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Dimensional instability of cement bonded particleboard : understanding its occurrence and reducing its magnitude

Fan, Mizi

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DIMENSIONAL INSTABILITY OF CEMENT BONDED PARTICLEBOARD:

Understanding its occurrence and reducing its magnitude

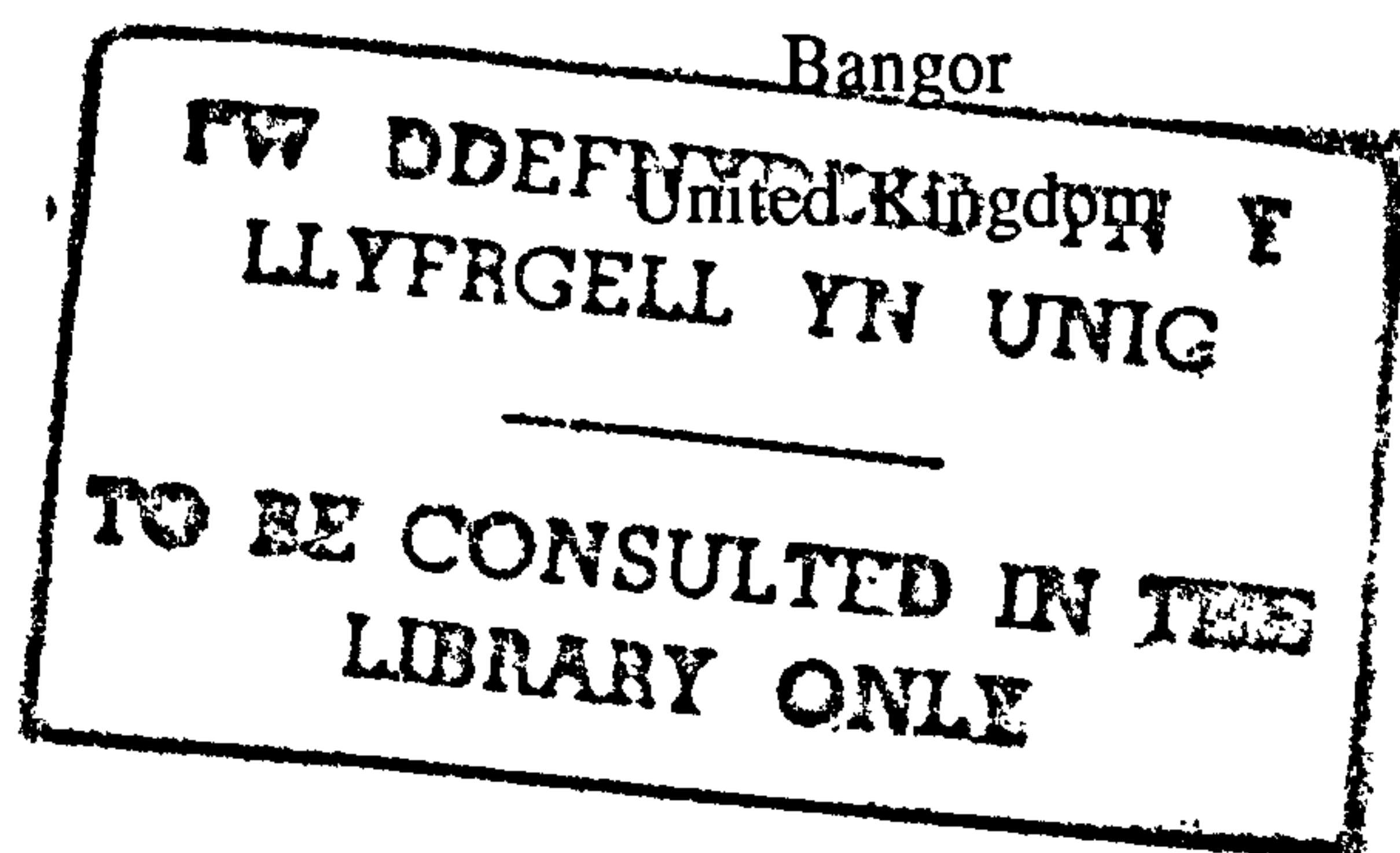
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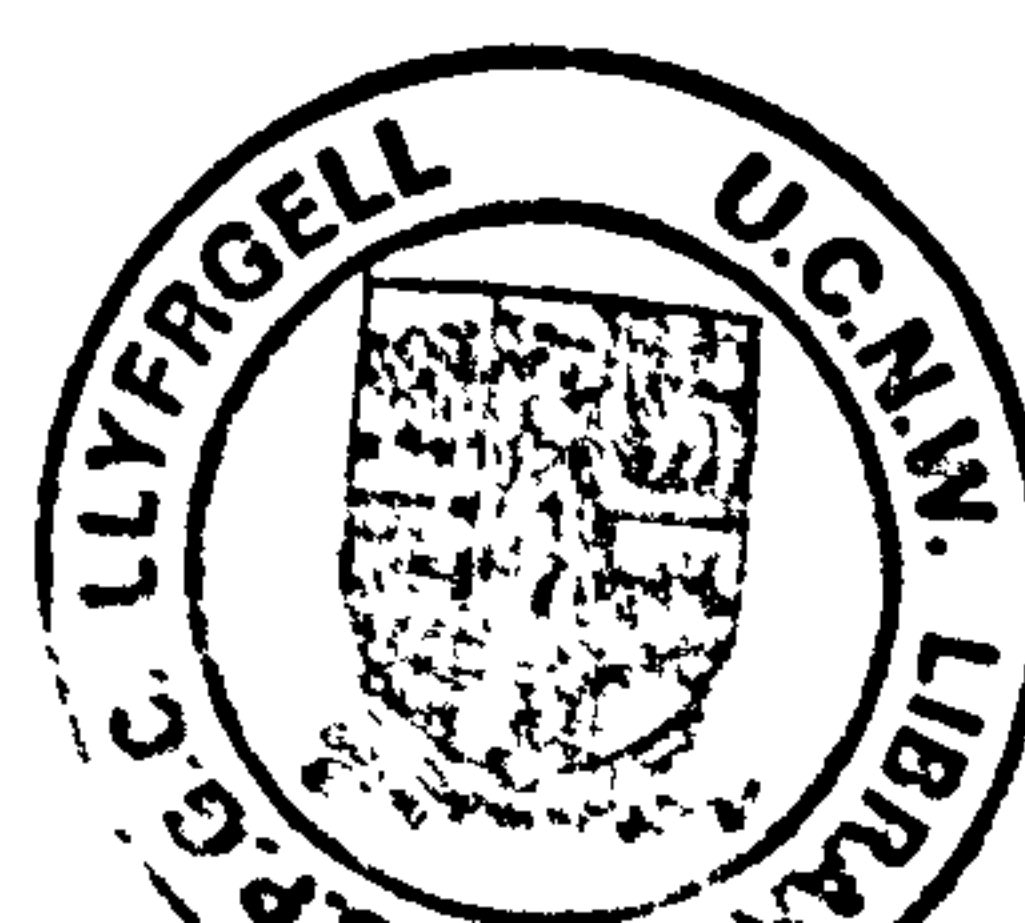
A thesis submitted in candidature for the degree of

PHILOSOPHIAE DOCTOR

of the

UNIVERSITY OF WALES

1997



SUMMARY

The instability of Cement Bonded Particleboard (CBPB) has been investigated. The study involved two main areas - understanding its occurrence and reducing its magnitude. The quantitative appraisal and qualitative interpretation of the instability were through investigations on CBPB, wood chips and cement paste. Aspects studied included the sorption of the three materials, SEM, image analysis and carbonation of CBPB, and stabilization of CBPB using various pretreatments.

Initial studies examined behaviour over a long period of time following a single change in RH. It was found that both mass and dimensional changes of CBPB in response to change in RH were not of the type of other materials. Rather it consisted of 2 distinct stages with a distinct "inflection point" between them. This "point" highlighted the existence of two dominant mechanisms. The dimensional changes were closely related to the mass change, with the relationship comprising at least 5 distinct stages over the whole range of moisture change.

Parallel tests, which were carried out in CO₂ - free and normal air environments, concluded that it was carbonation that resulted in substantial increase in mass but a decrease in dimensions with time under constant RH and accumulated changes with the number of cycles under cyclic RHs. The rate of mass increase was considerably higher than dimensional decrease. Numerical models have been developed for predicting the changes.

Collective appraisal of the mechanisms of movement of CBPB concluded that the reaction of moisture with the constituents of CBPBs and the condensation or carbonation of cement paste appeared to be the predominant features. A mathematical model was developed based on mass transport theories. The models have been combined with moisture diffusion theory and carbonation or condensation rules by introducing Fickian and non - Fickian terms. Numerical tests of the models have been carried out for various RH changes in order to assess the efficacy of the model.

Techniques for the preparation of wood chips removed from CBPB, the manufacture of cement paste and their measurement have been developed. The results have illustrated the contribution of individual material components to the CBPB. The behaviour of both the dissected chips and the cement paste was very similar to that of CBPB but with a significant reflection of stress relief of wood chips and carbonation or moisture condensation of cement paste. The changes were fitted to the models developed.

Adsorption and desorption measurements were determined for a set of cycles. Hysteresis loops changed (vertical movement) in successive cycles. The slopes and areas of the hysteresis loops for CBPB lay between those of cement paste and dissected chips.

A technique for quantifying the structure of CBPB has been developed. SEM and image analysis were used to confirm physical interpretations and to provide a numerical basis for quantitative modelling. Both the orientation of chips and percent areas occupied by components in both the horizontal layers and vertical surfaces have been quantified.

From an understanding of the structure of CBPB, a mathematical technique for modelling CBPB as a composite was developed using equations relating to wood chips and cement paste. The behaviour of CBPB was the mean effect of those of its components but with the mass change being weighted according to the mass fraction and the dimensional change according to the volume fraction.

Stabilization for CBPB has been investigated through surface coating, production parameters, intermediate change in RH, storage, pre - drying and liquid or vapour water exposure.

ACKNOWLEDGEMENTS

This research was funded by Department of the Environment through the former Timber Division at the Building Research Establishment and Cape Boards Ltd. The overseas student fee was made up by the British Council through the ORS Awards Scheme. For this support I am very grateful.

My very grateful thanks are expressed to the many colleagues and staff who so willingly helped me in some form or other throughout three years. In particular thanks are due to my supervisors:

Professor J.M. Dinwoodie

Dr. M.C. Breese

Dr. P.W. Bonfield

Professor W.B. Banks

for their supervision, guidance, encouragement and contributions.

Finally I wish to especially thank my wife and son for their inspiration and help.

This thesis is dedicated to them.

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PART 1

**INTRODUCTION,
LITERATURE REVIEW
AND METHODOLOGY**

Chapter 1

INTRODUCTION

1.1 The Wood - Cement System

1.1.1 Cement - Bonded Particleboard

When particles of wood are bonded together by cement and produced as a panel, this panel is called Cement Bonded Particleboard (CBPB). It consists of about 65 % Portland cement and 35 % softwood chips (by mass).

1.1.2 Technology and Processing of CBPB

See Appendix I.

1.1.3 Development of Wood - Cement Systems

Cement - bonded wood products are not a novel concept and the basic concept of incorporating plant fibres, such as wood particles or agricultural residuals with inorganic matrices is very old. Wheat or rice straw was added to mud to produce brick in prehistoric times and this is still practised in the less developed parts of the world (Alen and Hamroush, 1986). During more recent times the same concept has been applied using wood fibres and particles in conjunction with Portland cement or other inorganic materials. Mineral bonding agents for so-called stone floors have been used since the beginning of the century (Pampel and Schwarz, 1979). Apart from this application magnesite - bonded, light - weight "wood wool" cement slabs have also become known. Since 1928 there has been continuous work on improving wood wool cement slab boards, and a commercially successful combination of wood and cement was developed in Austria and Germany under the trade name of "Heraklith" (Kollmann, 1955; Morath, 1966; Sandermann, 1970), and in North

America as "Excelsior" boards (Dinwoodie and Paxton, 1983). This product was initially produced with magnesite as a binder but later using Portland cement (Dinwoodie and Paxton, 1983; Circa, 1940).

From 1930 onwards wood chips, mainly wood shavings, were adopted in addition to wood wool for the manufacture of cement bonded moulded products known as "Durisol" and comprised of stone (brick) for external and internal walls, roofing slabs and curtain facings (facades) (Herzig, 1966) .

With the gradual evolution of resin bonded particleboard technology much was learned that is also applicable to cement bonded wood particleboards. A considerable amount of research and development was carried out by Elmendorf Research Inc. on cement bonded panel product development in the US. Two concepts were combined: cement bonding and wood particle orientation. In 1962, Elmendorf published a proposed method for the manufacture of high density wood cement board for the building industry by the addition of planer shavings and thin chips (US patents No. 3.164.511 and 3.271.492) (Pampel and Schwarz, 1979). The wood particle orientation concept resulted in the later development of OSB.

Based on Elmendorf's ideas, this technology was modified by a group of Swiss firms, and in 1968 / 1969 a pilot plant was set up at Dietikon by Durisol Villmergen, AG to produce a three layer board which became known as C - B board (Dinwoodie and Paxton, 1983).

Meanwhile, Durisol AG, following plans first proposed in 1973 began manufacturing a product with smooth, fine - grained, cement enriched surface, characteristic of the present day cement - bonded wood particleboard. In 1974, a new plant was built in Dietikon to manufacture a product under the name of "Duripanel".

Further plants using the same system were erected in Vietnam (1976), Germany (Wunstorf) and Hungary (Szombathely) (1977 / 1978) with products being imported into the UK under the name of "Fulgurit" (later "Cemchip") and "Granyp" respectively.

In 1978, Durisol AG was taken over by Eternit. More plants were set up, one at Neubeckum in Germany (1981), replacing Dietikon's one destroyed by fire in 1980, and others at Kuala Lumpur in Malaysia under the trade name of "Tacpanel" or "Cemboard" and Japan (1982); with further plants at Mexico, Russia and UK.

In addition to the wood chip product, considerable effort has been made in the research of the fibre reinforced composite (cement bonded fibre board) in the last two decades (Sattler and Roffael 1990 in Moslemi, 1990), especially on the use of lignocellulose, because the major health hazard posed by asbestos created interest in its substitution by other suitable fibrous materials in cement composites [in the UK over 80 % of the 220,000 tonnes of fibre-reinforced cement produced in 1989 contained alternative fibres (West and Majumdar, 1991)]. At the present time cement bonded fibreboard appears to be prospering in North America.

Overall relating to particle size the various product can be categorised as follows:

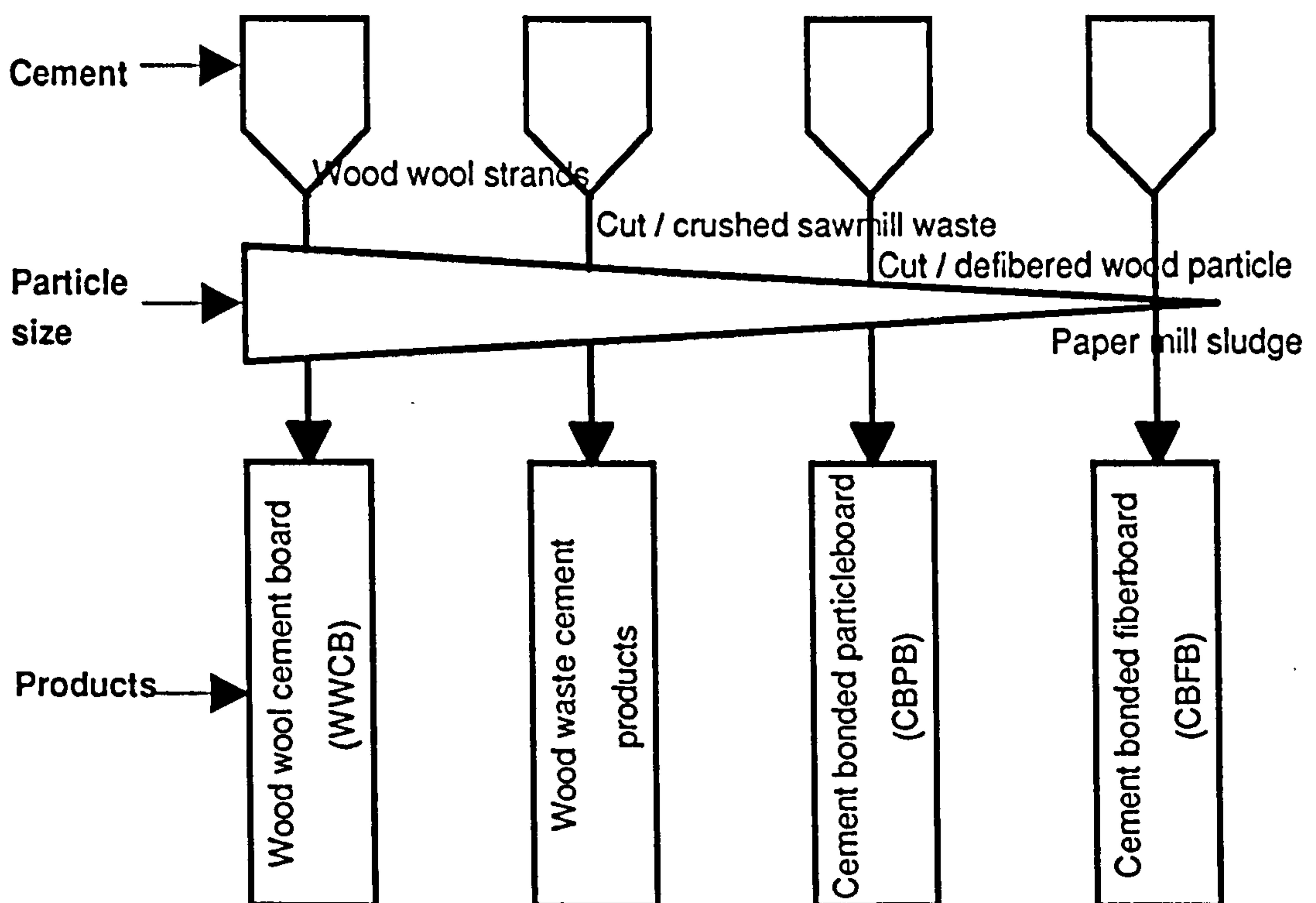


Figure 1.1 An overview of cement bonded products

1.2 Properties of CBPB

1.2.1 Properties of Untreated Products

CBPB properties offer a variety of advantages. In some aspects, these properties are unique to this kind of material. Table 1.1 provides quantitative information on some of the physical and mechanical properties of CBPB (Dinwoodie and Paxton, 1983; 1978).

