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# DIMENSIONAL INSTABILITY OF CEMENT BONDED PARTICLEBOARD

## Part 2 Behaviour and its prediction under cyclic changes in RH

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**Summary**. This paper examines the dimensional instability of cement bonded particleboard (CBPB) and discusses the behaviour of CBPB during cyclic changes in relative humidities (RH). The results indicated that the changes of CBPB in both mass and dimensions reflected the changes in RH; in a cycle 90 – 65 – 35 – 65 – 90 %RH the change of per percentage change in RH was 1.0 : 1.3 : 1.3 : 2.5 for mass, 1 : 2 : 2 : 1 for length and 1.3 : 1.1 : 1.0 : 1.0 for thickness. The changes were closely related to the structure of CBPB and the nature of the cement paste and wood chips. Thickness change was double that of length change between 65 and 35 %RH and triple that between 65 and 90%RH. The rate of change in mass was much higher than that in dimensions. The hysteresis loops were dissimilar to those of other wood and wood – based materials, with the loops of mass change closed between 65 and 90 %RH while the loops for dimensional changes were open. A set of the former loops moved upward and the latter moved downward with increasing number of cycles, corresponding to an accumulated increase in mass, but decrease in dimensions. The models developed for CBPB under constant and a single changing RH were successfully applied to changes under cyclic RH.

The sorption behaviour and dimensional movement of CBPB has been shown to be influenced not only by RH, but also by its intermediate history, with the maximum values for change within every phase of sorption, in both mass and dimensions, being higher for the cycling between 35 - 90 %RH than the cycling regime 35 - 65 - 90 %RH. The ratios of dimensional changes to mass change of CBPB were greater under the latter regime than under the former regime.

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## Introduction

It has been observed that the pattern obtained when CBPB is subjected to a single change in RH does not coincide with the curves arising from other materials (Fan, 1997; Fan, *et al*. 1997). Being a hygroscopic materials, CBPB gains or loses moisture with the frequent fluctuation in atmospheric RH. Thus, it should exhibit isotherms which are different between the different ranges of RH.

Hysteresis phenomenon of wood and cement materials is well studied and interpreted (e.g. Powers, 1948; Skaar, 1988; Dinwoodie, 1987). Additionally, the volumetric change of wood beyond that produced by water may be significant, such as the effect of alkali (Kollman and Cote, 1968) and the bulking of cell wall (Goldstein, 1977; Rowell, *et al*. 1981). For cement paste, some of irreversible shrinkage, generally between one thirds and one half of the reversible shrinkage (Czernin, 1980; Feldman and Sereda, 1970), occurs in the first cycle of drying or wetting due to fundamental change in structure (Helmuth and Turk (1970), or a decrease in the total energy of the system as RH change (Ishai, 1968). Carbonation of cement paste has also long been recognised, producing an irreversible shrinkage. However, the rate and degree of carbonation and carbonation shrinkage were essentially related to the moisture content in the material. Pores filled with water hinder the penetration of carbon dioxide because of the low rate of diffusion of $CO_2$ in water, whilst reaction of carbon dioxide with water molecules is absent in the completely dry pores.

Studies on wood have also shown that the equilibrium moisture content (EMC) on adsorption is higher when a dry sample is exposed to a given RH in one single step than when it is brought to the same RH via a series of adsorption steps (Skaar, 1988). Intermediate sorption curves of hygroscopic materials lie between those for the full - cycle adsorption and desorption when the direction of sorption is reversed at points between 0 and 100 %RH: there is no abrupt jump from the full adsorption curve to full desorption curve but rather a smooth crossover occurs (e.g. Peralta, 1995).

This paper is part of a series described the nature and behaviour of CBPB, this part of the project was designed and conducted to examine the response of CBPB to changes in RH over a series of cycles, to evaluate the hysteresis of CBPB due to the moisture adsorption and desorption, and to generate information on the nature and behaviour of the intermediate sorption curves through different ranges of RH. It is expected that the results will be of practical importance to the application of CBPB.

## Experimental materials and procedure

Panels of commercially produced CBPB, 12 mm and 18 mm thick, were obtained from French and UK manufacturers. These boards were cut up to produce panels 600 x 600 x 12 mm and 600 x 300 x 18 mm respectively. After conditioning at 20 $^{0}$C / 65 %RH to equilibrium, specimens were subjected to controlled cycling RH.

The program of RH change was selected to embrace the extremes of RH likely to be encountered in service. Thus, the cycling regimes were: -

20 $^{0}$C / 90 %RH−−−−−−→20 $^{0}$C / 65 %RH−−−−−−→20 $^{0}$C / 35%RH
↑←-----------------20 $^{0}$C / 65 %RH←----------------↓

The samples were moved from one condition to another after the constant dimension or constant mass was achieved. The actual temperature and RH of the conditioning chambers were monitored continuously and frequently calibrated.

Mass, thickness and length were recorded after 24 h, 48 h, 72 h and then at 72 h intervals and the percentage change of mass and dimensions with respect to the initial conditioning values were calculated.

## Results and discussion

### The different reactions of mass and dimensions to an initial RH change

The values of mass and dimensional changes resulting from an initial adsorption at 90 %RH as well as the first complete cycle of changing RH are presented in Figure 1; it may be seen that an initial adsorption at 90 %RH brought about large increases in both mass and dimensions. The initial increase in RH from 65 to 90 %RH resulted in an increase in mass and length by 3.72 % and 0.133 % respectively, whilst after exposure to the same conditions in the first complete cycle the values were only 1.95 % and 0.041 % respectively. Most of this difference could be attributable to either the structure change, or a decrease in the total energy of the system in the cement paste (Ishai, 1968; Helmuth and Turk, 1970). The extremely rapidly initial increase in thickness with change in RH from 65 to 90 %RH may also be attributable to the immediate swelling of wood chips as soon as adsorption on wood chips. For the whole panel, the possibility of stress release can not be excluded.

