fig. 5). After 5 cycles, the accumulated increase in mass was about 1.6%, but decrease in length was about 0.0013% with respect to the values at 90% RH

in adsorption. The equations developed previously (Fan 1997) were applied to the experimentally determined maximum values of accumulated changes of cement paste at 35, 65, and 90% RH (based on the maximum values after preconditioning in 65% RH) (Fig. 4).

$$\Delta M = A_m t^2 + B_m t + C_m$$

$$\Delta L = A_l t^2 + B_l t + C_l \qquad (1)$$

where

ΔM = mass change of cement paste;

ΔL = length change of cement paste;

t = duration of exposure;

A_x, B_x, C_x = coefficients related to the feature of materials and environmental conditions.
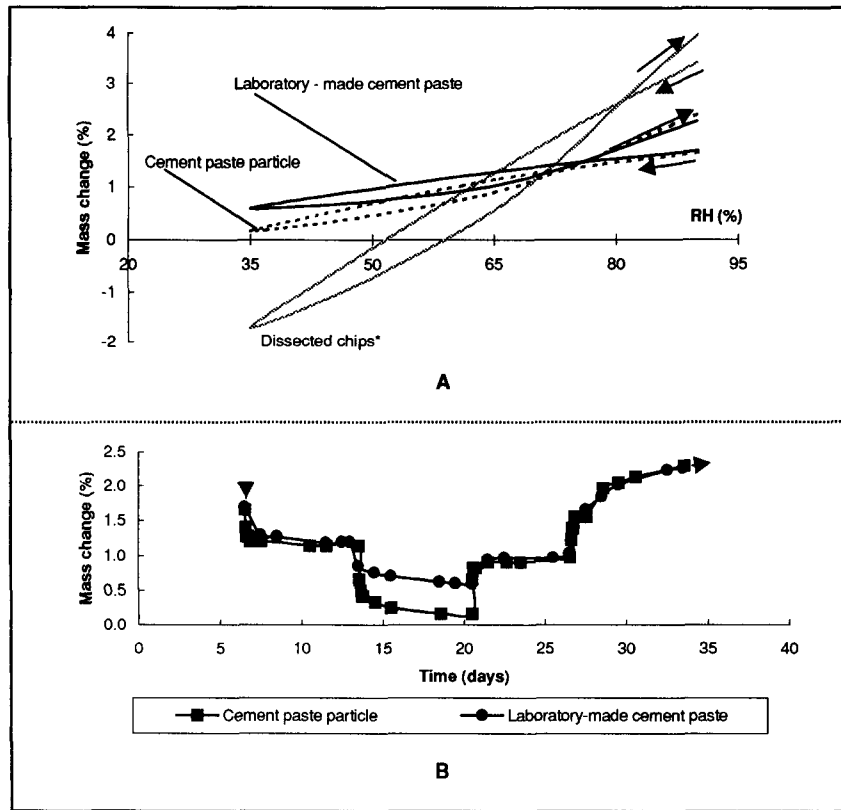
FIG. 6. Comparison of sorption loops (A) and mass change against time (B) between laboratory-made cement paste and cement paste particle from CBPB in one complete cycle: 90-65-35-65-90% RH (*from Fan et al. 1998c).

Coefficients are given in Table 3. The degree of fit of the functions to the experimental data was very high. It is apparent that the trend of accumulated changes of cement paste with increasing number of cycles, whether in mass or dimensions, was very similar to that of CBPB. However, in comparison with those of CBPB (Fan et al. 1999b), the coefficients ("A" and "B") of equations for cement paste are much higher (ranging from 3 to 10 times)

TABLE 3. *Coefficients of mathematical equations for mass and dimensional changes of laboratory-made cement paste in a series of cycles.*