Table 1.1 Comparison of the mean property values of CBPB with resin bonded particleboard

Property	CBPB (BRE)	CBPB (BRE)	CBPB (Bison- werke)	Resin bonded chipboard (EN312 - 7)
Thickness (mm)	12	18	18	13 - 20
Density (kg / m ³)	1250	1220	1100-1200	–
MOR (N / mm ²)	10.4	10.3	8.8-12.7	20.0
MOE (N / mm ²)	4940	4890	2940	3100
IB (N / mm ²)	0.73	0.72	0.39-0.59	0.70
Impact (height) (mm)	324	413	–	–
Thickness swelling (24 h)	0.96	0.74	1.2-1.8	8
Longitudinal swelling (24 h)	0.09	0.11	–	–

It can be seen that CBPBs have a lower modulus of rupture than resin bonded particleboards but are superior in modulus of elasticity and tensile strength.

Furthermore CBPB has excellent machinability enabling the manufacturer or the user to incorporate intricate cuts or joints.

Like resin bonded particleboard, the properties of CBPB are closely related to its density. A linear relationship between the density and MOE was found for all thickness of CBPB boards with a correlation coefficient of 0.73 (Dinwoodie and Paxton, 1983).

1.2.2 Durability of CBPB

A major advantage of cement bonded particleboard is thought to be the ability to withstand outdoor exposure. CBPBs have performed well in accelerated weathering tests. Research in the Building Research Establishment demonstrates that these boards easily pass the V313 test (an accelerated ageing test) (Dinwoodie and Paxton, 1983). An investigation at the University of Idaho subjecting laboratory made samples to the cycles of 24 hours of soaking in 20 °C water, 24 hours of freezing in -17 °C, and 22 hours oven drying at 100 °C shows a good retention of properties. The retention of properties for both tests above is summarised in Table 1.2 .

Table 1.2 Retention of properties of CBPB after aging tests
Commercial CBPB tested by BRE (Dinwoodie and Paxton, 1983)

Thickness (mm)	12	18	24	28
IB (N / mm ²) (Raw)	0.73	0.72	0.60	0.72
IB (N / mm ²) after V313	0.49	0.33	0.38	0.39
Residual swelling after V313 (%)	0.62	0.33	0.35	0.27

Laboratory made samples by University of Idaho (13 mm thickness) (Moslemi, 1994)

Test	MOR (MPa)	Shear (KPa)	WA (%)	TS (%)
Raw materials	5.96	2269	38	2.0
After accelerated test	3.69	1651	44	0.9

Long term exposure to actual weather conditions was also carried out by BRE. Test work on a wide range of brands of Portland cement bonded particleboard over 15 years has indicated that the products are capable of providing very satisfactory levels of long term performance. Strength and stiffness of unstressed CBPB appear to increase for first several years (Figure 1.2) (Dinwoodie and Paxton, 1990 in Moslemi, 1990), while the performance of stressed CBPB under both constant or cyclic relative humidity (RH) is similar to, or better than, synthetic resin bonded particleboard.

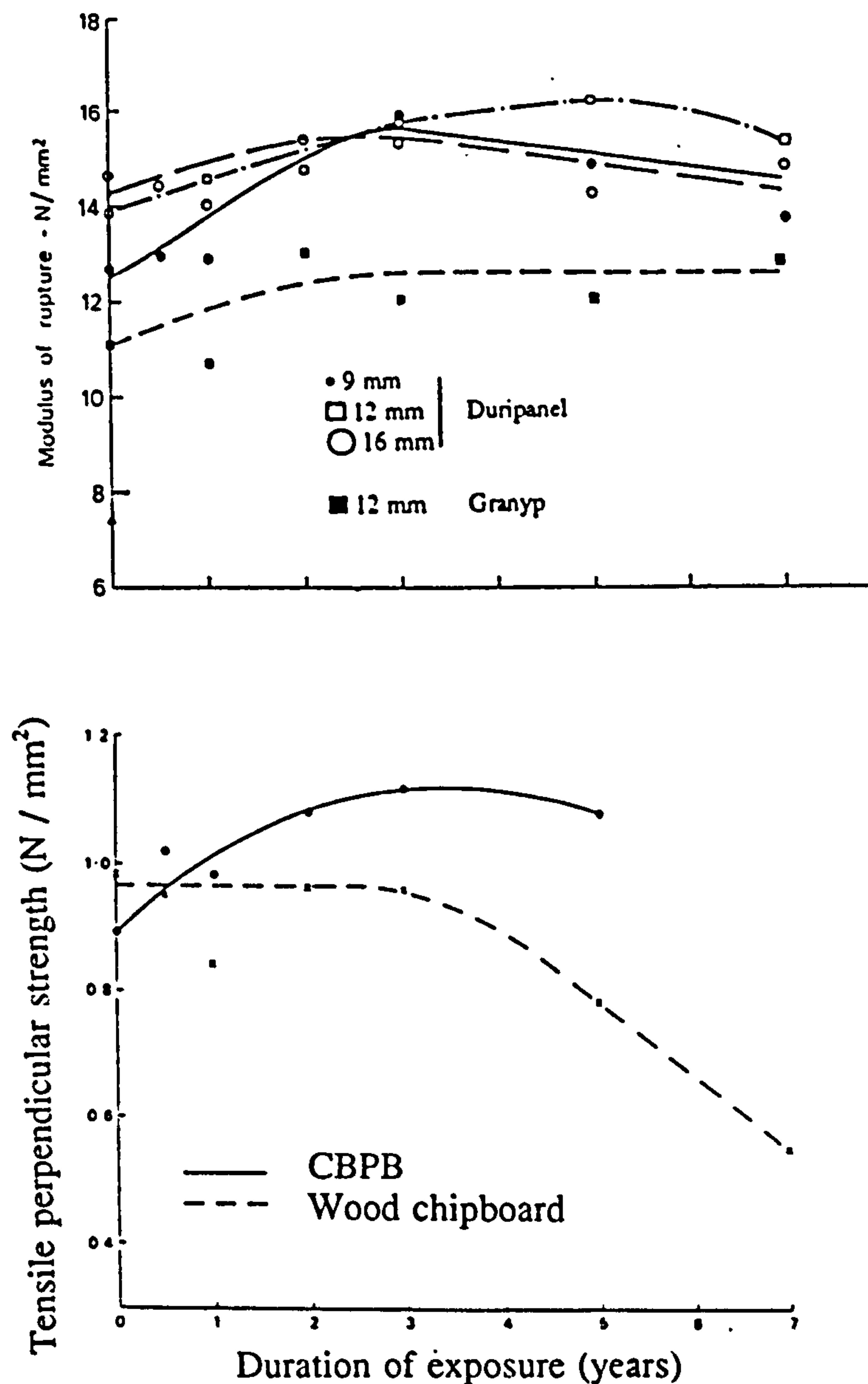


Figure 1.2 The performance of CBPB (including Duripanel and Granyp) and a good quality moisture resistant chipboard (type III) under long term natural weathering

In addition biological deterioration due to insects and fungi is minimal with these particleboards: the highly alkaline nature of the material coupled with the cement - encased structure of wood particles makes such attacks very difficult.

Fire resistance is another particularly important consideration for CBPB. Tests reveal that the performance of CBPB in fire is not as high as asbestos or gypsum boards, but considerably higher than resin bonded particleboard and plywood. Based on German and British standards, CBPBs are classified as "highly fire-resistant".

1.3 The Application of CBPB

So far, CBPB has found itself a specialised niche in the market that reflects its outstanding merits of high stiffness, high durability, very good protection against fire and high sound insulation. There is widespread use as a wall lining in public buildings, as well as a cladding material. More specialised uses embrace flooring (where there is a risk from water spillage), sound insulation and the construction of protective elements for fireproofing.

However, CBPB has one principal disadvantage. It is dimensionally unstable even under constant, let alone under changing RH (Figure 1.3) (Fan, et al, 1996), although its performance is much better than resin bonded particleboard and slightly better than a good quality plywood. CBPB is certainly not a stable product, and unfortunately hairline cracking has occurred in wall linings using unfeathered joints.

The continuing commercial success of CBPB as a wall lining is strongly related to the development of a more stable product. Information is urgently required on determining why CBPB is unstable and how to reduce its susceptibility to moisture.

1.4 Objectives and Programme of the Project

This PhD project is aimed at gaining a better understanding of dimensional instability of CBPB and to reduce its magnitude (perhaps by reducing the hygroscopicity of either constituents or of the pressed and cured composite panel). This will help to realize the full potential of such products, guide their correct utilization, exploit the potential commercial market and promote the further development of wood - cement

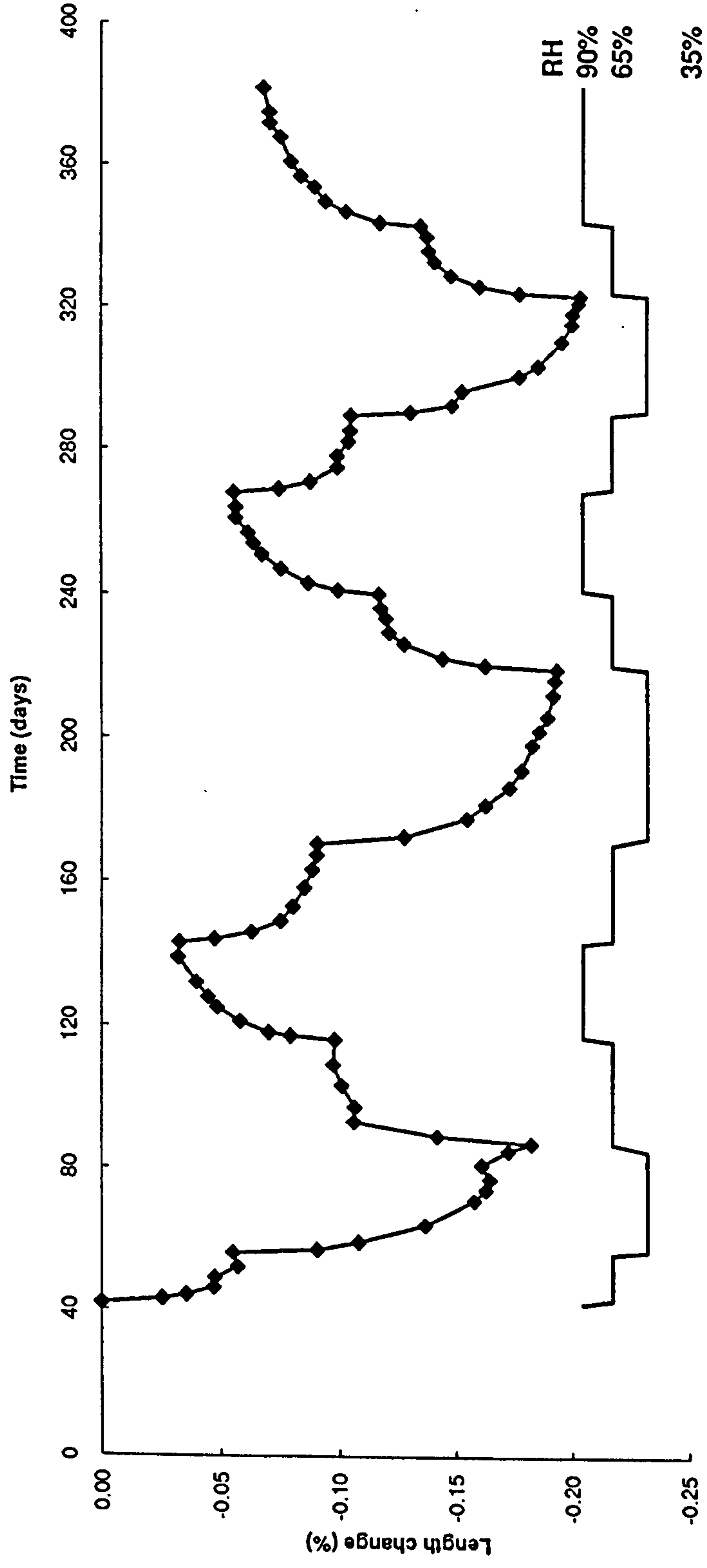


Figure 1.3 Change in length of 18 mm CBPB subjected to cyclic humidity

particleboard.

The programme of the research is as follows:

Stage 1:

Examine the structure of CBPB under both optical and scanning electron microscopy. Then:

- a) determine the percent area of cement paste, wood chips and voids;
- b) determine the size distribution of individual chips and their orientation;
- c) develop simplified conceptual models of the composite with the aid of image analysis;
- d) determine and quantify the contribution of the components in both the length and thickness directions.

Stage 2:

Using the above observations, subject strands or chips of wood, cast or pressed blocks of cement paste and small blocks of CBPB to a number of RH regimes, to determine:

- a) the equilibrium moisture content of these materials at various RH levels;
- b) the hysteresis loop for each material for each cycle; compare shapes of each loop and degree of loop closure;
- c) the mass (%) of water present in each material at each RH level;
- d) the dimensions (l, w, t) of each material at each RH level.

Stage 3:

Determine the permeability of boards, chips and paste to both vapour and liquid water.

Stage 4:

Determine whether "free" water occurs in any of the materials in the range of RHs examined.

Stage 5:

Examine the carbonation of cement paste in CBPB and evaluate its effect on the behaviour of CBPB.

Stage 6:

Examine the possibility of applying moisture diffusion theory and the laws of

thermodynamics.

Stage 7:

Interpret the results obtained in stages 1-5 using fibre-composite theory and develop appropriate mathematical models.

Stage 8:

Assess the effect of storage period and pre -drying on the behaviour of CBPB.

Stage 9:

Examine the possibility of applying surface coatings to CBPB which will prevent the ingress of water vapour, and yet be compatible with the highly alkaline surface and be readily applied under factory conditions. Monitor changes in mass and dimensions of coated panels at different relative humidities.

For simplicity, this programme can be presented diagrammatically as in Table 1.3.

Chapter 2

LITERATURE STUDY

There has been a vast amount of research into the problems associated with moisture in materials, especially for timber and its products, which are particularly sensitive to moisture and can be critical in a building's performance. Some of the problems and mechanisms are the same for both cement and timber, but the magnitude of effects can in some cases be completely different. For timber, two books by Skaar (1972, 1988) give an introduction to theory associated with water in wood and make a good starting place for further enquiries into timber. In the cement paste area, Powers and Brownyard (1948) gave a detail explanation of moisture situation in their book *The Studies of the Physical Properties of Hardened Cement Paste*.

2.1 The Structure of CBPB

Many papers and books have discussed the structure of materials due to the close relationships with the strength, moisture adsorption and stability.

2.1.1 Structure of Hardened Cement Paste

The microscope reveals that both microcrystalline and colloidal materials occur in hardened cement paste, the colloidal material appearing as an amorphous mass enclosing microcrystalline $\text{Ca}(\text{OH})_2$ and unhydrated residues of the original cement grains (Figure 2.1 A) (Domone in Illston, *et al*, 1994). Pores, either filled with water or empty, are also detectable in the mass. There are two kinds of pores in hardened cement paste, gel and capillary; the capillary pores are continuous in some specimens which are interconnected only by gel pores, but not continuous in others (Power, 1958). A few models have been suggested to describe the structure of the hardened paste and to explain its behaviour, however, the Powers' model provides the most basic representation. Powers' model was proposed to describe the microstructure of

the hardened cement paste and to explain the properties and behaviour (Powers 1958, 1960) based on a considerable body of data from the adsorption isotherms of hardened cement paste (Powers and Brownyard 1948) (Figure 2.1 B).

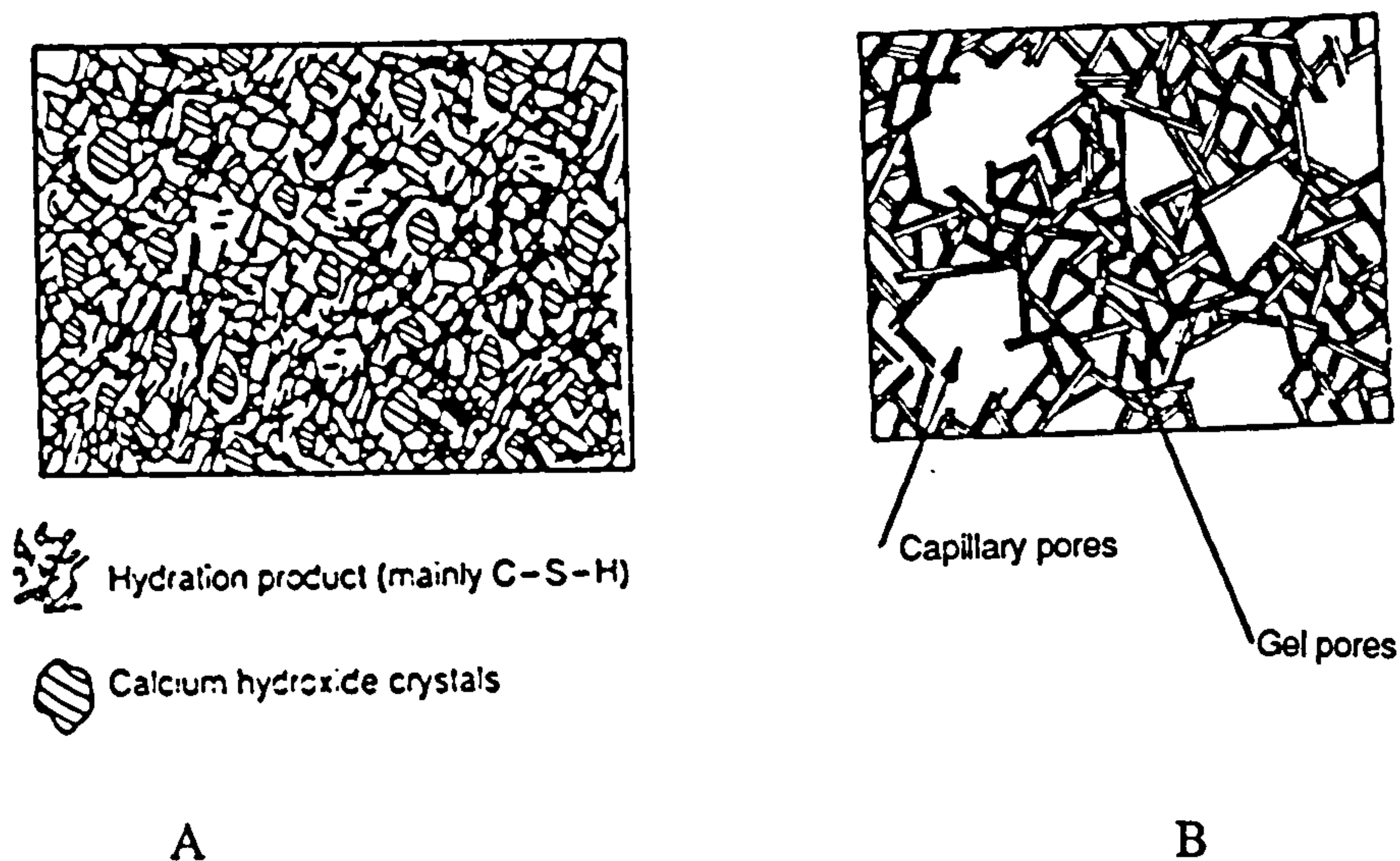


Figure 2.1 Schematic description of the structure of the cement gel. A - mature paste presenting denser C - S - H around Ca(OH)_2 crystals, residual unhydrated cement and capillary void [From Domone (1994)]; B - a model showing colloid - size particles and porosity [From Powers (1960)].