### The behaviour in mass and dimensions within one complete cycle of RH

From Figure 1, it will be seen that the changes, both in mass and dimensions, reflect change in RH. In one complete cycle, there existed obvious differences in mass and dimensional changes at those parts of the cycle embracing either high or low RHs. When the first complete cycle is considered, the RH change from 90 to 65 % resulted in only a small change in the mass whilst changing from 65 to 90 %RH caused an appreciable increase in mass. By contrast, a nearly complete recovery was found in length change between on transferring CBPBs from 90 to 65 %RH and from 65 to 90 %RH. Complete recovery was also found for both mass and length changes during RH changes from 65 to 35 % and from 35 to 65 %. During the cycle 90 - 65 - 35 - 65 - 90 %RH, the ratio of length change over the different stages of the cycle was 1 : 2 : 2 : 1, whilst it was 1.0 : 1.3 : 1.3 : 2.5 for mass. These results reflect the behaviour of both the cement paste and the wood chips in CBPB when their relative contents were taken into account. The marked increase in mass above 80 %RH is due most likely to capillary condensation, which are in agreement with the results of previous work carried out on cement paste (Feldman, 1964; Power, 1948). The phenomenon, that a much greater length movement of CBPB occurred below 65%RH than above this RH, coincided with that of carbonation shrinkage of cement paste observed by Swenson and Sereda (1968), who found maximum carbonation shrinkage occurred when samples were conditioned at 50 %RH; much lower values were obtained at higher and lower RH. In particular, the largest part of carbonation-induced-shrinkage of cement paste was postulated by these authors to be a consequence of cycles of induced drying shrinkage.

In addition to the considerable differences in behaviour of mass and length discussed above, another significant characteristic of CBPB is the different behaviour of length and thickness with respect to RH change (Figure 1). The very different degree of swelling or shrinkage in the three principle axes, owing to the complex structure of the wood, could be responsible for much of the recorded difference, especially so in view of the isotropic nature of the cement paste.

In Figure 1 the trend of thickness (T) and length (L) change is similar for both adsorption and desorption, but the change in thickness per percentage change in RH was considerably higher than that in length. Thus, $\Delta L$ / $\Delta T$ is 1.0 : 3.1 for desorption and 1.0 : 2.9 for adsorption during RH change between 65 and 90 % cycle, and 1.0 : 2.0 and 1.0 : 1.9 between 35 to 65 %RH. It appears that a similar change in percentage of thickness occurred over the whole range of RHs. The large carbonation shrinkage of cement paste was not reflected in the behaviour of the thickness change of CBPB due probably to the dominance of the considerably higher transverse movement of chips. The main questions is how much of this change was contributed by the wood chip itself in terms of the different structure along the thickness and length (or width)? This was studied in the numerical modelling and image analysis and will be reported on further papers.

### Behaviour of mass and dimensions in successive cycles

Most interesting results were obtained from a set of cycles. With increasing number of cycles, there was an accumulated increase in mass and decrease in dimensions. This is shown in Figure 2 (cyclic curves) in which the values are expressed in terms of the original values at 90 %RH. Total recovery did not take place during cyclic RH; the degree of irrecovery was very high in the first cycle, but decreased over successive cycles.

It is evident that both reversible and irreversible deformations occurred in the CBPB subjected to the environmental cycles. Reversible swelling and shrinkage is well known in terms of wood and cement paste, and the mechanisms of these have been well interpreted (Dinwoodie, 1981; Soroka, 1979; Illston, *et al*. 1979). Irreversible behaviour of CBPB has been related, first, to the carbonation of cement paste in the CBPB which not only increased the mass of the cement paste, but was also accompanied by an irreversible carbonation shrinkage, and, second, to the alkali degradation of the wood chips 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 chips). There are, at least, two types of stress (and resulting strains) in CBPB subjected to cyclic RHs, 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 chips. Thus, when wood chips and cement paste adsorb or desorb moisture under cyclic RHs, the amount of shrinkage or swelling per unit volume of each component is different, resulting in the generation of internal stress. If the swelling of dry wood is restrained by the influence of external forces, the anatomical structure of the wood will be changed. Subsequent re - drying to the original moisture content is accompanied by a reduction of the dimensions, i.e. by a permanent deformation (Kollman and Cote, 1968). The effect of mechanical stress on deformation is most apparent when wood which is restrained from movement is subjected to cyclic moisture changes (Skaar, 1972). Therefore, this inevitably intensifies the irreversible shrinkage of CBPB. The change in mass and length within a single cycle of changing RH, and especially the accumulative change between consecutive cycles are clearly illustrated in Figure 3.

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 RH cycle was different. This difference is related to the structure of CBPB (Fan, *et al*. 1997). Additionally, the moisture gradients due to the cyclic RH changes may bring about an adverse effect on the different change between thickness and length (or width).

### Relationship between the mass and dimensional change in one complete cycle

Because similar mass and dimensional changes of CBPB were found for all cycles, detailed examination was restricted to a single complete cycle. The relationship between dimensional and mass change of CBPB in the first complete cycle is plotted in Figures 4 (data points). Where the dots are densely accumulated around markers B, C, D and E are the final stage of the exposure. It can be seen that the relationships both between length and mass change and between thickness and mass change are similar to those occurring over a single RH change (Fan, *et al*. 1997). On desorption, the relationship appears to be linear; however, on desorption a linear relationship was found only below 65 %RH. Above this, the relationship was non – linear due probably to moisture condensation.

**Sorption and dimensional change isotherms (hysteresis loops)**

For CBPB the hysteresis loops for mass, length and thickness as a function of RH are shown in Figure 5 for a set of cycles. The successive loops were obtained upon subsequent sorption after the sample had been allowed to come to equilibrium. In the case of mass change the bottom loop in Figure 5A is the first loop; for dimensions the top loop in Figure 5B and 5C is the first loop.

As was the case for the long term exposure of CBPB at 90 %RH (Fan, *et al*. 1997), the rate of change under adsorption varies greatly with the level of RH due to the complex structure of CBPB. The hysteresis loop is not of the types usually found for wood or other wood particleboard: the maximum width of the hysteresis loop did not occur in the middle stage, but could be located anywhere depending on the changing range of RH. It was shown (Figure 5A) that the decrease in mass on desorption was linear, whilst the mass change on adsorption is closely associated with the level of RH, with the curves being convex to RH axis. Within each cycle, 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. This difference in the change of mass gave rise to an intersection between the desorption and adsorption curves, located between the RH 65 % and 90 % instead of at 90 % - a reflection of the progressive increase in mass in successive cycles. The point of intersection relates to the levels of vapour pressure (RH) above which condensation can occur, and the CBPB produces a unique isotherm which can be interpreted as being determined not only by the reaction of CBPB with water, but also the condensation of moisture within the CBPB. The history of sorption of wood seems to be valid for CBPB only under desorption and adsorption at lower RHs.