Model	$Y = Ax^2 + Bx + C$			
Coefficient	A	B	C	R2
Mass at 90% RH (a)	$-2.00E-05$	0.0129	1.6945	0.98
Mass at 65% RH (d)	$-5.00E-05$	0.0172	1.0933	0.99
Mass at 35% RH (d)	$-3.00E-05$	0.0163	0.3158	0.97
Mass at 65% RH (a)	$-3.00E-05$	0.0161	0.6644	0.98
Length at 90% RH (a)	2.00E-06	-0.0005	0.0204	0.99
Length at 65% RH (d)	1.00E-06	-0.0004	-0.0028	0.97
Length at 35% RH (d)	4.00E-08	-0.0003	-0.0475	0.98
Length at 65% RH (a)	9.00E-07	-0.0003	-0.0168	0.93

Note: a = adsorption to that RH; d = desorption to that RH.

than those for CBPB, indicating that the accumulated changes of the cement paste were more significant at the beginning of cycling, but declined more rapidly than those of CBPB.

Comparison of cement paste particle with laboratory-made cement paste

Because similar correlation between mass changes of cement paste particle from CBPB and laboratory-made cement paste was found for all cycles and under a single change in RH [the details have been reported earlier (Fan 1997)], detailed examination was restricted to a single one complete cycle (Fig. 6B). It can be seen that the trend of change in mass of laboratory-made cement paste is very similar to that of the cement paste in CBPB (the cement paste particle in test). Changing values at 65 and 90% RH are very close between the two materials except for that at 35% RH, which are probably due to the inclusion of wood chip powder in the cement paste particle tested as aforementioned.

CONCLUSIONS

1) A technique for the laboratory production of cement paste, having the same production parameters as those in the manufacture of CBPB, has been developed. Comparison of the behavior of cement paste particle from CBPB with that of laboratory-made cement paste showed that the features of laboratory-made cement paste were very close to that of cement paste in the CBPB, confirming that the results obtained from the laboratory-made cement paste would represent the contributions of the cement paste to the behavior of CBPB.

2) The trend of the changes of the cement paste was very similar to, but the degree of the change of the cement paste at various conditions was different from, that of CBPB for all results, due to the effect of moisture reaction and carbonation. During 344 days of constant RH exposure, the final mass for laboratory-made cement paste is 1.014 times initial, while for cement paste in CBPB, it is 1.018 times the initial mass. The length and thick-

ness changes of CBPB were about 1.5 and 7.8 times the change of laboratory-made cement paste, indicating that the inclusion of wood chips accelerated the carbonation reaction; the carbonation induced increase in stresses exerted on the wood chips resulted in an extra deformation of the wood chips.

3) The relationship between mass and dimension of the cement paste under sorption can also be divided into two distinct stages with a distinct "inflection point," forming a horizontal "V"-shaped curve. The unique nature of this change was more distinct than that of CBPB, with mass change of the cement paste per unit length change occurring after the "inflection point" being about 8 times greater than that of CBPB.

4) The change of cement paste was dependent on the level of RH. The sensitivity of cement paste to various RH levels was different from that of CBPB. The adsorption/desorption ratio of cement paste was about 1.8 times that of CBPB on moving samples between 65 and 90% RH. The drying shrinkage of cement paste was more significant and the swelling on wetting less significant than that of CBPB.

5) The difference in mass and dimensional change of cement paste between adsorption and desorption gave rise to a hysteresis loop that was very similar to that of CBPB. The loops for mass change intersected each other between adsorption and desorption curves at between 65 and 90% RH, while the loop for length change formed an open loop; this resulted in the hysteresis loops for mass change moving upward, but for length change moving downward with increasing number of cycles.

6) With increasing number of cycles, the mass progressively increased, but length decreased. This accumulated movement was well fitted to the functions developed for the behavior of CBPB and was described in earlier papers in this series. Higher coefficients in the equations of accumulated changes in mass and length of the cement paste than those of CBPB indicated that change in the cement paste was more significant at the beginning of cycling

but declined in successive cycles more rapidly than those of CBPB. A good degree of fitting of models to the data permitted the prediction of accumulated change of the cement paste and using these formulae for modelling CBPB as a composite to be described in a further paper in this series.

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