The model assumes that the hardened cement paste has three volume forming constituents, that is, unhydrated cement, cement gel and capillary space. The gel incorporates all the hydration products (both crystalline and microcrystalline). Both the gel and the capillary space may contain water. The cement gel is a rigid substance made up of colloid-size particles and has a characteristic porosity of 28 %. The average width of the pores involved is 15 Å and these pores are known as "gel pores". The gel is always the same regardless of the stage of hydration, the type of cement, the water / cement ratio and the water content: w_a (combined water) / the weight of the cement = constant = 0.23. Similarly the gel porosity is constant, so that the specific volumes of gel including pores (=0.567) and of gel solids (=0.411) are constant. Another component of the hardened paste formed by much bigger pores is known as "capillary pores". The volume of the capillary pores depends on the original ratio of water / cement and the degree of the cement hydration.

The properties of the hardened paste are primarily determined by its structure rather than by its chemical composition. The particles and interparticle spaces in hardened paste are exceedingly small and most of the fluid is in the force - field of the solid particles; that is much of the water, perhaps all of it, is adsorbed, and consequently the viscosity is higher than that of free water (Powers, et al, 1958). Hughes (1985), reviewed the literature on flow through porous media, suggested the permeability of hardened paste should be related to pore distribution and pore conductance.

The drying of the granules produced a permanent shrinkage that reduced the porosity of the granules below that of the paste in the original specimen (Power, 1948).

2.1.2 Structure of Wood

There is a close relation between the structure of wood and moisture characteristics. Where no references are given, the account is mainly based on standard textbooks, such as Dinwoodie (1981), Skaar (1972, 1988) and Siau (1984).

Four orders of structural variation can be recognised, that is, macroscopic, microscopic, ultrastructural and molecular.

Macro - structure Conspicuous features of defect free wood are the alternating light and dark annual growth rings. In generally one growth ring contains earlywood and latewood fibres. The structure of earlywood is thin-walled (about 2 μm for softwood) with large cell cavities (lumens). The structure of latewood is thick-walled (up to 10 μm for softwood) and slightly longer (10%), with small lumen. The density of the latewood is often twice that of the earlywood.

Regions of so - called sapwood and heartwood are also clearly visible at macro - structural level.

Micro-structure The structure of wood under a microscope is very complex, Figure (2.2). Overall 90-95 % of cells are aligned in the vertical axis, while the remaining percentage is present in bands (rays) aligned in one of two horizontal

planes known as the radial plane or quarter-sawn plane (Figure 2.2). This different distribution of cells in three principal axes is one of reasons for the high degree of anisotropy present in timber.

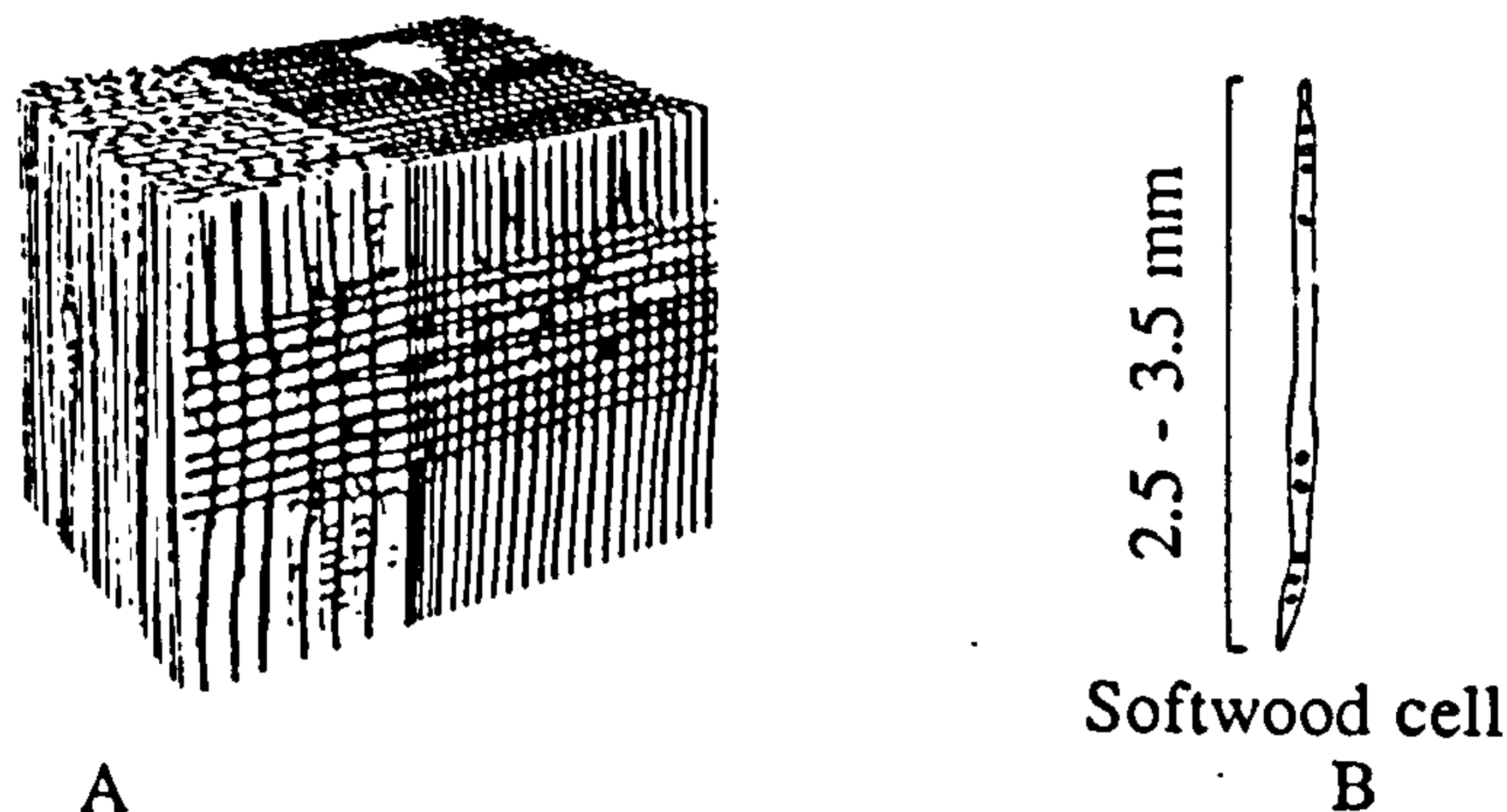


Figure 2.2 Gross structure (A) and tracheid of a softwood [From Dinwoodie (1994)]

For softwood, the prosenchymatous, or fluid-conducting elements, are the longitudinal tracheid and ray tracheid (Behr, et al, 1969; Wardrop and Davies, 1961). The lumens are connected by pores of different kinds, which are known as pits (simple, bordered and semi-bordered pits), to permit the passage of mineral solutions and food in both the longitudinal and horizontal directions. Most pores have membranes which may be close or destroyed. The characteristics of pits can cause a profound influence on the degree of the absorption of liquid. A dimensional summary of softwood structure elements is given in Table 2.1 (Bolton, 1976; Siau, 1984).

Cell wall constituents The cell wall consists of a number of layers (Figure 2.3) which have different compositions and orientation of the cellulose microfibrils. Over three quarters of the cell wall is composed of the middle layer of the secondary wall which is thick and exhibits a similar orientation in a right - hand spiral with a pitch of $10 - 30^\circ$ to the longitudinal axis. Therefore the ultrastructure of this layer has a very marked influence on the behaviour of the timber.

Table 2.1 Summary of dimensions of softwood structure elements (µm)

Structure element	Southern pine (Siau)	Spruce (Bolton)
Tracheid length	3,500	2,400 - 4,000
Tracheid diameter	33	21 - 42
Tracheid lumen diameter	20 - 30	8 - 35
S ₂ layer thickness	4 - 10	-
Diameter of pit chamber	6 - 30	8 - 17
Number of pit per tracheid	-	10 - 100
Effective radii: pit opening	0.01 - 4	0.3 - 0.4

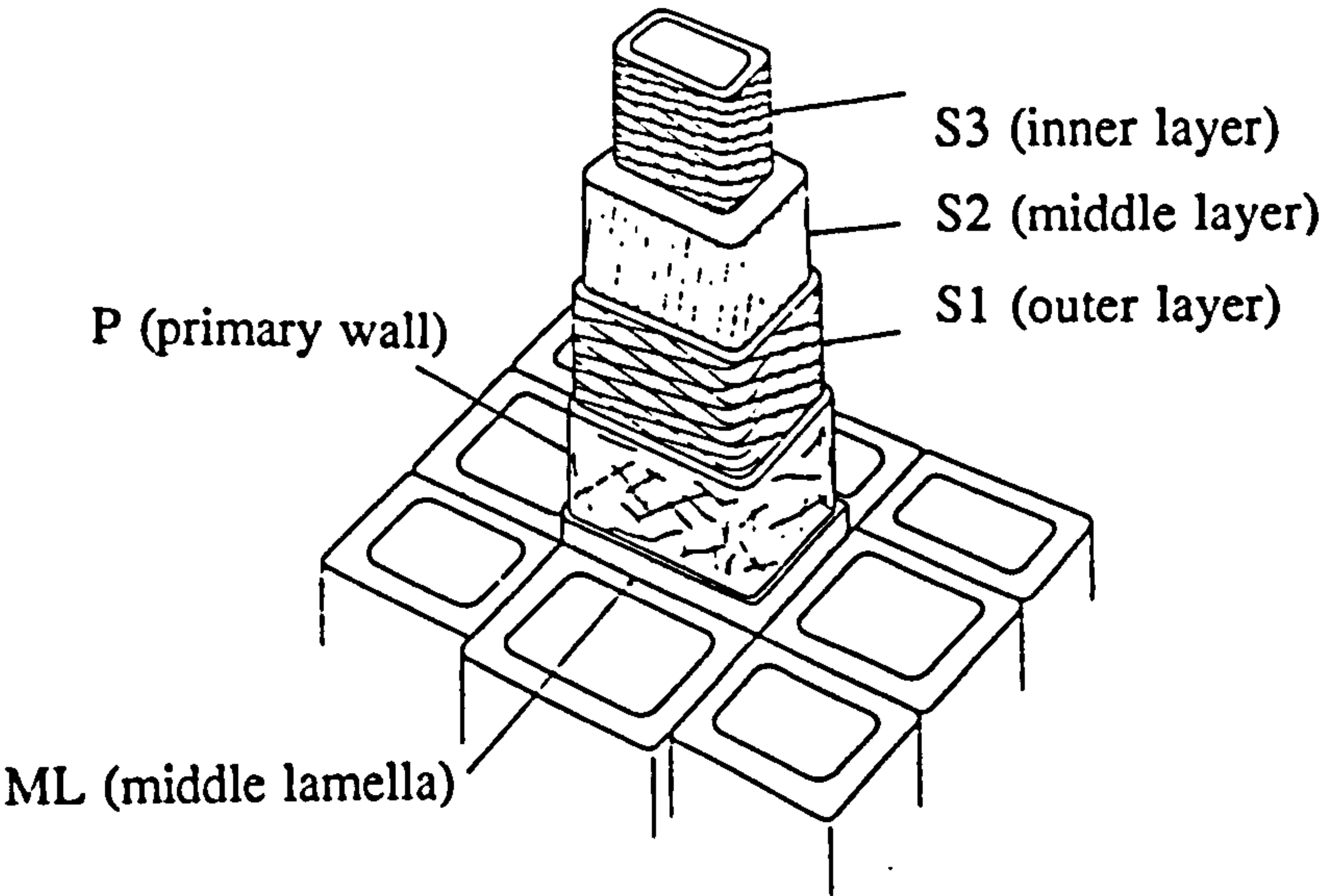


Figure 2.3 Diagrammatic view of the cell wall showing orientation of microfibrils in each of the major cell wall layers [From Dinwoodie (1994)]

Wood is mainly composed of three polymers - cellulose, hemicellulose and lignin, 40 - 50 %, 20 - 25 % and 25 - 30 % respectively. Wood can be defined as a natural composite which ascribes the role of 'fibre' to the cellulosic microfibril while the lignin and hemicellulose as separate components of the matrix (Figure 2.4

A). The cellulosic microfibril confers the high tensile strength to the wood owing to the covalent bonding both within and between the anhydroglucose unit forming the molecular chain. The hemicelluloses are usually intimately associated with the cellulose, effectively binding the microfibrils together with a certain degree of hydrogen bonding and van der Waals forces. The lignin is regarded as lying to the outside of the fibril forming a sheath to protect the hydrophilic (water-seeking) cellulose and hemicelluloses and being responsible for cementing together the fibrils imparting shear resistance in the transference of stress throughout the composite.

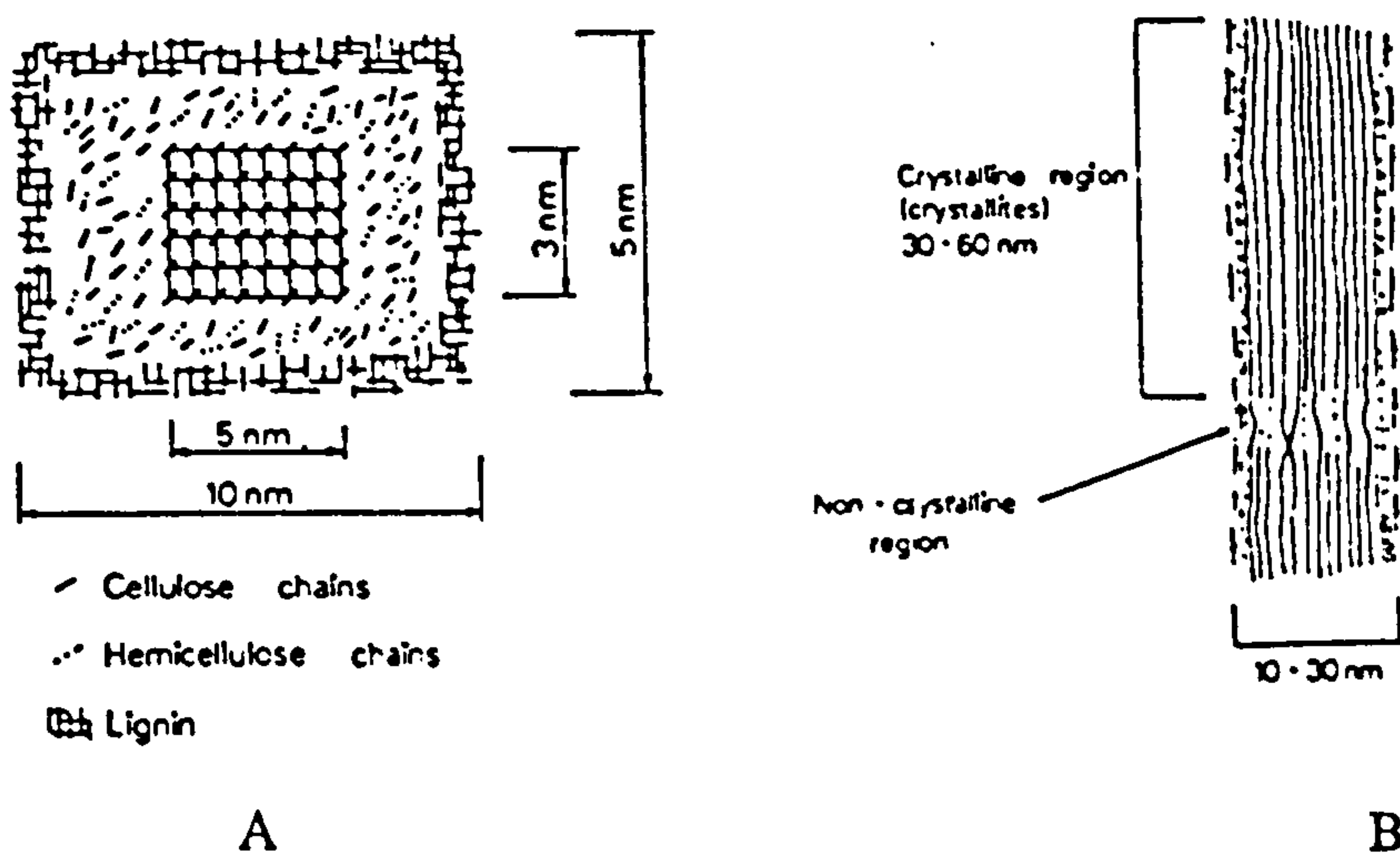


Figure 2.4 A - a model of the cross section of a microfibril illustrating homogeneous crystalline cellulose surrounded with mainly hemicellulose and then amorphous lignin; B - a portion of a microfibril with crystallites and amorphous regions [From Dinwoodie (1994)]

Cellulose is a non-branched polymer consisting of 8000-10000 glucose units. Several cellulose molecules are arranged parallel to each other called microfibrils (Figure 2.4 B). In some parts of a microfibril the cellulose chains are ordered with respect to each other (crystalline) and in other parts disordered (non-crystalline or amorphous). The amorphous cellulose absorbs water vapour, i.e. it is hygroscopic. The water molecules attach to the OH groups on each glucose unit due to the highly attractive nature of OH group to water molecules. In the crystalline region the absorption is very limited with most OH groups bonded between neighbouring cellulose chains.