In addition, CBPB exhibits certain irreversible phenomena not found among some other types of materials. This may also be seen in Figure 5A. Comparison of the first with the second hysteresis curves shows a marked difference between them. No explanation for this feature could be established in terms of the wood unless the wood chips are produced from dried green wood which gives the highest equilibrium moisture content at a given RH (Skaar, 1972). However, this significant deviation between the successive cycles, especially between the first and second cycles, is believed to be due to two factors relating to the nature of cement paste, one of which is thought to be irreversible shrinkage of the cement paste thereby reducing the capacity of the sample to hold evaporable water. The other reason is thought to be the additional hydration of the cement paste in the CBPB which occurs while the sample is subjected to vapour pressures above about 80 %RH (Powers and Brownyard, 1948).

After the first cycle, the curves produced by the successive cycles are practically similar (Figure 5A). However, the vapour pressure at which the loop closes is getting higher as the number of cycles is increased, and this gives rise to a change in the size of the hysteresis loop. It appears that the width of loop at 65 %RH decreases as the number of cycle increases (excepting that of the first cycle). However, a very similar width of the hysteresis loop is observed between the 9th and 10th cycle. Like the width of loop at 65 %RH, the amount of change between the successive cycles at 90 %RH is reduced with increasing number of cycles. The difference in the mass increase between the first and second cycles is 1.12 % but is only 0.09 % for the difference between the 9th and 10th cycles. However, in contrast, the values arising from adsorption are higher than those derived from desorption.

The result above indicates that the CBPB becomes "stabilised" after long - term exposure: cyclic changes in moisture may result in a change in the structure of CBPB with the possibility that the successive hysteresis loops of CBPB would coincide after a considerable number of cycles.

As the 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. At 90 %RH, the increase in the mass of CBPB was 2.10 % and 2.78 % for the first five and first ten exposures respectively. It should be noted that the continued hydration only has the effect of increasing the minimum mass of cement paste and the upward movement of the successive loops can only be explained in terms of the carbonation of cement paste in the CBPB during exposure.

The features pointed out in Figure 5A for mass are not present for length and thickness (see Figures 5B and 5C). The dimensional changes produced curves concave to RH axis for both adsorption and desorption, those for length showing a higher degree of curvilinerity (Figure 5B). The adsorption curve is not intersected by the desorption curve. However, the values arising from desorption are higher than those arising from adsorption. In contrast to mass change, as the number of cycles increased, the hysteresis loops moved lower and lower and length gradually decreased. There were decreases of 0.038 % and 0.053 % after the fifth and tenth exposure at 90 %RH. The degree of movement of each loop was reduced with increasing number of cycles.

The results above showed that the sorption - induced - dimensional change was basically similar to that of cement paste: large proportion of the change in length occurred in the low RH region of the isotherm. A decrease in slope, in contrast to the increase found for mass, occurred at higher RHs. Similar results were also observed for the adsorption of water on"'Cab-O-Sil" silica, precipitated calcium carbonate and calcium sulphate hemihydrate (Feldman and Sereda, 1963). These results suggest that volume change in CBPB is due not solely to movement of water in or out of the system.

The pattern of change of CBPB plotted as the mass change (△W) versus length change (△L) for a set of cycles is shown in Figure 6. The curves for desorption appear to be nearly straight, and to be parallel between each loop. This indicates that the relationship between the length and mass change is very similar under desorption and is independent of the immediate RH. However, unlike previous Figures, the width of loop is getting wider with increasing number of cycles. The adsorption part of each loop was complicated by the condensation of moisture onto the CBPB. Condensation becomes more dominant with increasing level of RH, and results in a different relationship between mass and dimensional changes of CBPB. The slope of the loop of the length versus mass change plot reduces with increasing number of cycles. The location of the intersection between the adsorption and desorption curves increases with increasing number of cycles. This intersection point could probably be considered as the critical point in the history of change of CBPB between the regions of primary hysteresis and secondly hysteresis. A careful study of the hysteresis in some other materials has produced similar results (Powers, *et al*. 1959).

The graph for △T to △W is very similar to that for △L to △W.

**Effect of different RH regimes on behaviour of CBPB over three cycles**

It was found that higher levels of mass and dimensional changes occurred when CBPB was subjected to the RH cycle of 30 - 90 %RH (single step) compared to cycle 35 - 65 - 90 %RH (multistep) (Table 1). Within each cycle the adsorption phase reached the same limiting mass change value, whilst the desorption phase reached the same limiting dimensional change values for both single and multistep process.

It would appear that desorption or adsorption curves for the mass and dimensions of CBPB on cycling under multistep cycle are enclosed within those curves derived from cycling under single step. During every adsorption or desorption phase (half cycle) (every row in Table 1) the maximum change values, whether mass, length or thickness changes, arising from multistep cycling are lower than those from single step cycling. For example, over the third period of adsorption, the maximum mass, length and thickness changes resulting from multistep are 92 %, 91 % and 88 % of the maximum changes arising from single step respectively. The explanation for the pronounced effect of sorption history can be related to the effect of the moisture gradient which results in a stress gradient: a higher gradient of vapour pressure brings about a higher gradient of moisture concentration (at least at the first stage of exposure), resulting in a higher degree of moisture adsorption or desorption. In common with other porous materials, a greater gradient of moisture concentration is normally accompanied by a greater stress (or stress gradient), thus producing high dimensional changes in each phase of sorption.

However, the effect of the vapour pressure gradient on the dimensional change is less or delayed compared to the effect on the mass change due to effects of other mechanisms (Figure 7). The dimensional changes per unit mass change (the ratio of △L / △W or △T / △W) for multistep cycle are greater than those for single step cycle, in contrast to relationships of the mass or dimensional changes and time. The results suggest that there exists a different reaction between CBPB and moisture under different sorption histories; both sorption sites and structure may change differently when using single or multistep to reach the same RH. On adsorption, when samples were first conditioned to a lower RH, and then to a high RH, moisture was absorbed at first into smaller sizes of pores and subsequently filled larger sizes of pores. However, if samples were subjected to high RH at the beginning of adsorption, the filling of larger sizes of pores may push some adjacent "particles" closer, blocking some of spaces at the first stage and resisting further adsorption in the smaller size of pores. Thus, the amount of moisture adsorbed in the smaller size of pores was relatively less over single step than over multistep cycle, and accordingly, lower percentage dimensional changes per unit mass change were produced under single than under multisetp cycle. This result is in agreement with the result derived from the cementitious research in which the evaporation of gel pore moisture results in greater dimensional change compared to the evaporation of capillary pore moisture (Powers, 1948). However, on desorption, the higher gradient of vapour pressure (RHs) at the beginning of desorption may caused a rapid contraction of the "particles", the paths of moisture transportation or evaporation may be partly blocked resisting further movement of moisture and subsequently reducing the sorption in the smaller size of pores.

Although the phenomenon has not been investigated extensively here, there is little reason to doubt that CBPB shows essentially the same behaviour as that described for in other cementitious based materials (Rao, 1941; Urquhart, 1960). At a particular temperature, the curves of full ad- and de- sorption define the limiting equilibrium values and thus may be viewed not as equilibrium loci, but as borders that outline the hysteresis area. Hence, the isotherms of full sorption should be correctly referred to as boundary isotherms. Any point within the hysteresis region may be reached depending upon the condition to which the material is initially subjected. Thus, if the process of ad- or de- sorption is reversed at any point short of the horizontal extremes of the loop, the part of the curve previously generated will not be retraced, but instead the points will cut across the loop. If at any stage of adsorption in this range the process is reversed, the resulting downward curve will cross over from the adsorption to the desorption curve. If the desorption curve is reversed, then a new rising curve will cross over toward the adsorption curve, but instead of joining the adsorption curve, the new curve will rise more or less parallel to the adsorption curve. The temperature and RH to which a sample of CBPB is exposed does not uniquely define the equilibrium of the material: it is also necessary to specify the sorption history of the CBPB.

## Prediction of changes under cyclic RH of 90 - 65 - 35 - 65 - 90 %

### Prediction of the accumulated change in CBPB with time or number of cycles

The equations described (Fan, *et al*. 1997) were fitted to experimentally determined maximum changes in mass and dimensions of 12 mm CBPB at 35, 65 and 90 %RH (based on the maximum values after preconditioning in 90 %RH) (Figure 2). The coefficients are given in Table 2; this table also illustrates ($R^2$) the very good fit of the line to the experimentally derived data.

It is apparent that the trend of an accumulated change of CBPB under cyclic RHs, whether in mass or dimensions, was very similar to that under constant RH. A comparison of the curves fitted shows that the forms of curves through 35, 65 and 90 %RH are very similar, whether for mass or dimensional changes. However, in comparison with those under a constant environmental condition, the rate of change was much more significant. This is because the rate and degree of carbonation and carbonation shrinkage are related to the RH (moisture content) in the material which affects the rate of diffusion of $CO_2$.

For practical applications, the accumulated change was plotted as a function of the number of cycles. Logarithmic functions of the number of cycles are found to be the best predictors for the mass increase and dimensional decreases. The coefficients of the equations are also included in Table 2. The degrees of fit ($R^2$) is very high for both mass and dimensional predictions.

By comparing the adsorption curves (and their equations) with the desorption curves, differences due to the sorption history can be predicted. Although the predictions above are the maximum values for the various stages, it is possible to predict the results within these ranges.

A comparison of coefficients between 12 mm and 18 mm (Table 2) shows that the trend in the change of the two thickness of CBPB was very similar though the magnitude of the change was different; the higher change occurred in the 18 mm CBPB.

### Prediction of cyclic change of CBPB

Using the models developed in an earlier paper in this series for a single change in RH (Fan, *et al*. 1997), a prediction in the change of 18 mm CBPB under cyclic RH was carried out. The fitted curves and experimental data are pointed in Figure 8. The efficacy of the models in representing the data is confirmed.

### The relationship between mass and dimensional change of CBPB

In Figure 4 the theoretical equations described (Fan, *et al*. 1997) were also fitted (lines) to the experimental data derived on 18 mm CBPB in one complete cycle. Like those under a single change in RH, the relationships follow the theoretical predictions regardless of the intermediate change in RH. CBPB, in moving from 90 to 65, then to 35 and then back to 65 %RH, shows linearity between movement and mass change, but from 65 to 90 %RH the relationship is exponential. This illustrates the flexibility and efficacy of models developed.

## Conclusions

1) The changes in the mass and dimensions of CBPB reflect the changes in RHs ranging from 35 to 90 %. The adsorption curve under higher RH was dominated by the condensation of moisture within the CBPB. The rate of length change over the lower level of the RH cycle was double that over the higher level of the cycle while the rate of thickness change was similar between the two levels of the cycle. There existed a significant different in mass change between ad- and de- sorption during cycling between 65 – 90 %RH. The fact that initial exposure brought about pronounced irreversible changes both in mass and dimensions of CBPB paralleled that of cement paste, and the observed behaviour suggested that there existed still further chemical and physical reactions within CBPB.

2) The change in the thickness of CBPB under cyclic RH was much higher than that in length. Double the rate of thickness change to length change appeared during change in RH between 35 and 65 %RH, and triple the rate during change in RH between 65 and 90 %RH, a reflection of the behaviour of both the cement paste and the wood chips.

3) Both reversible and irreversible movement occurred in CBPB subjected to cyclic RH, giving rise to hysteresis loops for both mass and dimensions which were dissimilar to those for wood or other wood particleboards. All hysteresis loops did not close at the ultimate RH. Ad- and de- sorpion curves for mass change intersected at between 65 and 90 %RH, depending on the number of cycles. However, the ad- and de- sorption curves for dimensional change did not intersect over the range of RHs tested.

4) The hysteresis loop for mass change moved upward and those for dimensions moved downward with increasing number of cycles of RH change, but the degree of these movements, which corresponded to an accumulated increase in mass and decreases in dimensions over the successive cycles, decreased with increasing number of cycles. The accumulated changes in mass, length and thickness amounted after 10 cycles to about 2.8, 0.06 and 0.10 % respectively.

5) The width of the hysteresis loops for mass, length and thickness, plotted against the RH,

decreased as the number of cycles increased, indicating that a structure change in the CBPB occurred during the RH cycle. The width of the hysteresis loops for length and thickness change, plotted as the mass change, increased with the number of cycles. This not only suggests that the dimensional change per unit mass change increased but it also confirms the existence of structural change.

6) The sorption behaviour and dimensional movement of CBPB has been shown to be influenced not only by temperature and RH, but also by its intermediate history. The maximum change values within every phase of sorption, in both mass and dimensions, were higher for single step than multistep cycle. The rates of dimensional changes to mass change of CBPB were greater under multistep than under single step cycle though the trends of the relationships are similar. The full or wider range ad- and de- sorption isotherm simply defined a delimiting loop that enclosed a hysteresis region, and any point within this region may be reached through a given intermediate curve by subjecting CBPB to an appropriate step. However, within each cycle the adsorption phase reached the same limiting mass change value but the desorption phase reached the same limiting dimensional change values, for both single and multistep process.
7) Under cyclic RH, the changes of CBPB comprised cyclic and accumulated changes. The changes were applicable to the models developed from CBPB under constant and single changing RH. This confirmed the flexibility and efficacy of the models developed in part 1 of this series of papers.