Hemicellulose is a branched polymer (<150 units) with different kinds of sugar units. Hemicellulose has about the same hygroscopicity as amorphous cellulose, and has a lack of resistance to alkali solutions.

Lignin is also a branched polymer but is composed of phenyl-propane units. The structure of lignin is very complex and its hygroscopicity is lower than that of hemicellulose and amorphous cellulose.

Wood also contains minor fractions of extractive substances which may influence the liquid permeability, cement comparability, etc.

2.1.3 The composition of CBPB

2.1.3.1 Bonding between Wood and Hydraulic Cement

In reality the total bond strength is the sum total of two forms of bonding: physico-chemical adhesion and mechanical. The relative importance of each form depends on the physical and chemical properties of the adhesive and adherent. Many theories have described the bonding between any two dissimilar substances. The types of chemical bonds between the adhesive and adherent wood can only be one or more of three types: primary covalent bonding, secondary hydrogen bonding or van der Waals.

In CBPB, it is believed that the bonding mechanisms between wood and cement are 1) the mechanical interlocking process which is thought to be an important mechanism contributing to strength (Ahn and Moslemi, 1980; Steward, 1988; Kayahara, et al, 1979); 2) the hydrogen bonding and complexing between metal ions in the cement and the wood components; 3) the chemical interaction between the wood components and the cement. Both the second and third factors play less important roles in the strength of CBPB compared to the first factor (Steward, 1988). The fact that primary bonding occurs between compatible adhesives and adherent has also been stated by Troughton (1969) and Troughton and Chow (1968). It was considered that such chemical bonds cannot contribute significantly to the total bond strength in a practical situation due to the variable surface properties, such as adsorption of contaminants and a mono-layer of water. More details are included in

Appendix II.

2.1.3.2 Structure of the Interfacial Region between Wood and Cement

2.1.3.2.1 Introduction

The performance of fibre-reinforced cementitious materials is critically dependent on the bond between fibre and cement, which itself depends on the microstructure of the interface (Domone, 1994). The fibre - cement interface consists of an initially water - filled transition zone which does not develop the dense microstructure typical of the bulk matrix and contains a large volume of calcium hydroxide crystals which deposit in large cavities. Three layers are commonly observed in this zone: a thin (less than one micron) calcium-hydroxide-rich, rather discontinuous layer, directly in contact with the fibre, a massive calcium hydroxide layer and a porous zone up to 40 microns from the surface consisting of calcium silicate hydrate and some ettringite (Domone, 1994).

2.1.3.2.2 Structure of Wood - Chip - Matrix Interface

Relatively less investigation has been conducted for the structure of CBPB. However, a few authors (Ahn, 1979; Eusebio, 1993; Parameswaran, *et al*, 1977; Steward, 1986) have made systematic examinations into the interface between the chips and cement using scanning electron microscopy photomicrographs, and concluded that:

- 1) generally there is very close contact between the peripheral fractured lumen cell walls of the wood substrate and solid hydrated cement products. However, no evidence of any hydrated or unhydrated cement constituents penetrating non - fractured cell lumens within the wood substrate was found. Additionally, penetration of solid cement paste constituents into transversely orientated open cell lumens (in direct contact with a hydrating cement paste) appears not to be significantly greater than into peripheral fractured cell lumen on the radial or tangential wood substrate face. No hydrated cement products were found in the inner complete, non - ruptured chip wood cells;

- 2) macro - mechanical bonding plays a significant role in the total bonding;
- 3) close contact exists between hydrated cement paste constituents and the wood chip surface cell walls;
- 4) the concentration of calcium ions decreases with increasing distance from the wood cement interface and varies with grain orientation (longitudinal > transverse). The calcium ions are deposited throughout the cell wall and not as a layer on the cell wall lumen surfaces. The visible discolouration of a wood substrate in contact with a hydrating cement paste is associated with the diffusion of calcium ions;
- 5) Degradation of the cell wall constituents due to alkali hydrolysis is highly probable, with the macro-discolouration of the wood substrate;
- 6) the complete cells immediately adjacent to the cement are deformed, being nearly flattened, and sufficient cement paste enters the peripheral fractured cell lumens before pressing.

Quantitative or qualitative information regarding the structure of CBPB in terms of the distribution and orientation of individual chips and voids across the board thickness, length or width is still not available.

2.2 Moisture Related to the Substrate

The mechanics by which a single pore can take up water are well known. Washburn (1921) considered the mechanics and produced results for the rate of penetration of a liquid into a small pore. This work has been used as the basis for further work in the adsorption of liquid by porous media. Philip (1957) first used the concept of sorptivity in soil mechanics, but later it found acceptance in building science.

2.2.1 Water in Cement Paste

A solidified paste of typical characteristics is capable of giving up or absorbing a volume of water equal to as much as 50 per cent of the apparent volume of the paste. These facts engender the idea that whatever the chemical constitution of the new material produced by chemical reaction, the new material is laid down in such a way as to enclose water - filled, interconnected spaces (Powers, 1948).

2.2.1.1 The Type of Water and its Characteristics

The state of water in the materials influences the characteristics of materials, especially surface chemistry and structure. In cement paste it characterises the specific surface area of hardened cement paste, size of gel pores, size of particles, porosity of the gel and density of the paste. There are several classifications of water in hardened cement paste by different authors (Powers, 1948; Ishai, 1965; Feldman and Sereda, 1968, 1970). The agreement is about the chemically - bound combined non - evaporable water and the free water (gel and capillary pore) in cement paste, whilst the disagreement is about adsorbed water, Table 2.2.

Table 2.2 Adsorbed water in hardened cement paste (From various authors)

Powers'	non	adsorbed (gel)	adsorbed (gel)
Ishai's	intercrystal water between layers of CSH crystallites strongly bound, can't be removed under normal drying, 1 mol	intercrystal water adsorbed between adjacent crystallite surface < 8 A ⁰ , 2 mol	adsorbed on the surface on the crystallite, 1 - 2 mol deep, 4 - 8 A ⁰
Feldman & Sereda	interlayer	interlayer	physically adsorbed

In the Powers' model, adsorbed and free water (about 50 %) are free to leave the paste without destroying the potential bonding value of the paste. It does however have important effects on the hardened paste, the paste shrinks as water is lost and swells as it is gained (Powers, 1948). The intercrystalline (zeolitic) water is not considered in Power's model, but is thought to be strongly bound to the solid and cannot be removed during normal drying (Ishai, 1965; Kalousek, 1955). This suggests that part of the evaporable water should be regarded as part of the solid, and the pore content of the paste would be less than the volume of the evaporable water.

2.2.1.2 Moisture Sorption in Cement Paste

The term "sorption" is used to describe a state in which there exists an average molecular concentration of any material higher or lower than the molecular concentration of the same material in a free state at the same pressure and temperature. In cement, usually only physical sorption is involved. Overall the process is reversible, the water loss on drying being the same as the gain on wetting, but between the extremes very different equilibrium water contents are found for adsorption and desorption at a given value of RH. Thus there is a large hysteresis loop. The typical example for hardened cement paste is described schematically in Figure 2.5 A.

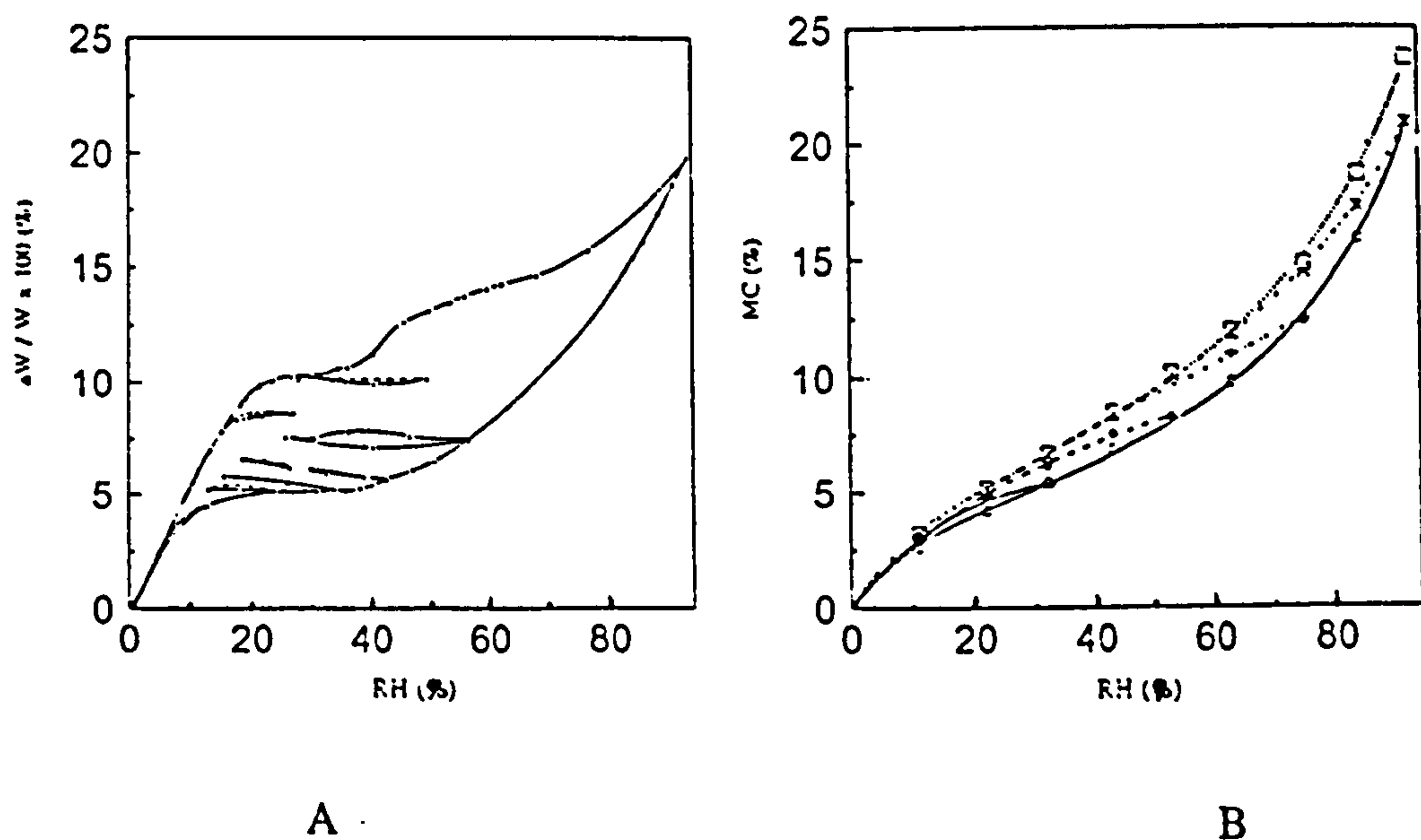


Figure 2.5 Sorption curves with scanning loops. A - hydrated Portland cement compacts [From Feldman (1968)]; B - wood [From Peralta (1995)]

2.2.1.3 Factors Affecting the Sorption of Cement Paste (water content)

A) *Hydration of cement paste* The water content in dry paste (i.e. at $P / P_0 = 0$) equals the amount of chemically bound water, and this amount increases with age, as well as the amount of evaporable water. However, near saturation ($P / P_0 > 0.9$), the amount of evaporable water decreases with age (Soroka, 1979). The evaporable

water at saturation is a measure of the porosity of the cement paste, and it may be concluded that porosity decreases with age. Capillaries in fresh paste are continuous. Hydration of cement increases the solid content of the paste, and if it is increased sufficiently, the original capillaries become blocked by gel (Power, et al, 1959).

B) *W / C ratio* At the same degree of hydration, absorbed water (evaporable water) increases with the ratio of W / C due to the increasing porosity of hydrated cement paste. However, in the pressure range below 0.45, the water held is found to be independent of W / C ratio: it is determined by the volume of gel pores (Soroka, 1979).

C) *Curing temperature* It has been noted that the curing temperature has a significant influence on the structure of cement paste, resulting in completely different isotherms. Powers and Brownyard (1948) found that no pores of the size of gel pores in a normally cured paste are present in paste treated in an autoclave, and the size of the pores in the later paste is much greater and that virtually all pores are empty at RH below 80 %RH.

2.2.2 Moisture Sorption in Wood

It has been mentioned that the cells of wood are hollow and hygroscopic. Water in the cell cavities, known as the "free water", has little influence on the properties of wood other than its weight. However, the water in the cell walls (that is known as "bound" water) is bound to the matrix constituents forming the sheath to the microfibril and has a considerable influence on the properties of wood. The amount of free water that a piece of wood can retain is governed by the volume of the cell cavities and intercellular spaces, and the amount of bound water in a piece of wood is determined by the conditions of the surrounding air [see Figure 2.5 B adapted from Peralta (1995)]. The isotherms in Figure 2.5 B show corresponding curves for desorption lie above the curves for adsorption, as there is a hysteresis in the sorption behaviour. The isotherm gives the moisture content of wood up to RHs near 100 %. At this point the cell walls of wood are saturated with moisture. The moisture content

is then around 30 %. This is called the "fibre saturation point". The lumens, however, may also be filled with water by immersing the wood in liquid water, and moisture can increase up to a maximum of more than 200 %. It is apparent that under vapour exposure (35 % - 90 %RH), for the wood chips in CBPB there is no liquid water present, and all moisture is absorbed / desorbed by the cell wall substance.

As mentioned above, hardened cement paste is predominantly a gel (an aggregation of colloidal particles), and it has a high capacity for evaporable water (through the surface and capillary) due to its exceedingly small and numerous pores, e.g. at 90 %RH a pore with a radius of 0.01 μm will be filled with water. However, this is not the process by which water is absorbed in wood. The cell wall has only about 2 % pore volume (Stamm, 1964) and the lumens are too large for this kind of condensation to occur. Vapour sorption in wood is by sorption on binding sites in the wood constituents. Therefore the questions arise as to what are the characteristics of water in chips and in cement paste, how much water is occupied by cement paste and how much by chips in CBPB at certain RH levels, and hence the percentage of deformation occurring in them respectively?

2.2.3 Moisture Movement in Porous Materials

2.2.3.1 Moisture Transport Phase

The transport of water through a porous material may occur by one of several different mechanisms. Rose (1963) concluded that four transport phases could be identified: 1) adsorption, 2) condensation / vapour transport, 3) liquid and vapour transport, 4) liquid transport. Clearly there can be (under normal situations) the possibility of both liquid and vapour movement of water in porous materials. Therefore diffusion processes need to be considered for both liquid and vapour phases.

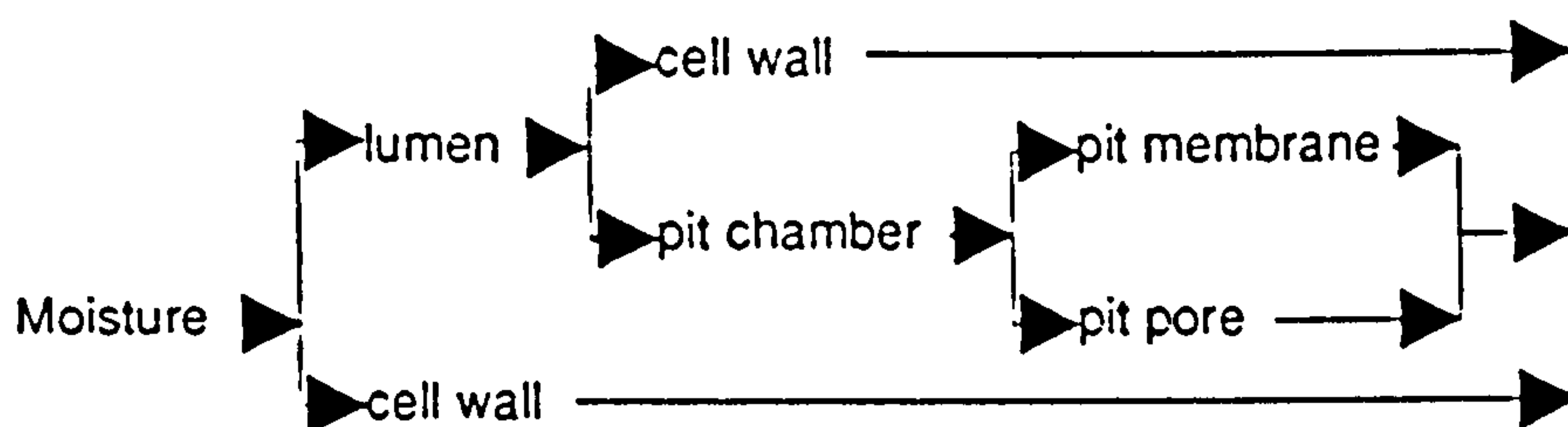
When the material has eventually reached equilibrium, the pressure exerted by the relevant phase is the same throughout the material. For the vapour phase in equilibrium a pocket of vapour deep within the material has a vapour pressure equal to that at the surface and consequently the surrounding air. Any gradient in these

pressures results in an adjustment in the phase towards equilibrium, and the consequence is a movement of water through the material. That is, the gradients in vapour pressure and capillary water pressure are the driving forces behind any water diffusion through a material.