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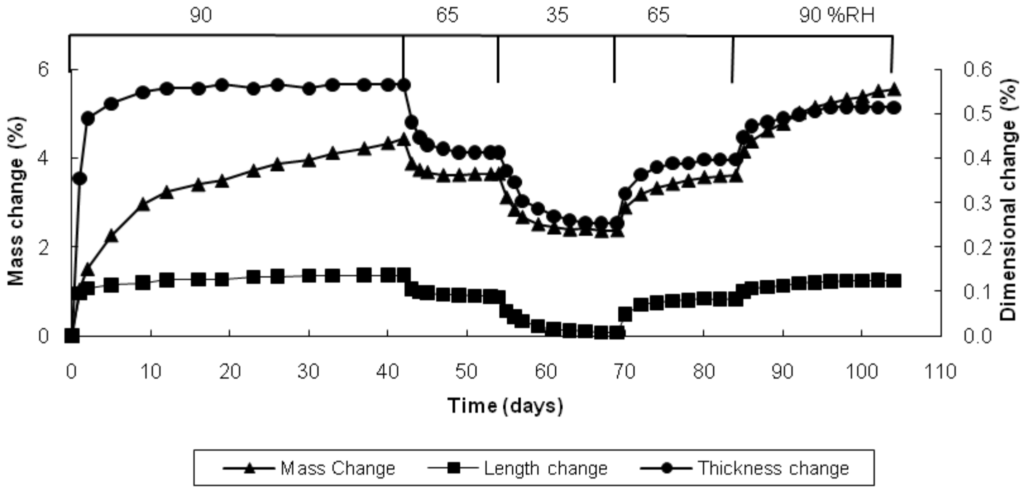


**Figure 1 Change in mass and dimensions of CBPB over initial adsorption and the first complete cycle**

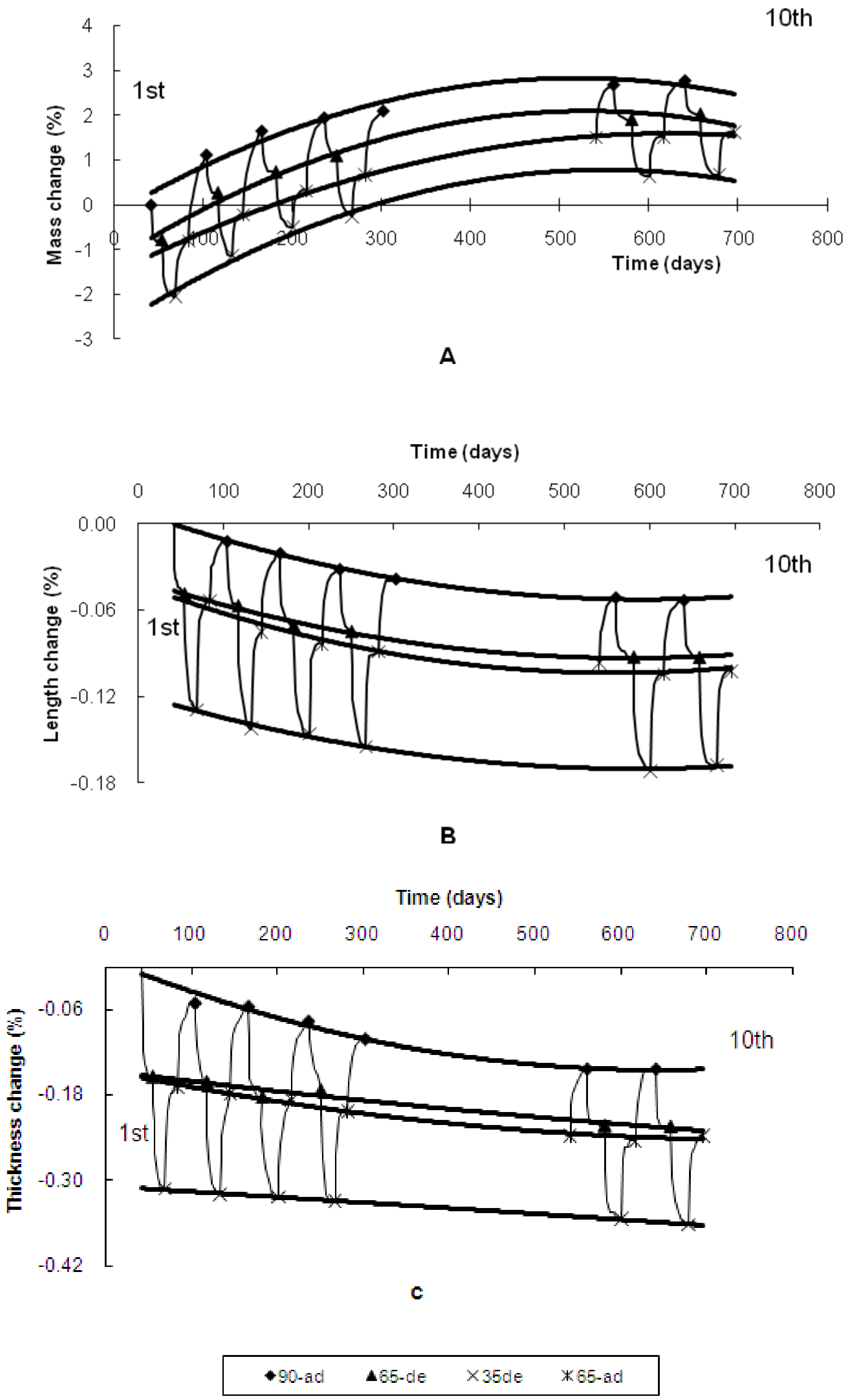
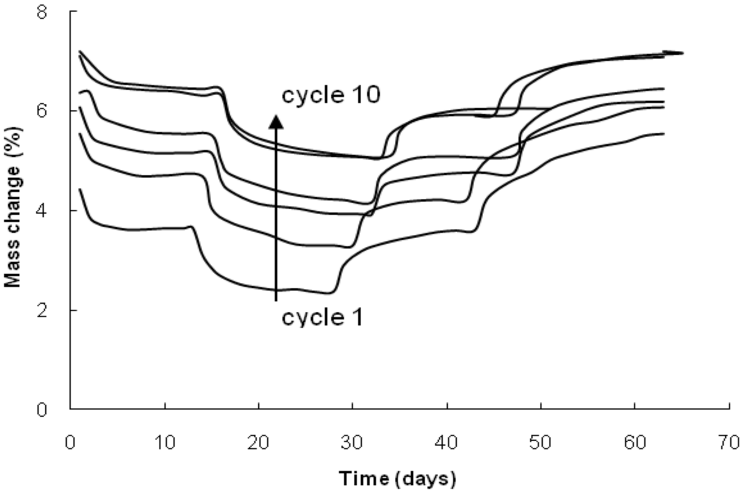
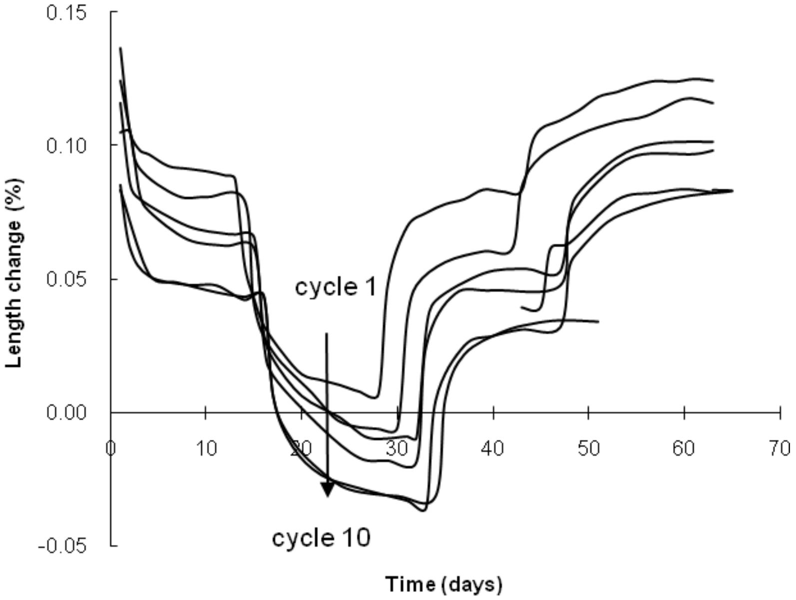