2.2.3.2 Transport under Unsaturated Conditions

It is important to distinguish between water transport under saturated and unsaturated conditions. The flow of water in materials under unsaturated conditions is of interest in a great many more situations than the specialized case where a material has already reached saturation. At this time the moisture exists as bound water and water vapour, and the moisture movement occurs by diffusion, which is assumed by many authors to be the dominant mechanism for water transport in materials.

Diffusion processes have been studied in great depth, and it has been found that they can be described with similar mathematical expression. The basic equation describing diffusion is Fick's law (1855). The process of attaining equilibrium is assumed to be an exponential function of time (Morton and Hearle, 1962; Crank, 1975). For wood the complex structure gives rise to complications in the diffusivity of moisture. The transport of water molecules in wood is mainly by bound water flow and by water vapour diffusion. The flow of moisture is modelled through coupling the flows in the different components of the wood cell as follows (Stamm and Nelson, 1961):



However, it is difficult to determine the individual flows in the different components. The slow and delayed sorption of moisture in the cell walls has also been studied (Christensen, 1965).

2.2.3.3 Transport under Saturated Conditions

In the saturated case only liquid water transport occurs, and so the situation is somewhat simplified. Flow in a saturated material will only occur if there is an external pressure differential applied across the material. An equation governing free water flow is Darcy's law. In the cementitious area, Powers (1948) computed the data of ten year's experiments and concluded the flow of water through a given specimen of hydrated paste complies with Darcy's law, but it is liable to be complicated by effects of osmotic pressure. Spooner (1982) claimed that the rate of flow of water in a saturated element could be calculated using a version of Darcy's law.

However, as Claesson (1978) has pointed out, the problem is that we cannot differentiate between the flow of liquid and vapour in a material through measurement. At the extremes, a wet material will predominantly exhibit liquid water transport, and a dry material will exhibit mainly water vapour transport. Also the vapour and the liquid phases interact with each other as the water movement take place.

2.2.3.4 Other Transport Mechanisms

There are other mechanisms, such as transport through adsorbed water layers that line pores, that can in certain circumstances be significant factors in the movement of water. Martlay (1926), Newmann (1931) and Ogura and Umebara (1957) recognized that an external resistance influences moisture movement through wood and accounted for this resistance by empirically adding an "equivalent thickness" of wood in the direction of moisture flow. Choong and Skaar (1969, 1972) provided a method for quantitatively separating internal and external resistance to moisture sorption in wood. Some factors affecting the surface diffusion were also investigated by Collman and Schneider (1960), Salamon and McIntyre (1969), Steinhagen (1974), Rosen (1978), Avramidis and Siau (1987).

In the cementitious area, Radiy (1974) looked at the ways in which surface diffusion, molecular streaming and capillary suction processes would be expected to

interact with each other from the theoretical point of view.

2.3 Mechanisms of Movement of Wood and Cement Paste

2.3.1 Introduction

Volume changes of materials include expansion on hydration (concrete), shrinkage and swelling, creep, thermal expansion or chemical attack of aggressive solutions, etc. The following review and discussion is limited mainly to volume changes caused by moisture content. An exception is carbonation shrinkage which will be included in a later section.

The drying out / wetting of any system containing fine particles will invariably result in some shrinkage / swelling. The volume change of CBPB is affected by the proportion of the wood and cement components. The particular property of both wood and cement paste in CBPB (high porosity and the extremely wide range of pore size distribution) is mostly responsible for volume changes of CBPB during drying or wetting. However, the actual extent of this shrinkage / swelling will depend on a number of factors: the conditions of drying (such as the RH and the velocity of the air); properties of materials (which, for cement, depend on the W / C ratio), the degree of hydration, type of cement, the effect of carbon dioxide and even the creep of paste. For wood chips it depends on the species of tree, the position of wood in the trunk, the orientation of wood, the age of tree and even the felling season.

The phenomenon of shrinkage, associated with the drying out of materials rich in fine particles, can be explained in simple ways. When the film of water surrounding a conglomerate of grains forming an integral capillary system thins out, as a result of water evaporation, the grains are drawn closer to each other by a corresponding amount, resulting in a reduction in volume and the mass. However, under practical conditions, the action is affected by

- 1) a resistance to the shrinkage force: in the first stage of drying out, the mass suffers a volume reduction corresponding to the volume of the evaporated water, after reaching a certain drying strength value, the evaporating water begins to leave behind an increasing number of air - filled pores and the total extent of shrinkage

corresponds to a fraction only of the volume of the evaporated water: the more rigid the system and the higher its strength, the less shrinkage;

2) The diameter of the capillaries from which water evaporates: the smaller is this diameter the larger the shrinkage force;

3) The characteristic of the capillary systems: the tendency of a system to give up its water is dependent upon the degree of subdivision of the water. The tendency to evaporation of water exposed to the action of capillary force is lower than that of "free" water.

The relationship between the capillary radius and the RH below which the drying out of a capillary can commence was obtained by Haller (1942 cited in Czernin, 1980) (Table 2.3) .

Table 2.3 The relationship between the RH and the radius of capillaries

RH (%)	99.9	90.0	89.9	34.8
Capillary radius	1 μm	0.1 μm	0.01 μm	0.001 μm

The phenomenon of capillary condensation can be regarded as a counterpart of the relationship between the drying out and capillary diameter. A capillary system which has been dried out at a low RH will be re - condensated with water vapour from air and refilled with water when is in contact with air with a higher moisture content.

Thus the water content of a capillary system depends on the moisture content of the surrounding air. At 100 %RH all the capillary voids are filled with water, while under conditions approaching 0 %RH they becomes empty. At all intermediate RH, the quantity of the capillary water is determined by the RH of the air and the structure of the system, and if water is driven out, the body will shrink and swell under adsorption.

2.3.2 Shrinkage and Swelling of Cement Paste

2.3.2.1 Introduction

The phenomenon of drying shrinkage in cement paste has been discussed in great detail (Helmuth and Turk, 1967; Powers 1965; Ishai, 1966; Roper, 1966; Helmuth and Verbeck, 1968; Lankard and Shook, 1970; Wittman, 1973; Feldman and Sereda, 1964; etc.). Maximum shrinkage occurs on the first drying of the paste, and a considerable part of this shrinkage is irreversible. Further cycles of drying and wetting result in additional, but usually smaller, irreversible shrinkage. After some time, however, the process becomes more or less completely reversible. Continuous immersion of cement paste in water causes smaller swelling, Figure 2.6 A (Domone, 1994 in Illston; Feldman and Sereda, 1970).

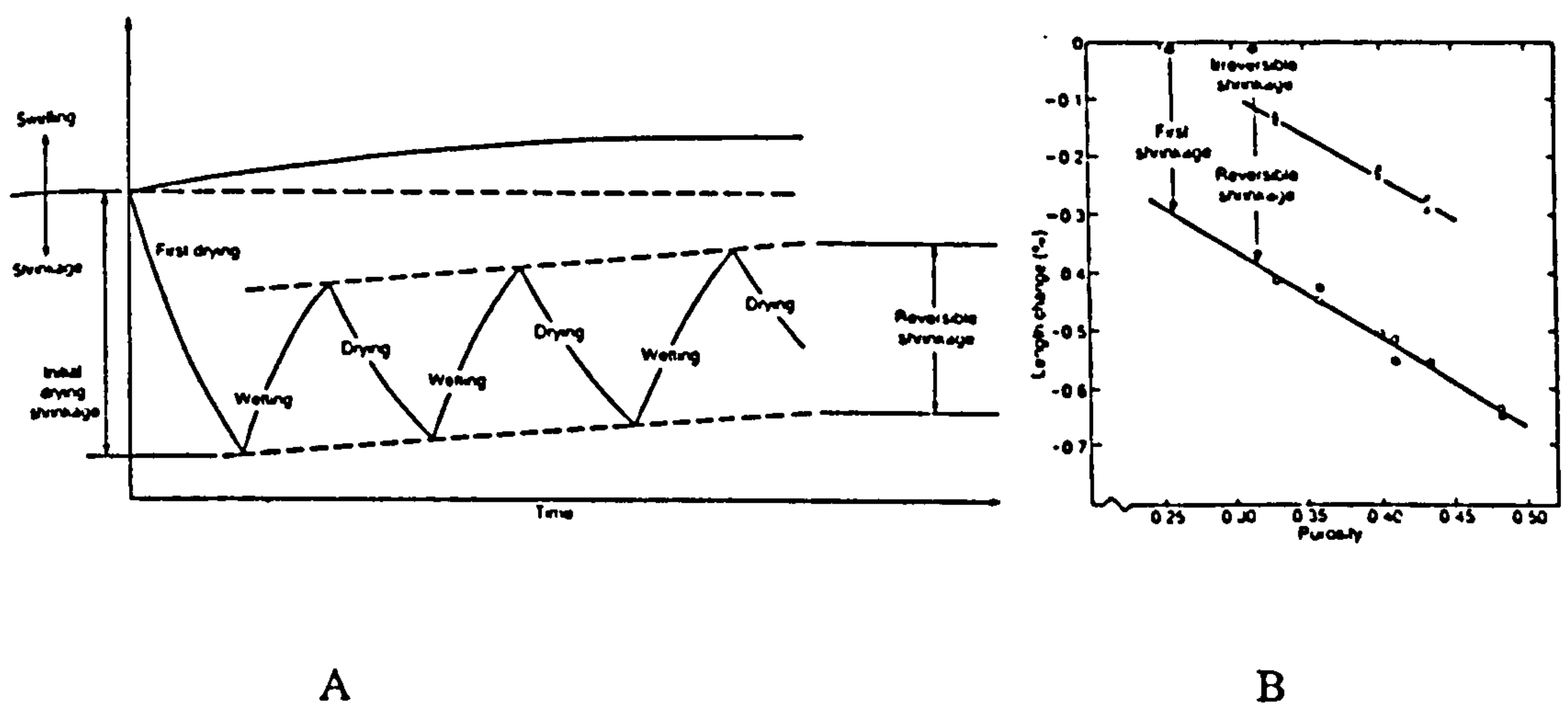


Figure 2.6 Reversible and irreversible volume changes of cement paste. A - a model of swelling and shrinkage due to alternate cycles [From Domone (1994)]; B - irreversible shrinkage of cement paste after drying at 47 %RH [From Helmuth and Turk (1967)]

2.3.2.2 Initial Irreversible Shrinkage of Cement Paste

It has long been recognised that in cement paste some of the shrinkage which mostly occurs in the first cycle of drying or wetting is irreversible. The irreversible shrinkage of hardened cement paste is generally between one third and one half of the reversible shrinkage (Czernin, 1980; Feldman and Sereda, 1970).

Helmuth and Turk (1967); Ishai (1968) and Feldman and Sereda (1970) were probably the first of several to tackle this problem. Helmuth and Turk concluded that

the stabilization process which occurs on first drying is related to fundamental changes in the paste structure, including a decrease in pore volume and a decrease in the specific surface area of the hydrated cement pastes. Irreversible shrinkage is dependent on porosity of cement paste (Figure 2.6 B).

Ishai (1968) interpreted the mechanism of irreversible shrinkage of paste in several ways, categorised by the RH. Above 40 %RH the shrinkage of paste is due to capillary tension. The capillary tension produces the isotropic compressive stresses in solid phase, giving rise to the sustained compression on the intercrystalline water. This compression squeezes out the water laterally, consequently reducing the particle spacing in the gel and the volume of the paste decreases. The reduced spacing involves a decrease in the total energy of the system and the associated volume decrease is therefore not recoverable; below 40 %RH the evaporation of the intercrystalline water occurs, causing a reduction in the particle space and also resulting in a decrease in the total energy of the system. This is not recoverable; in addition to the evaporation of intercrystalline water, the gradual exit of intracrystalline water begins as the RH is lowered to 10 %, and additional contraction of the paste takes place.

However, Feldman and Sereda (1970) believed there is a positive re - entry of the intracrystalline water. They suggested that on first drying some surfaces of the gel particles approach each other to form new bonds. Due to the retaining of many of these bonds on re - wetting, there exists a certain degree of irreversibility of volume decrease. The final exit of the interlayer water also causes irreversible shrinkage as a result of intensive drying below 1 %RH. The irreversible shrinkage on complete drying was attributed to reorientation of the CSH (hydrates of calcium silicate) layers. Nevertheless, the movement of interlayer water is essentially reversible.

Irreversible shrinkage caused by severe drying conditions was also mentioned by Czernin (1980). Under such conditions the dehydration of the individual gel particles makes a further contribution to the shrinkage: the interlayer water which is considered to exist chemically combined and to possess the characteristics of a solid capable of transmitting loads is driven out, and the voids it leaves behind undergo partial collapse. This manifests itself in an increased amount of shrinkage in relation

to the loss of water that occurs. However, under higher RH some of the lost interlayer water will be reincorporated into the gel.

Therefore, it is not surprising that the cement paste in CBPB undergoes dimensional changes with the RH change, resulting in an undesirable contribution to the dimensional instability of CBPB.

2.3.2.3 Reversible Shrinkage / Swelling of Cement Paste

Four principle mechanisms have been proposed for the shrinkage and swelling in cement pastes. However, there exists a wide range of different opinions with different authors. A summary of these is presented in Table 2.4 (Soroka, 1979). The main features of the mechanisms are briefly discussed below.

Table 2.4 Summary of shrinkage mechanisms of cement paste after various authors

RH (%)	0	10	20	30	40	50	60	70	80	90	100
Powers (1965)	←-----Variations in swelling pressure -----→ ←Augmentation by capillary→										
Ishai (1965)	-Variations in surface energy- ←---- Capillary tension----→										
Feldman & Sereda (1970)	←Movement of→ ←Capillary tension and variation→ interlayer water in surface energy										
Wittmann (1968)	←----Variation in ----→ ←Variation in swelling pressure→ surface energy										

A) *Capillary tension* The relationship between the radius of curvature of a meniscus (r), the surface tension (F) and vapour pressure (p) is given by Kelvin’s equation:

$$\ln(\frac{p}{p_0}) = \frac{2F}{RT\rho r}$$

where, R is the gas constant, T is the temperature in Kelvin, ρ is the density of the liquid.

Therefore, on exposing the cement paste to gradually decreasing RH, the pores gradually become empty in order according to their size (from capillary to gel pores). As the radius of the meniscus decreases, the tensile stress in the capillary water increases. The stresses must be balanced by compressive stresses in the surrounding solid, such will subject the paste to compressive stresses, causing the elastic volume decrease, i.e. shrinkage. This mechanism can explain why at different stages of drying there are different ratios of water loss / dimensional change.

Cementitious studies assume that the mechanism of capillary tension is effect when drying paste from higher RHs to 40 %RH. As such most of the shrinkage is attributable to this mechanism (Ishai, 1968). However, Powers (1968) considers swelling pressure as the main mechanism at any RH but capillary tension is of limited importance even for RH over 50 %. Feldman and Serda (1970) regard the capillary mechanism to be of some importance at RHs higher than 35 %. In their opinion, as far as the swelling of paste is concerned, the capillary tension mechanism is not of any great importance over the whole region. Some 80 % of the volume increase is attributable to re - entry of water into the layered structure of the CSH particles and swelling pressure and movement of interlayer water constitute additional mechanisms by which shrinkage can be explained.

B) *Surface tension* When a molecule at the surface of a material is not equally attracted and repelled by the neighbouring molecules from all directions, a resultant force acts downwards at right angles to the surface. Drying increases surface tension and the increased compressive stress causes volume decrease. In cement paste this mechanism is suggested to be valid only with the RH up to 40 % where variations in the water content of the paste are mainly due to variations in the amount of adsorbed water. At higher RH some of water in the capillary of the paste is outside the range of surface forces and a change in the amount of this type of water cannot affect surface tension. In fact, widely differing opinions existed in the role of surface energy changes in causing shrinkage. According to Wittman's tests (1958), shrinkage and swelling are mainly caused by changes in surface energy of the gel particles up to 40 %RH: the relation produced was a straight line. However, Feldman (1968) concluded that so far as shrinkage and swelling are concerned, surface energy effects

are of secondary importance. Powers (1948) suggested it as even less important.

C) Disjoining pressure (swelling pressure) Under a geometric constraint, the thickness of the adsorbed layer cannot always be fully developed, forming areas of hindered adsorption. In this area a swelling and "disjoining" pressure is developed tending to separate adjacent particles. Due to the mutual attraction between the gel particle (a tension in the interparticle bond), swelling is limited and the water in the area remains under pressure.

On drying the thickness of the adsorbed water layer reduces, resulting in the reduction of the area of hindered adsorption, hence reducing the pressure, causing an overall shrinkage. This assumption is in agreement with Power's model. However, Feldman and Sereda completely reject this mechanism with the suggestion that the interparticle bond is a solid to solid contact, and adsorption water cannot break the bond.

D) Movement of interlayer water Movement of water into or out of the layered CSH particle could cause volumetric changes because such movement would affect the spacing of the layers. This was considered as the main mechanism of shrinkage and swelling. However, other models assumed the interlayer water may be removed but will not re - enter the structure. This was argued as the mechanism of reversible or irreversible shrinkage.

2.3.2.4 Factors Affecting Shrinkage of Cement Paste

The shrinkage of cement paste is not only related to water loss but also to chemical changes (involved to the cement composition and other agents). In view of the subject of the present thesis, only several factors associated with the structure of the paste are discussed below.

A) Water / cement ratio It is well known that the volume of the cement paste is equal to the sum of the volumes of the anhydrous cement and the mixing water. Therefore, the initial porosity of paste is

$$P_i = \frac{R}{(V_c + R)}$$

where, R is the water / cement ratio and V_c is specific volume of cement. It can be seen that the initial porosity of cement paste increases with increasing the ratio of water / cement.

Drying shrinkage depends on the structure (porosity) of cement paste and water types in the cement paste. As expected, Haller (1940) (cited in Soroka, 1979) concluded that at an early stage of drying, the W / C ratio has no significant influence on shrinkage due to evaporation occurring in bigger pores (capillary pores), regardless of the amount of water loss; more intensive drying makes the smaller pores (gel pores) begin to empty. At this time, the same amounts of water loss may cause different amount of shrinkage when the ratio of gel to capillary water is not the same, with the paste with higher W / C ratio producing the higher shrinkage.

B) Degree of hydration of cement paste Hydration of cement paste is conditional, of course, on the presence of water. Soroka (1979) stated that on hydration (W / C = 0.309, T = 25 °C), by 365 days only 74 % of the cement had hydrated. Further hydration involves the diffusion of water through the layer of CSH gel. Hydration of cement increases the solid content of the paste (gel content). The increase in gel content increases the volume of gel pores at the expense of capillary pores, producing higher shrinkage, as supported by Verback and Helmuth (1968); Roper (1968).

It should be noted that in CBPB all hydration characteristics are substantially affected by sugar, tannin, and hemicellulose (Moslemi 1983, Biblis, 1968, Fan, 1989 and 1992), with tannin and hemicellulose having the greatest effects (Miller and Moslemi, 1991).

C) Heat treatment of paste (or autoclave) In view of the manufacturing method of CBPB, the shrinkage of CBPB may be affected by the temperature presented in the two curing processes (one 70 - 80 °C "oven boosting" and another 105 °C "oven dry"). Autoclave treatments affect the structure of the paste and its composition, and

as expected, subsequently affects the dimensional behaviour. Menzel (1934) who investigated the drying shrinkage of cement paste with different content of silica under 21 °C and 176 °C, found that the autoclave considerably reduces shrinkage. Powers and Brownyard (1948) who experimented at 215 °C as the treating temperature, and controlled the same degree of hydration, found the size of pores in heated curing paste is much greater than that in normal cured paste.

Another concern is the effect of heating on the hydrated cement paste, on which information is rather limited. Lankard and Shook (1970) heated cement paste using four different heating schedules and found that Portland cement paste heated at atmospheric pressure up to 260 °C exhibits considerable volume instability; all cement paste studied showed a permanent contraction after various schedules of heating; the magnitude of the permanent contraction of heated paste was correlated to environmental and body parameters.

D) Porosity of Cement Paste As mentioned, the porosity of paste increases with increase in W / C ratio and decreases with increase in the degree of hydration. Hence the shrinkage increases with the porosity. Helmuth and Turk (1967) are probably two of the first authors conducting this investigation. They found shrinkage of matured cement pastes increases linearly with increasing the porosity. However this applies to the irreversible part of shrinkage and the reversible part remains independent of porosity (Figure 2.6 B).

2.3.3 Shrinkage and Swelling of Wood

2.3.3.1 Shrinkage / Swelling

In the field of wood dimensional change is normally divided into two groups, with those occurring as a result of initial drying down from green to dry condition termed "shrinkage" whilst those occurring as a result of daily or seasonal changes in RH of the atmosphere being referred to as "movement", although both can usually concurrently apply.

From the fibre saturation point to the oven - dry state the shrinkage in the

longitudinal direction of wood is very small, usually only about 0.1 %, whilst in the radial and tangential directions the average values are near 5 and 10 % respectively. The marked difference between longitudinal and transverse shrinkage is mainly due to the microfibrillar angle of the S2 layer of the cell wall. Differences in shrinkage between tangential and radial directions have been accounted for by a number of factors, among which the more important are the restricting effect of rays, differences in degrees of lignification, small differences in microfibrillar angle and the increased thickness of the middle lamella. Volumetric shrinkage is slightly less than the sums of the three directional components.

In fact, the volumetric swelling of the gross wood strongly depends on the dimensional changes occurring in the cavities. Three possibilities are: 1) the lumens or cavities may shrink; 2) the lumens may remain constant in size; 3) the lumens may swell. If all of the swelling takes place into cell cavities, no external dimensional changes take place at all. This extreme case could occur only if a sufficiently strong restraining layer outside of the cell prevented any swelling externally. Chips within the CBPB may involve this case.

As general rule, the cell cavities appears to change only to a small extent during change of moisture content, due probably to a balance of the restraining effect of the three layers of the second wall and the different orientation of the fibrils. However it is possible that collapse occurs during drying (Skaar, 1972) - this also may happen in the chips within CBPB.

2.3.3.2 Dimensional Change and Stress of Wood

Dimensional changes in wood are affected to a greater or lesser degree by mechanical stresses which may arise from moisture gradients, mechanical restraints, macroscopic tissue swelling anisotropy, and micro and submicroscopic anisotropy with the cell wall itself.

A) Moisture gradients The stresses associated with drying of lumber have been studied in some detail and actually form the basis for most lumber drying schedules. During initial stages of normal drying some hygroscopic shrinkage in the surface

takes place first and this is resisted by the wet core. As a consequence, the outer layers are under severe tensile stress whereas the inner layers are under a milder compressive stress. As drying progresses further the compressive stress in the interior increases and the tensile stress in the extreme outer layer decrease. Because of the strong tendency of wood to "creep" under conditions of stress, particularly transverse to the grain, the outer layers shrink less than the material in isolation would, but the inner layers have been somewhat compressed and therefore tend to show greater shrinkage. In terms of volume, the overall shrinkage across the width / thickness is determined largely by the amount of compression set, regardless of the usually more pronounced tension set in the surface. Greater shrinkage in the transverse shrinkage was confirmed by Espenas' studies (1971). At the late stages of drying the outer layer is under compression and finally the stresses essentially reverse themselves from those existing at the first. Hittmeier (1967) also concluded that the width swelling is delayed compared with the thickness swelling for both flat - and quarter - sawn samples. This is attributed to the fact that most of the diffusion of water into the dry sample takes place in the direction of thickness. During the early stages of soaking, outer layers take up water and tend to swell, but they are restrained from swelling in the width direction due to the stronger (drier) interior wood. Swelling does take place in the thickness direction and may even be somewhat greater than normal because of the Poisson ratio effect in the moist surface layers. Later, as interior wood finally becomes moist, the width swelling increases more rapidly than increase in thickness. This situation seems not to be the case in small chips. However, it could be a case if the overall bulk of CBPB is considered.

B) Mechanical restraint The effect of mechanical restraint on hygroscopic dimensional changes is very marked in wood owing to the large component of inelastic deformation associated with mechanical stress. Mechanical restraint is used to reduce cupping, twisting, crooking and cracking of lumber during drying (Fan, 1991; Simpson, 1982). The effect of mechanical stress on shrinkage is most apparent when wood which is restrained from movement is subjected to cyclic moisture changes (Skaar, 1972). If the swelling of dry wood is restrained by the influence of external forces the anatomical and molecular structure of the wood will be changed,

hence it follows that subsequent re - drying to the original moisture content is accompanied by a reduction of the dimensions, i.e. by a permanent shrinkage (Kollmann and Cote, 1968; Skaar, 1972), Figure 2.7. This phenomenon was also found in the dimensional changes of temporarily restrained wood prior to 9 wetting and drying cycles. This caused a reduction of the dimensions by about 22 % (Knight and Newall, 1938 cited in Kollmann and Cote, 1968). A more systematical investigation was also published by Perkitny (1937/38, cited in Kollmann and Cote, 1968) Figure 2.8.

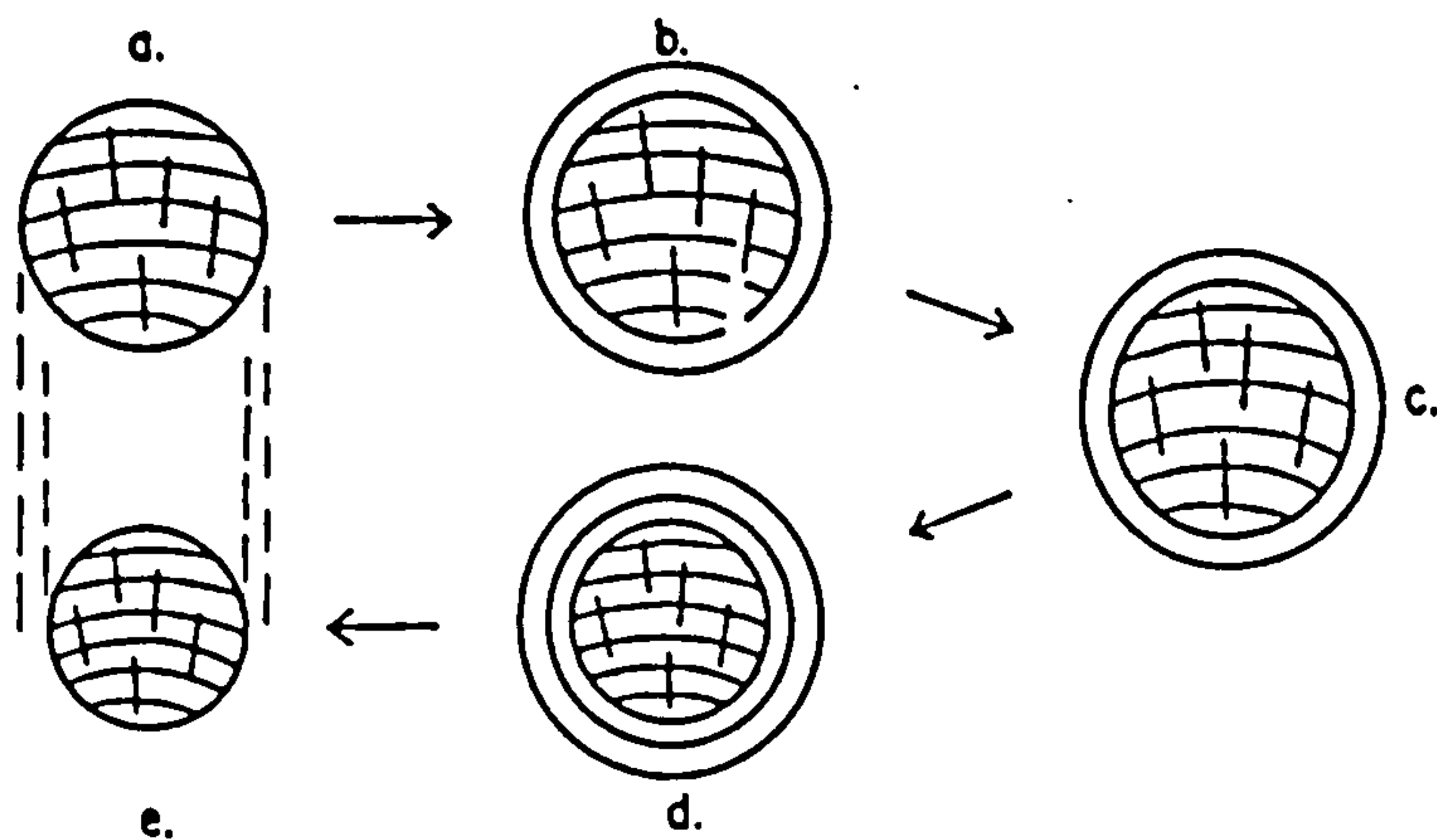


Figure 2.7 Schematic of restraint swelling in the transverse directions of wood showing the effect of compression in "a" and "e" [From Skaar (1972)]

Tiemann (1944) also restrained wood in one direction during drying, attained a tension set, and found the wood to be then of larger dimensions in this direction than in the unrestrained wood.

It is worth noting that at constant vapour pressure a compressive stress reduces sorption and a tensile stress increases it (Barkas 1949).

The effect of mechanical restraint would play an important role in the movement of CBPB under cyclic RH exposure. Tougher cement paste enveloped wood chips, such under cyclic exposure cement paste will restrain wood chips due to a different degree of swelling or shrinkage between wood chips and cement paste or delay in the movement of cement paste.

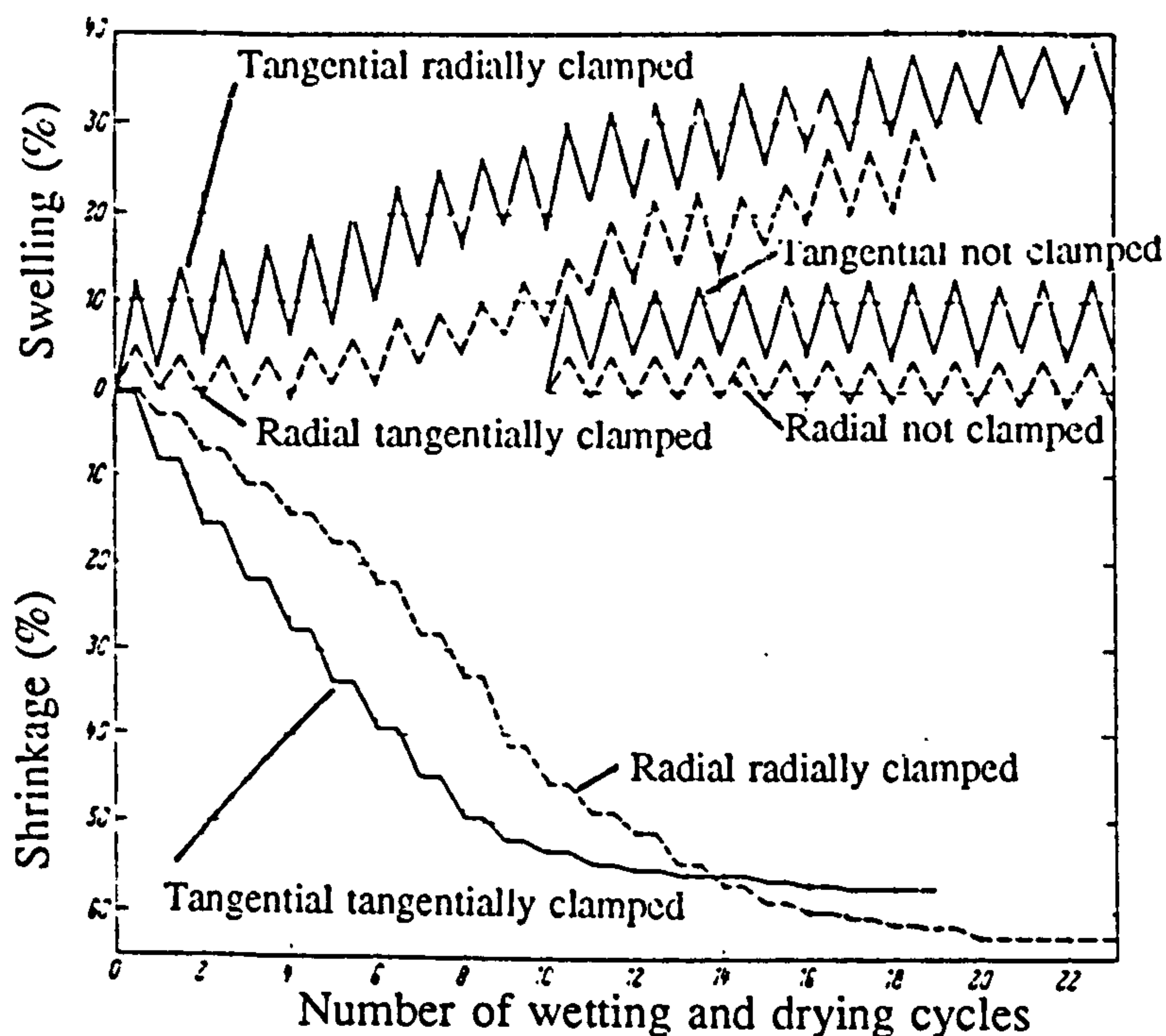


Figure 2.8 Swelling and shrinkage of clamped and free wood under cyclic wetting and drying [From Kollmann (1968)]

2.4 Effect of a Hydrated Ordinary Portland Cement on a Wood Aggregate

2.4.1 Introduction

Two main features, the chemical composition of the liquid phase of hydrating Portland cement and the change in temperature during the hydration and curing process of the CBPB, could affect both the physical and chemical properties of the wood chips.

There are three major components in the liquid phase, Ca^{2+} , SO_4^{2-} and OH^- ions on the addition of water to an unhydrated Portland cement / wood mix. These ions form a complex including CaOH^+ and an ion pair CaSO_4 , as well as K^+ and Na^+ ions from the smaller quantities of alkaline oxides in unhydrated OPC (Bailey and Hampson, 1982). Although information on the exact concentration of ions in the

liquid phase constituent is not available so far, like other cementitious materials, an excess of water is added for complete hydration or satisfying the wood aggregate. A supersaturated solution of calcium hydroxide, containing ions of unhydrated soluble cement constituents, will form and the resulting liquid phase has a pH of about 12.5. Such a solution principally has the potential of both causing alkali degradation and bulking of the cell wall.

The hydration of Portland cement is an exothermic reaction, a considerable amount of heat being liberated. The principal sources of thermal changes which occur during the hydration of cement are the heats of solution of the several constituent anhydrous compounds and the heats of precipitation of the several hydrates from solution. The algebraic sum of these heat values is the heat of hydration of the cement at any given age (Roth and Chall, 1928; Thorvaldson, *et al*, 1930; Woods, *et al*, 1933; Lerch and Bogue, 1934; Verbeck and Foster, 1950; Brunauer, *et al*, 1955 cited in Bogue, 1955). Under the low thermal conductivity of the composite, the radiation of heat is prevented, and the mass of the composite then attains a high temperature (Bogue, 1955). Wood chips will be subjected to an increase in temperature for a finite period of time. Therefore it is not surprising that wood chips in CBPB may change in chemical composition, weight and subsequent properties due to this thermal effect.

2.4.2 Alkali Degradation of Wood

Solutions of strong bases, such as sodium, potassium or calcium hydroxide, are capable of removing the majority of the extractives and dissolving considerable quantities of the hemicelluloses. A consequence of this is that a chemically heterogeneous extract is formed (Browning, 1963). The effect of temperature and pressure on the degree of degradation of wood is very significant. At high temperatures and under pressure, most of the hemicelluloses and a high percentage of the lignin can be removed which, in fact, is a process used in pulping. At lower temperatures and pressure (normally $< 150^{\circ}\text{C}$ / atmospheric pressure), the degree of degradation is not so great, due partly to reaction mechanics or reaction kinetics, however, some of the lignin can be degraded even at room temperature, forming

alkali soluble products (Browning, 1963).