Figure 2 Experimentally determined and predicted change in mass (A), length (B) and thickness (C) of 12 mm CBPB (10 cycles in 90 - 65 - 35 - 65 - 90 %RH)



**A**



**B**

**Figure 3 Difference in mass (A) and length (B) changes of CBPB between successive cycles of RH: 90 - 65 - 35 - 65 - 90 %**

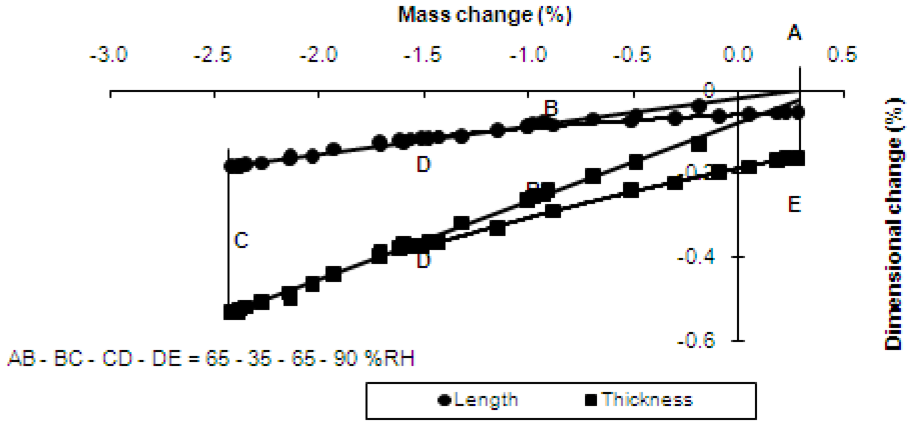


Figure 4 Experimental (markers) and calcalated (lines) curves for CBPB in one complete cycle of cyclic RH

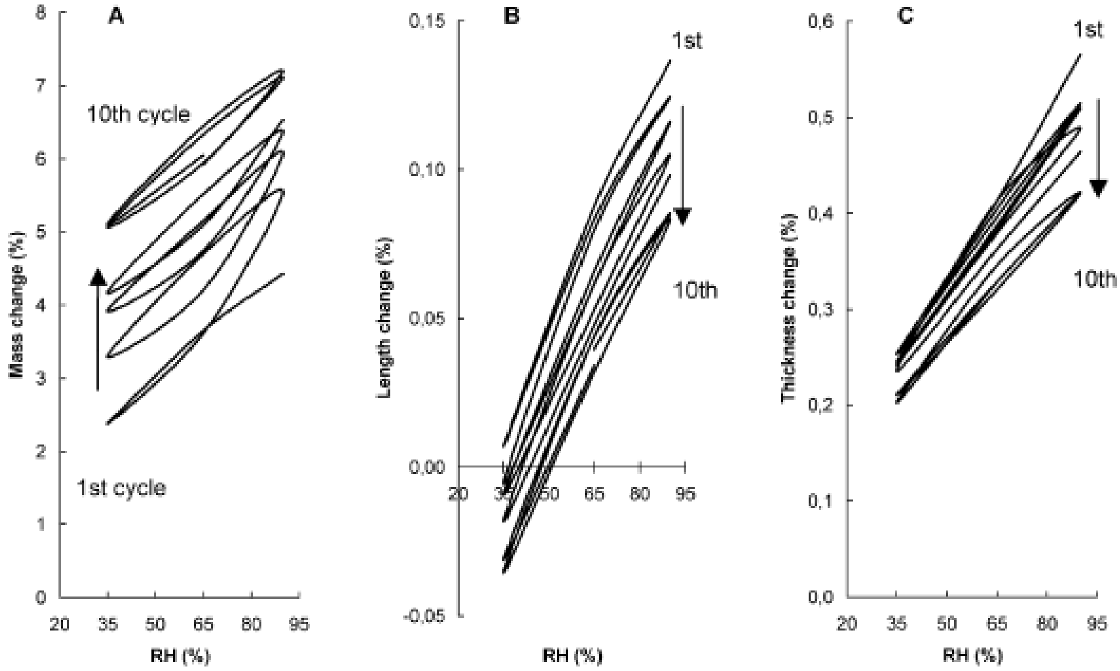


Figure 5 Sorption isotherms for mass (A), length (B) and thickness (C) of CBPB over a series of cycles

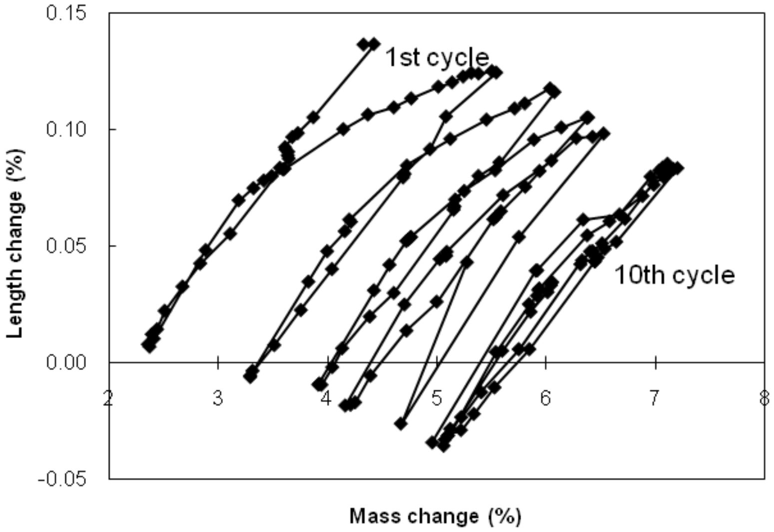


**Figure 6 Plot of length against mass change of CBPB over series of cycles**

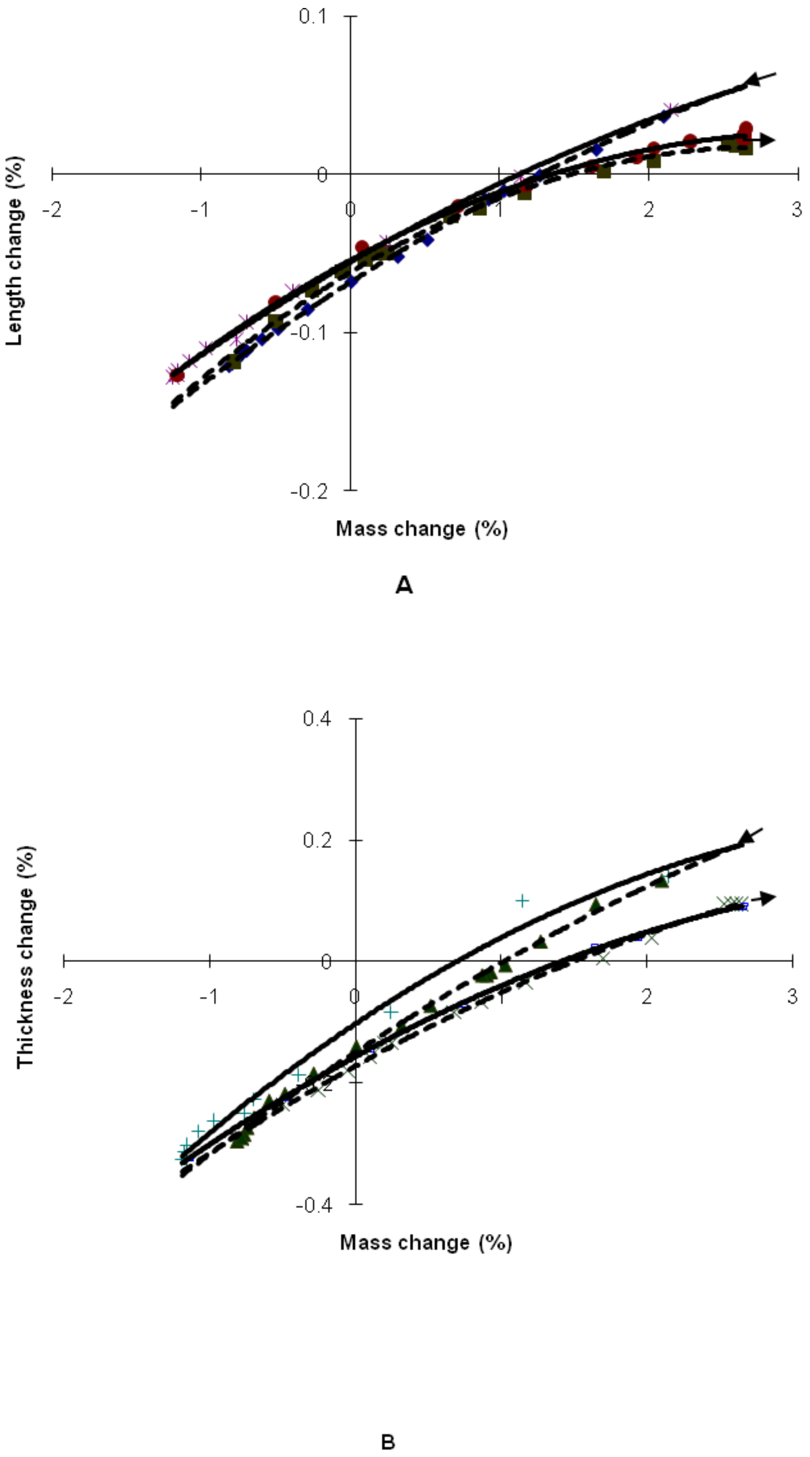
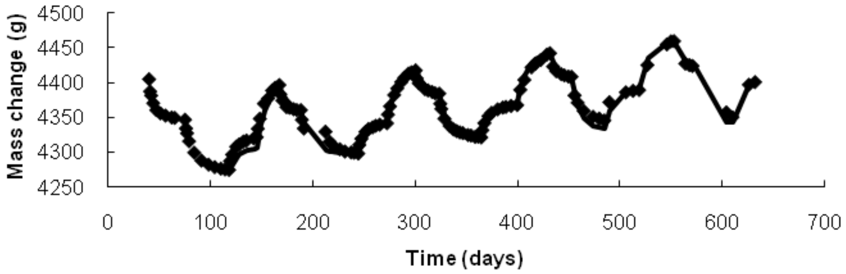
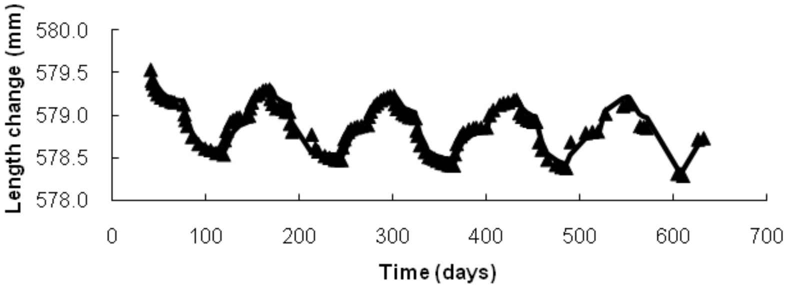