2.4.2.1 Mechanism of Degradation

A) *Degradation of the polysaccharides* The chemical degradation of the polysaccharide is by oxide degradation, a reaction mechanism known as "peeling" (below 150 °C), i.e. removing 1 end carbohydrate monomer from the reducing end of the polysaccharide chain. The residue of each carbohydrate monomer removed is predominantly iso- or meta- saccharinic acid, depending on whether the original polysaccharide chain linkage was 1,4 or 1,3 respectively. The residual saccharinic acid dissolves and undergoes further fragmentation, forming lower molecular weight acids e.g. lactic, acetic, formic and butyric acid (Kenner, 1955 in Browning 1963).

B) *Degradation of lignin* The action of alkali on lignin at temperature < 160 °C is two fold: increased solubility caused by hydrolysis, and condensation of the soluble fractions. These occur simultaneously. The bonds susceptible to attack are the alkyl-aryl ether linkages in the 4 position, with the formation of phenolic hydroxyl groups and the carbon-carbon linkage in the propyl side chain, between the β and γ carbon (Sarkanen in Browning, 1963).

2.4.2.2 Phenomenon of Degradation of Wood

At low temperatures, the degree of alkali degradation of cellulose is relatively small due to the initially high degree of polymerization and reduced alkali accessibility because of the protective sheath of hemicelluloses and its high crystalline nature. However, the alkali degradation of hemicelluloses under the same conditions is very significant, probably due to polysaccharide branching being accessible to alkali, and a large portion of hemicellulose will become soluble after alkali degradation (Kass, *et al*, 1970). This result was confirmed by a comprehensive study using sodium hydroxide by Wangaard (1966), with the order of the degradation (weight loss) being hemicelluloses > lignin > celluloses. Even very low concentrations at room temperature, such as 2 % NaOH / 20 °C, can result in substantial loss in strength

(Thompson, 1969; Narayanamurti and Ranganathan, 1947; Ross, 1956; Kass, *et al*, 1970).

With CBPB, more attention should be paid to the effect of calcium hydroxide solution, although the trends are the same for all alkalis, only the magnitude differing. This was studied by Ross (1956) and Manwiller and Godfrey (1973), who found only limited alkali degradation of the hemicelluloses and lignin, and very likely a lack of attack in the cellulose.

Very little work has been conducted on the investigation of the effect of curing Portland cement paste on the strength properties of wood. Simatupang (1978 cited Roberts, 1979) first suggested that the action of cement alkalis could result in embrittlement of wood wool strands. A reduction in tensile strength with increased exposure time at 20 °C and temperature after 1 day hydration was also found by Roberts (1979) and Cashman (1981). A more systematic investigation was conducted by Stewards (1988), who concluded that:

- 1) under the conditions existing within a hydrating CBPB, approximately 20 % and 17 % losses in maximum tensile strength and loading work respectively were recorded in *Pinus sylvestris*;

- 2) a significant degradation of the wood cell wall occurs during the hydration, with the hemicelluloses being preferentially alkali degraded.

2.4.3 Effect of Temperature on Wood (thermal degradation)

It is well known that as pyrolysis proceeds both physical properties and cell wall constituents undergo substantial changes. The heating effect on the rate and absolute degree of wood degradation is primarily due to the difference in the extent of oxide ratio and heat transfer. Overall the hemicellulose portion of the cell wall is the most susceptible to thermal degradation. Maclean (1951), who investigated the rate of disintegration of several timbers of both softwood and hardwoods using three means of heating, namely oven (air), steam (over 100 °C) and water, concluded that at any given temperature the rate of weight loss was greater for wood treated in steam or water than in air. Heating in water is obviously the closest representation of the conditions experienced by a wood aggregate in the curing / hydrating wood cement

composite.

Stamm (1956) also calculated the rate of weight loss (Douglas fir and Sitka spruce) of whole wood and its principle constituents, and found that at 150 °C hemicellulose weight loss is about four times as rapid as that for complete wood; cellulose degrades at about the same rate, while lignin degrades at about half the rate of whole wood. The rate of degradation is much faster, at equivalent temperatures, for steam heated wood than that for dry wood.

Hagglund (1951) even suggested that as a result of the thermal degradation of wood soluble carbohydrate material is formed, varying in quantity and form depending on the severity of the treatment. Further hydrolysis of the carbohydrate unit fractions gives rise to formic and acetic acid, with the evolution of carbon dioxide, which if not leached away from the wood (or neutralized) can enhance the degradation process.

2.4.4 Volumetric Changes for Wood beyond that Produced by Water

2.4.4.1 Effect of Alkali

The high swelling of wood in strong alkalis is well known (Kollmann and Côté, 1968). The increase in swelling runs parallel to an increase of the fractional volume occupied by the salt in the solution and a decrease of the relative vapour pressure over the solution. A well - defined inter - relationship between volumetric swelling and solution equilibrium pH exists beyond the swelling in water (Stamm, 1934 cited in Kollmann and Côté, 1968). It was found that above pH 7 volumetric swelling increases exponentially, such that a solution of about pH 12.5 results in about 0.7 % increase in volumetric swelling, and most of this occurs in the tangential direction (Stamm in Goldstein, 1977). An investigation of calcium hydroxide (OPC paste liquid model) was conducted by Steward (1988), who found calcium hydroxide had a significant effect on the swelling properties of wood, inducing decreased, rather than increased wood moisture dimensional stability. The gross thickness swelling of CBPB samples after the removal of rigid OPC paste remained relatively low compared to that of resin chipboard and in excess of 80 % of the thickness swelling

after solution exposure was recoverable on subsequent drying. Only a small proportion of the stability of CBPB may be due to alkali hydrolysis of the wood (preferentially hemicelluloses and lignin degradation) during hydration, reducing the tendency of the already less contorted wood chips to straighten.

2.4.4.2 Effect of Heating

Heat stabilization was at first believed to be due to the formation of linkages between adjacent cellulose chains as a result of splitting out of water between two hydroxyl groups and other minor breakdown products (Stamm and Hansen, 1937 cited Stamm in Goldstein, 1977). For effective heat stabilization, relatively high temperatures are necessary, and absence of oxygen. A linear relationship between exposure temperature and the logarithm of the heating time (oxygen free dry heating) of softwood was obtained by Stamm, *et al*, 1946 (cited Stamm in Goldstein, 1977), who also showed that a 10 % reduction in swelling and shrinkage can be achieved by heating for 24 hours at 140 °C. Such conditions may be experienced in the production of CBPB. Due to the presence of oxygen and water in the production of CBPB a higher rate of cell wall degradation will occur (about eighteen times as great) which results in a degree of heat caused dimensional stabilization of greater significance (Stamm, 1956). Unfortunately,

- 1) obtaining dimensional stabilization by this technique is accompanied by relatively large reductions in material properties, especially toughness, due to the thermal degradation of the most hygroscopic cell wall component, namely the hemicelluloses;

- 2) it was shown that in concentrated sodium hydroxide solutions and in pyridine heat stabilized wood swells to a greater extent than unheated wood. This was explained by the water soluble polymers being soluble or at least swelling in concentrated sodium hydroxide solution or pyridine (Seborg, *et al*, 1953 cited Stamm in Goldstein, 1977).

2.4.4.3 The Bulking of the Cell Wall

The bulking of fibres is through the deposition of chemicals or by chemically reacting with the cell wall, increasing the volume of the dry cell walls and reducing the external volumetric shrinkage of the wood (Stamm in Goldstein, 1977). The increase in dry wall volume is directly proportional to the amount of chemical added - the more chemicals deposited in the cell wall, the greater the degree of dimensional stabilization (Stamm, 1934 cited Stamm in Goldstein, 1977; Rowell and Youngs, 1981). It has been stated that reduction in the shrinkage due to bulking is merely because there is less moisture to be lost (Stamm, 1934 cited Stamm in Goldstein, 1977).

Bulking effects strongly depend on the bulking agent (Stamm in Goldstein, 1977). The ideal bulking agent for wood would be a non - corrosive, non - volatile solid, approaching infinite solubility in water which does not materially reduce the vapour pressure of water. The composition of the liquid phase in a hydrating cement is far from the ideal bulking agent because of the low solubility of the constituents, predominantly calcium hydroxide. However, sufficient calcium ions may be deposited within the cell wall due to its high affinity for alkalis imparting a degree of dimensional stabilization (Steward, 1988).

2.5 The Effect of Alkali Soluble Wood Constituents on the Properties of OPC

An adverse effect of alkali soluble substances of organic nature, such as impurities in inorganic aggregates, on the physical properties of cementitious materials is well documented (Abrams, 1920). Therefore it is not surprising that the hydration of OPC in contact with wood results in unfavourable effects due to interactions between the hydrating OPC and the wood constituents. The seriousness of the adverse reactions between the alkali soluble wood constituents and cement has long been recognised, initially with wood wool and later with wood cement chipboard. The two principle phenomena found are firstly the crumbling of surfaces adjacent to timber shuttering and secondly the formation of abnormally weak wood cement composites due to the

cement retardation.

The water soluble constituents [and often specifically the carbohydrates (single sugar units and polysaccharides)] have been commonly quoted as being mainly responsible for the retardation of cement in contact with wood (Sandermann and Brendel, 1956; Biblis and Lo, 1968; Dass and George, 1970; Yoshimoto and Minami, 1976). It is generally agreed that the mechanism of set retardation involves, in part, at least if not solely, the adsorption of compounds onto the surface of cement particles (grains), or early hydration products, particularly those of C_3A and C_4AF (Blank, *et al*, 1963; Bruere, 1966; Young, 1968 and 1972). Sandermann (1966 cited Roberts, 1978) found that the organic molecules became adsorbed onto the first few hydration layers around the cement grains, forming partially or completely impermeable membranes. A comprehensive review of other hypotheses, mainly concerned with organic compounds, has also been made by Young (1968 and 1972), who categorizes these theories into four sub-divisions viz. Precipitation, Nucleation, Complexation and Adsorption.

In addition to this retardation, it is not inconceivable that some of the alkali soluble organic wood constituents could act as "air entrainers" or "water reducing agents (plasticisers)". In fact this characteristic has long been employed in the cement and concrete industry to produce the desired effects of air entrainment or workability [such as conifer resin (colophony) and modified sulphite pulping waste liquor (lignosulphonates)] (Chittenden, 1972; Illston, *et al*, 1979).

Air entrainers act by reducing the surface tension of the mixing water thereby allowing stable air bubbles to exist in the cement paste. This results in an increase in the porosity and formation of a larger irregular volumes (Illston, 1979).

The phenomenon of water reducing is also explained by adsorption theories. The adsorption of the organic compound onto the surface of the cement grains leads to a build up of repulsion forces between the grains thereby reducing the viscosity of the paste, so allowing the use of a lower water / cement ratio (reduction in porosity) (Illston, *et al*, 1979).

2.6 The Action of Aggressive Agents on Cement Paste

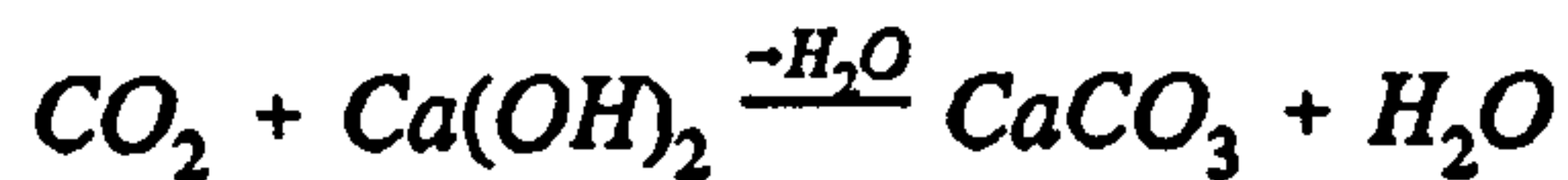
2.6.1 Introduction

Hardened cement paste can be attacked chemically either by a process of dissolution or chemical transformation or by both at the same time (Czernin, 1980). There are two main deteriorative processes occurring in hardened cement paste, i.e. chemical decomposition and dissolution (or leaching) (Zcernin, 1980). The scope of aggressive attack on cement paste is far too wide for inclusion within the framework of this thesis. However the sources of acidity of natural water are much more limited and practical, and one of these is carbon dioxide which will be detailed below.

Carbonation of cement paste normally involves a chemical reaction between atmospheric carbon dioxide and the products of cement hydration. The carbon dioxide in the atmosphere mainly derives from natural processes concerned with growth of vegetation on the Earth's surface and from industrial processes that use fossil fuels (Crane and Liss, 1985). Carbonation of cement paste has been long recognised. Early research on carbonation and its effects on Portland cement paste, mortar and concrete have been summarised by Lee and Desch (1956). Subsequent investigations have been reported by Verbeck (1958), Kroone and Blakey (1959), Hunt and Tomes (1962), Power (1962), Kamimura, *et al*, (1965), Ho and Lewis (1987), Parrot (1987), Sarott, *et al*, (1992), Thomas and Matthews (1992), Saetta, *et al*, (1993). The overall state of knowledge may be briefly summarised as follows.

2.6.2 The Mechanism of Carbonation

The mechanism of carbonation is likely to consist of mainly gaseous diffusion combined with chemical interaction. The chief chemical interaction is the reaction of CO_2 in the air (about 0.03 % by volume) with Ca(OH)_2 liberated during cement hydration and CSH, resulting in the decomposition of the hydration products of the cement paste in CBPB to form various minerals and water. Furthermore the other hydration products of the cement are broken down by the action of carbon dioxide. That is,



Carbonation proceeds inwards from the exposed concrete surface along a front roughly parallel to it. It takes place very slowly over a period of years. In well compacted dense concrete of low permeability exposed outdoors, its depth is generally limited to several millimetres from the surface. However, any cracks in the structure that provide a path for ingress of air will allow carbonation to penetrate further. This condition seems to be very relevant in the structure of CBPB in which the loose wood chips might provide pathways for carbon dioxide.

In dry, internal conditions, the depth of carbonation is roughly proportional to the square root of the duration of exposure. Its progress can normally be described approximately by

$$X = X_0 + C\sqrt{t}$$

where, X is the depth of carbonation, t is the time during which carbonation has been proceeding, X_0 is the initial depth of carbonation (which is normally small) and C is a constant related to concrete quality and environment conditions (Ho and Lewis, 1987).

However, it is more universal to be described as a polynomial relationship between the depth of carbonation and the duration of RH exposure (Lesage, 1985; Meyer, 1968).

2.6.3 Factors Affecting Carbonation

Carbonation depends on many factors, including the quality of the concrete and the conditions of exposure.

2.6.3.1 The Quality of the Hardened Cement Composite

In terms of composite quality, the most important factors that affect carbonation are

considered to be the permeability and physical structure of materials. They are determined by the ingredients and methods used in making the composite, which include its cement content and type, water / cement ratio, aggregate type, size and grading, degree of compaction and the curing condition.

A) Aggregate There is a wide variation in properties of aggregates and not surprisingly there is a fairly good reverse correlation between density and water absorption. The porosity of the aggregate provides a pathway for sufficient carbon dioxide to enter the carbonate cement paste to a slightly greater depth than average (Collins, 1986).

B) Ratio of water / cement The main factor that can be used to limit the rate of carbonation is the W / C ratio (Kurz, 1984; Meyer, 1968; Fattuhi, 1986; Collins, 1986). The ratio of W / C is strongly related to the permeability of cement paste (Power 1958). Lower water will reduce the permeability of CO₂ and hence allow less carbonation (Ho and Lewis, 1987). Average carbonation depth in concrete mortar was roughly proportional to total W / C ratio and maximum carbonation depth was increased in many cases by carbon dioxide passing preferentially through the porous aggregate. For example, Meyer (1968) tested 2.5 year old concrete, and found the depth of carbonation increased by 4 times as W / C ratio increased from 0.4 to 1.0; Lesage (1985) measured the effect of the different ratio and different durations on the depth of carbonation, obtaining about 5 times greater carbonation in concrete with a ratio of 1.05 than that with a ratio of 0.5 after the first 6 months' exposure, and about 6 times after 2 years' exposure.

C) Compaction of composite A large number of publications clearly show a pronounced reduction in the depth of carbonation with an increase in 28 day compressive strength because permeability is increased by inadequate compaction (Lesage, 1985; Nagataki, *et al*, 1986; Scholz and Wierig, 1984; Nischer, 1984; Ho and Lewis, 1987; Nagataki, *et al*, 1986). The evidence implies that carbonation of CBPB may be greater than that of concrete due to the structure of CBPB and the more flexible wood chips.

D) *Curing conditions* The cement in the surface layers of the composite will virtually cease hydration if the internal RH drops to about 80 %, causing a relatively high porosity and a high permeability in the surface layers and increasing the rate of carbon dioxide diffusion (Patel, *et al*, 1985). Such short term curing (as is the case in the manufacture of CBPB) increases the depth of carbonation at a given time (Kurz, 1984; Meyer, 1968; Fattahi, 1986). Carbonation decreased as curing duration was increased from one to seven days but remained practically unaffected when curing was extended beyond seven days (Ho and Lewis, 1987). Nagataki, *et al*, (1986) reported that the effect of curing was more pronounced with drier exposure conditions.

2.6.3.2 Exposure Conditions

Regarding the conditions of exposure of cement paste, of special importance are temperature, RH and carbon dioxide concentration, which can play a significant role in the rate and depth of carbonation. The rate of carbonation of concrete was proposed by both Saetta, *et al* (1993) and Wittmann (1983; 1986). The function is:

$$\frac{\partial c}{\partial t} = \alpha_1 f(h) f(g) f(c) f(T)$$

where, α_1 is a material parameter, $f(h)$ is the effect of moisture (RH), $f(g)$ represents the carbon dioxide concentration (from 0 to 1), $f(c)$ is the influence of the degree of carbonation, ranging from 0 to 1 and $f(T)$ is the Arrhenius equation.