Figure 7 Relations between length (A) or thickness (B) and mass change arising from two different RH cycles



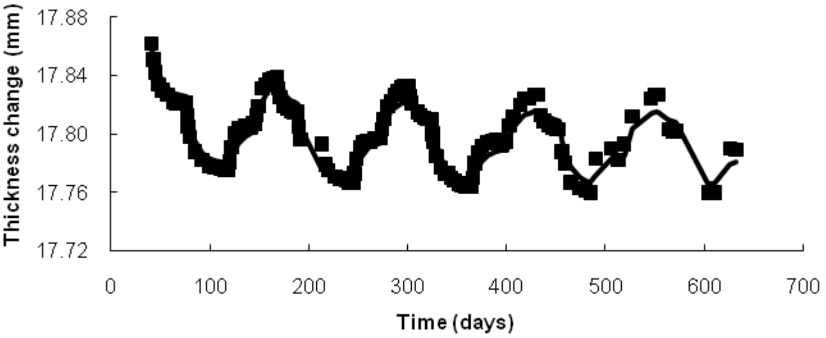
M=a+b*t+c*exp(-12.583E-2*t)

**A**



L=a+b*t+c*exp(-10.776E-2*t)

**B**



T=a+b*t+c*exp(-10.776E-2*t)

**Figure 8 Experimental and fitted curves of cyclic change in mass (A), length (B) and thickness (C) of CBPB in RH: 90 - 65 - 35 - 65 - 90 %**

Table 1 Maximum values for changes in mass, length and thickness of CBPB under various durations

| Cycle | Mass change (%) | | Length change (%) | | Thickness change (%) | |
|---|---|---|---|---|---|---|
| | Single - step* | Multi - step* | Single - step | Multi - step | Single - step | Multi - step |
| 1-ad** | 4.23 | 4.07 | 0.145 | 0.131 | 0.432 | 0.408 |
| 1-de | 3.31 | 2.88 | 0.168 | 0.155 | 0.455 | 0.425 |
| 2-ad | 3.80 | 3.43 | 0.148 | 0.135 | 0.404 | 0.386 |
| 2-de | 3.07 | 2.61 | 0.160 | 0.149 | 0.398 | 0.380 |
| 3-ad | 3.28 | 3.03 | 0.147 | 0.134 | 0.348 | 0.307 |
| 3-de | 2.71 | 2.37 | 0.151 | 0.144 | 0.365 | 0.339 |

* Single - step = 35 - 90 %RH; multi - step = 35 - 65 - 90 %RH;

** 1, 2, 3 = the numbers of cycle; ad = adsorption from 35 - (65) - 90 %RH; de = desorption from 90 - (65) - 35 %RH.

Table 2 Coefficients of mathematical equations for mass and dimensional changes of CBPB in a series of cycles (90-65-35-65-90 %RH)

| | Change against exposing time | | | | | | | | against number of cycles | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Model | $Y = Ax^2 + Bx + C$ | | | | | | | | $y = a\ln(x) + b$ | | |
| Coefficient | A | B | C | $R^2$ | A | B | C | $R^2$ | a | b | $R^2$ |
| Type of CBPB | 18 mm CBPB | | | | 12 mm CBPB | | | | | | |
| Mass at 90%RH (a) | -5.00E-07 | 0.0041 | -0.8785 | 1.00 | -1.00E-05 | 0.0117 | -0.2014 | 0.96 | 1.1654 | 0.2082 | 0.98 |
| Mass at 65%RH (a) | -2.00E-06 | 0.0052 | -1.9265 | 1.00 | -1.00E-05 | 0.0126 | -1.2447 | 0.98 | 1.1847 | -0.6432 | 0.99 |
| Mass at 65%RH (d) | -2.00E-06 | 0.0051 | -2.6265 | 0.99 | -8.00E-06 | 0.0100 | -1.5401 | 1.00 | 1.1012 | -0.8823 | 1.00 |
| Mass at 35%RH (d) | -4.00E-06 | 0.0065 | -3.7113 | 0.99 | -1.00E-05 | 0.0128 | -2.7444 | 0.99 | 1.1830 | -1.9532 | 0.99 |
| Length at 90%RH (a) | 3.00E-07 | -0.0003 | 0.0086 | 0.97 | 2.00E-07 | -0.0002 | 0.0079 | 1.00 | -0.0241 | 0.0025 | 0.99 |
| Length at 65%RH (a) | 5.00E-08 | -0.0001 | -0.0622 | 0.99 | 2.00E-07 | -0.0002 | -0.0392 | 0.99 | -0.0202 | -0.0471 | 0.99 |
| Length at 65%RH (d) | 3.00E-08 | -0.0001 | -0.0804 | 0.96 | 2.00E-07 | -0.0002 | -0.0423 | 0.94 | -0.0204 | -0.0580 | 0.96 |
| Length at 35%RH (d) | -2.00E-08 | -7.00E-05 | -0.1653 | 0.98 | 2.00E-07 | -0.0002 | -0.1188 | 0.99 | -0.0180 | -0.1290 | 0.98 |
| Thickness at 90%RH (a) | 1.00E-06 | -0.0010 | 0.0314 | 0.97 | 4.00E-07 | -0.0005 | 0.0115 | 0.98 | -0.0632 | 0.0024 | 0.98 |
| Thickness at 65%RH (a) | 2.00E-07 | -0.0004 | -0.2023 | 0.99 | 2.00E-07 | -0.0003 | -0.1446 | 0.98 | -0.0331 | -0.1433 | 0.90 |
| Thickness at 65%RH (d) | 3.00E-07 | -0.0004 | -0.2584 | 0.94 | 4.00E-08 | -0.0002 | -0.1453 | 0.96 | -0.0353 | -0.1581 | 0.93 |
| Thickness at 35%RH (d) | 4.00E-07 | -5.00E-04 | -0.4393 | 0.99 | -4.00E-09 | -8.00E-05 | -0.3081 | 1.00 | -0.0218 | -0.3057 | 0.91 |

* a = adsorption from lower RH to that; d = desorption from higher RH to that.