A) *Temperature* There is a substantial influence of temperature on the degree of carbonation. Saetta, *et al*. (1993), employing three different temperature (i.e. 1 °C, 20 °C and 90 °C), found increasing temperature causes an acceleration of carbonation. However, Daimon, *et al* (1971) stated that an increase of temperature increases the rate of carbonation but would also promote drying; depending upon the degree of drying, elevated temperatures could increase or decrease the later rate of carbonation.

B) *RH* RH influences carbonation in two ways. Atmospheric carbon dioxide can

only react with the cement hydrates when there is sufficient pore water to first dissolve it (Verbeck, 1958; Hilsdorf, *et al*, 1984; Hunt and Tomes, 1962). If the pores are completely dry the reaction of carbon dioxide with water molecules is absent. However, if the pores are filled with water, the penetration of carbon dioxide is hindered because of the low rate of diffusion of CO_2 in water, though the carbonation reaction can occur readily under saturated conditions when carbon dioxide is freely available. The rate of carbonation at ordinary temperatures is greatest at an ambient RH around 50 % to 75 % (Kamimura, *et al*, 1965; Verbeck, 1958; Hunt and Tomes, 1962; Wierig, 1984) (Figure 2.9 A).

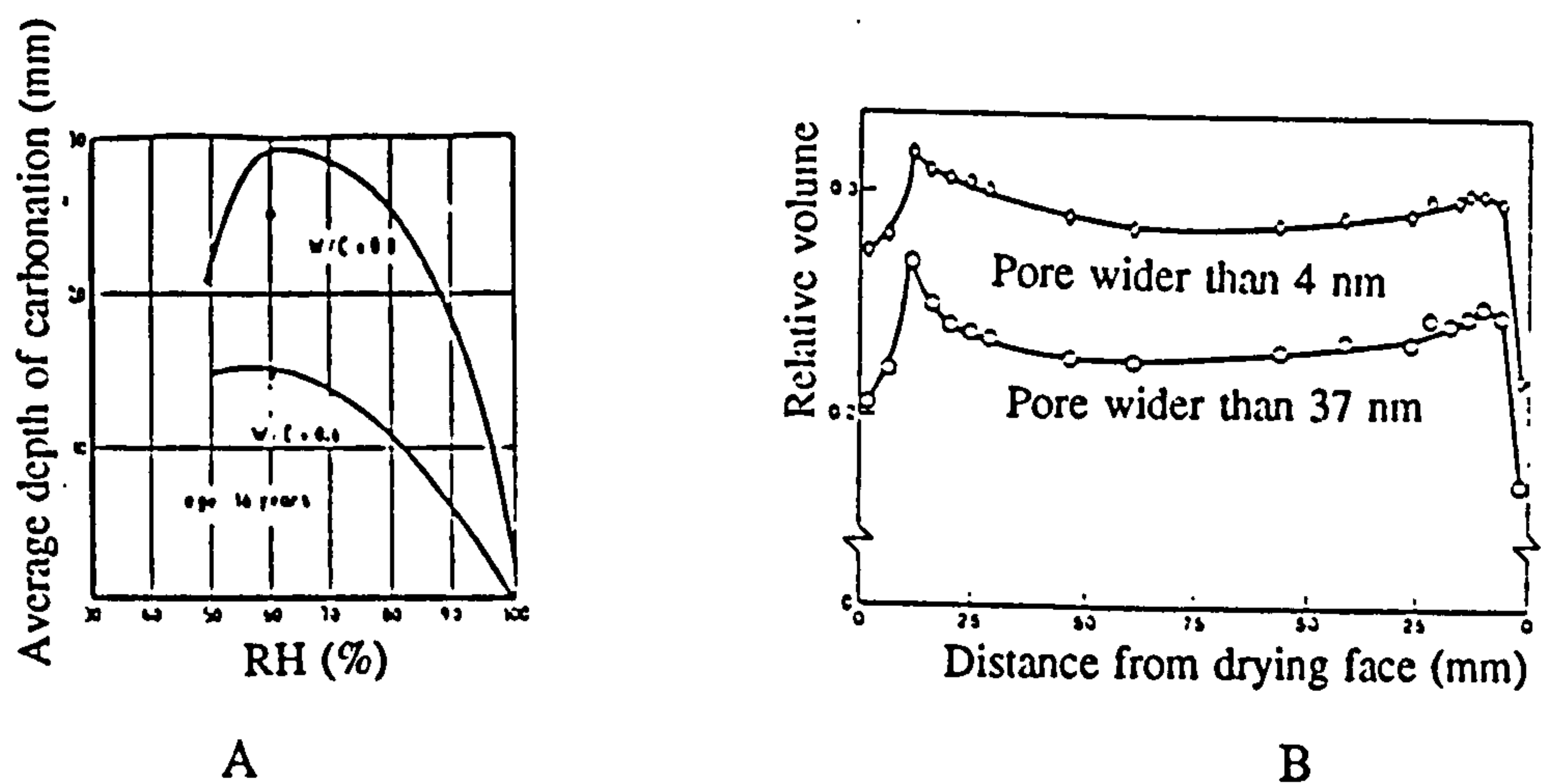


Figure 2.9 Effect of carbon dioxide on cement paste. A - relationship between the carbonation and RH of cement paste [From Wierig (1984)]; B - structure change of cement paste after 650 day - exposure, $W / C = 0.59$ [From Patel, *et al* (1985)].

It is the RH in the carbonated zone and at the carbonation front that affects the rate of carbonation and these are indirectly linked to the ambient RH. Thus carbonation can occur during the initial drying of a saturated sample exposed at a low RH and there can be an effect of sample size (Verkerk, 1958). Periodic rewetting was shown by Schubert (1976) to significantly reduce carbonation due to the lower rate of carbon dioxide diffusion through the partially saturated pores of the cement paste matrix. Variable moisture conditions may cause a change in the shape of the carbonation depth versus time curve (Meyer, 1968), with the rate of carbonation significantly decreasing with increase of moisture. This suggests that the CBPB

cycled in 35 and 90 %RH may create the different rates of the carbonation.

C) *The concentration of carbon dioxide* The rate of carbonation increases with an increase in the concentration of carbon dioxide (Nischer, 1984; Daimon, *et al*, 1971; Fukushi *et al*, 1985). However there is only a small increase beyond 1 % of carbon dioxide by volume: about 2.8 % weight gain was obtained at 1 % CO₂, 3.1 % at 5 % CO₂, 3.5 % at 25 % CO₂ and 3.7 % at 100 % CO₂ (Verkerk, 1958). The results of Nischer (1984) also show that the effect of a higher carbon dioxide level is greater in concretes having a strength less than 30 Mpa.

2.6.4 Effects of Carbonation

Substantial carbonation occurs even at the low CO₂ concentration normally found in the atmosphere. It is not limited to the hydroxide present, but is also associated with other components in the paste. The resulting modification of the cement gel is reflected in certain changes in properties. Except at early ages, strength is improved. Hardness, impermeability, and volume stability are favourably affected. The most dramatic effect of carbonation, however, is a large increase in shrinkage under intermediate conditions of RH as mentioned above.

A) *Permeability* The carbonation reaction generally causes a reduction in porosity of the exposed surface because the volume of calcium carbonate formed exceeds that of the parent hydrate (Figure 2.9 B) (Panel, *et al*, 1985; Hilsdorf, *et al*, 1984; Pihlajavaara, 1968; Rozental and Alekseev, 1976). The average pore radius is decreased in comparison to non - carbonated materials (Dewaele, *et al*, 1991), and progressive carbonation caused a decrease in permeability (Panel, *et al*, 1985; Hilsdorf, *et al*, 1984; Martin, 1986; Dewaele, *et al*, 1991). In a similar investigation of cement grout, Dayal and Klein (1987 cited in Dewaele, *et al*, 1991) concluded that the reduction in carbonated grout permeability is caused by the precipitation of calcite and other carbonation products on the surfaces and in the pores of the grout contacted by CO₂ - modified solutions. A 60 - fold reduction in permeability of a partially-carbonated grout sample was obtained on high pressure injection of gaseous

CO₂ to induce carbonation (Dayal and Klein 1987), and a fully - carbonated grout was found to have reduced the permeability by 10⁻³ to 10⁻⁶ times (Dewaele, *et al*, 1991). However, Dewaele, *et al* (1991) also concluded that the marked reductions in permeability prevent the development of an extensive zone of carbonation in grout material even when the carbonating in flowing solutions are placed under extremely high hydraulic gradients.

The change in diffusion rate was also reported by Sarott, *et al* (1992) who found disc shaped samples of hardened cement paste under atmospheric conditions showed a considerable decrease in diffusion rate with time due to carbonation, whereas no such effect was observed in the experiments performed in the controlled CO₂ free conditions.

A) Effect on alkalinity The hydrated products of cementitious material in concrete normally provide a highly alkaline environment. However, the alkalinity is reduced by carbonation. It follows that the corrosion protection of the steel in reinforced concrete will be diminished. This topic has been reviewed several times in cementitious studies but not relating to CBPB. In view of alkali induced wood degradation, carbonation could cause a favourable effect on CBPB, whether mechanical or physical properties, due to the decrease in the value pH.

C) Shrinkage by carbonation Carbonation shrinkage differs from drying shrinkage in that its cause is chemical, and has nothing to do with loss of water from the hardened cement paste. Carbon dioxide in combination with water (as carbonic acid), attacks the hydration products - the calcium hydroxide is dissolved and calcium carbonate crystallises out in the pores. Water is released, so that there is an increase in weight and a decrease in the volume of the hardened cement paste. The effect of atmospheric carbon dioxide on the shrinkage process has received attention only in fairly recent years. An hypothesis for the mechanism of carbonation shrinkage based on "dissolution of calcium hydroxide crystal while the crystals are under pressure" has been advanced by Powers (1962). Concurrent studies indicated, however, that less than one mole of water is released per mole of reacted CO₂, even at early stages of the reaction (Alexander and Wardlaw, 1959; Hunt and Tomes, 1962). This

suggested that other mechanisms may also be involved. It was also suggested that carbonation shrinkage is associated with dehydration and polymerisation of the hydrous silica carbonation products (Swenson and Sereda, 1968).

The tendency to absorb carbon dioxide is strongly dependent on the degree of drying of the shrinking paste (Figure 2.10) (Kamimura, *et al*, 1965). Curve A describes the shrinkage of mortars as a result of drying in CO_2 - free air (ie represents drying shrinkage only), curve B as a result of drying with subsequent carbonation, and curve C as a result of drying with simultaneous carbonation. Curves BA and CA represent additional shrinkage due to subsequent or simultaneous carbonation, respectively. Accordingly it may be concluded that carbonation involves a considerable shrinkage which depends on the moisture content of the paste and the stage at which carbonation occurs. Subsequent maximum carbonation and carbonation shrinkage occur at about 50 %RH and simultaneous shrinkage at about 25 %RH. The difference in the results was attributed to the difference in the carbonation sequence in the two series. A major part of the carbonation reactions are accompanied by release of water. As drying is a time - dependent process, the internal RH of the sample simultaneously undergoing carbonation will be higher at any given time than the ambient RH.

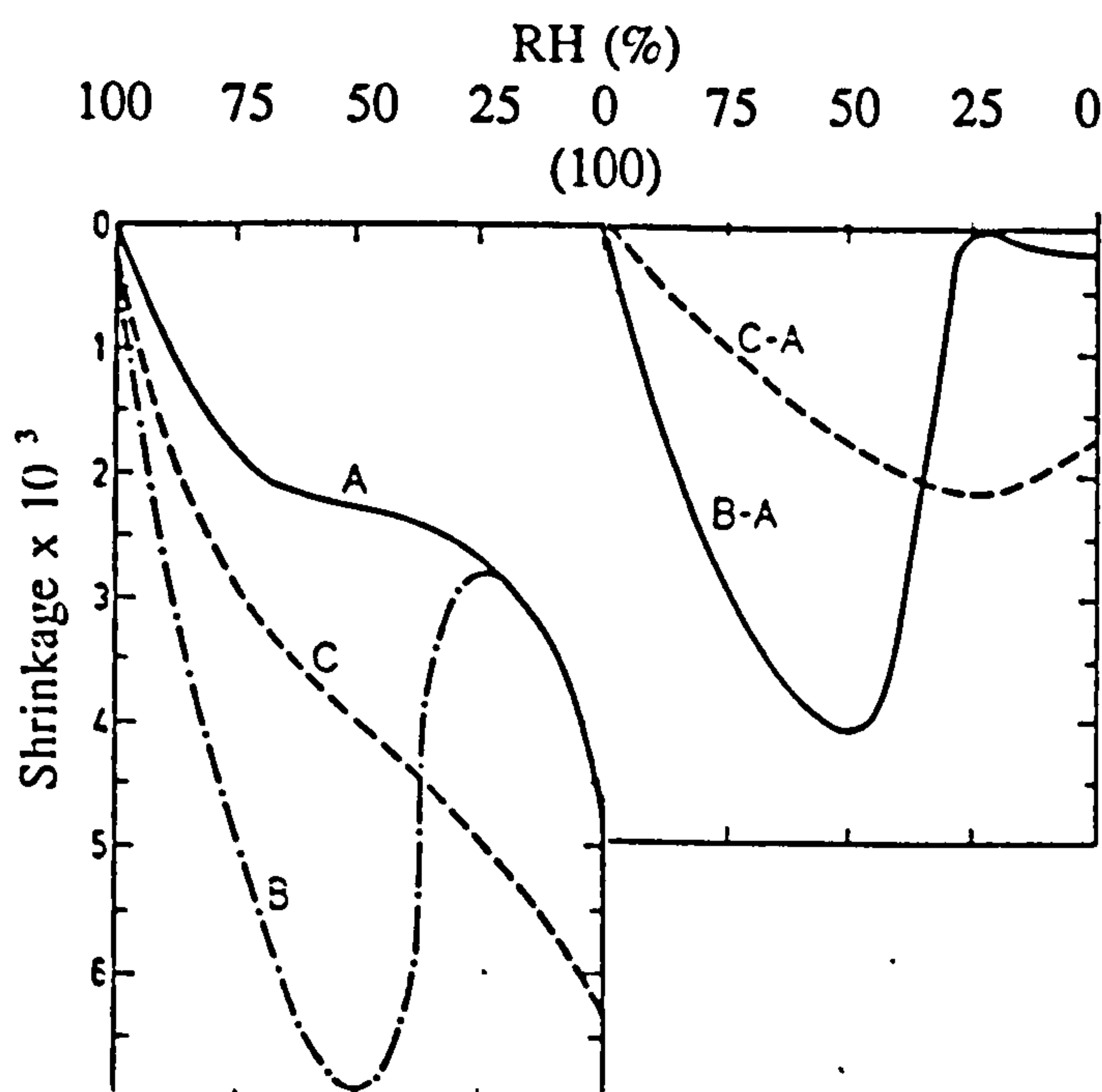
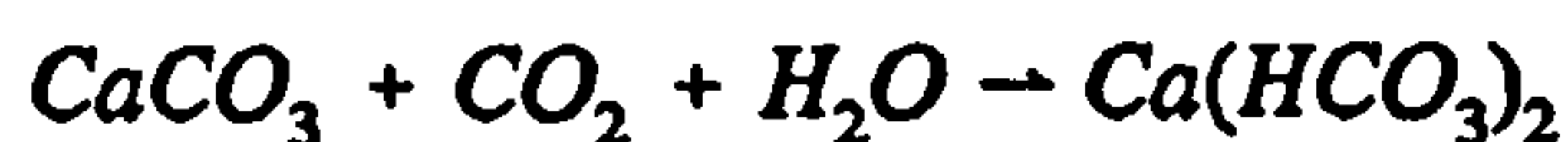


Figure 2.10 Effect of carbonation on shrinkage of cement mortar. [From Kamimura, *et al* (1965)].

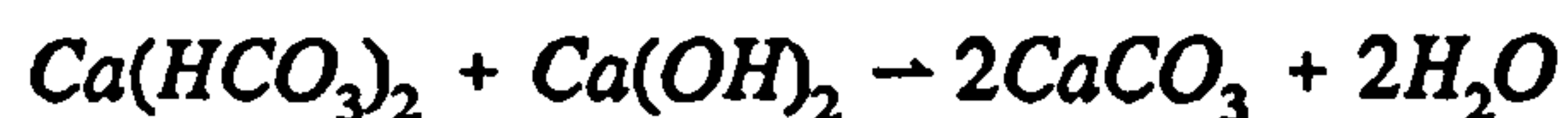
Some carbonation, but no carbonation shrinkage, occurs at 100 % and at 25 %RH. Below 25 %RH there is some disagreement. Carbonation shrinkage is a separate phenomenon from drying shrinkage and is superimposed upon the latter. It is largely irreversible, as compared with shrinkage due to loss of water. Carbonation appears to be accompanied by a decrease in the amount of non-evaporable water in the paste. However, changes produced by carbonation do not appear to affect the rate of hydration, at least at later ages.

2.6.5 Carbon Dioxide Attack as Dissolution of Cement Paste

It has been found that the CO_2 cannot only exist as "free" but also chemically combined in calcium bicarbonate which is an easily soluble bicarbonate of calcium (a double salt) (Zcernin, 1980), i.e.



If water is allowed to evaporate (e.g. when cement paste is heated), calcium carbonate will precipitate and carbon dioxide will be given off. On the other hand the calcium bicarbonate may react with calcium hydroxide to form the insoluble calcium carbonate, i.e.



2.7 Application of the Rule of Mixtures to CBPB

2.7.1 CBPB as Composite Mixture

According to the definition by Dietz (1972), who stated that a composite is a combination of materials in which the constituents retain their identities in the composite on a macro scale, that is, they do not dissolve or otherwise merge into each other completely, but act in concert, CBPB is considered as a composite mixture of materials.

With regard to strain to failure, composites divide into two systems: one is

"Brittle fibre - ductile matrix" and the other is "Ductile fibre - brittle matrix". The main types of reinforcement in composites are continuous fibres, short fibres, whiskers and particulate reinforcement. In view of the discontinuous short fibre feature of CBPB, "Ductile fibre - brittle matrix" would be the most comparable to CBPB.

2.7.2 Rule of Mixtures

The rule of mixtures states that the performance of a composite is summed by the contribution of the individual constituents of the composite weighted according to the amount of each present. The mixture theory has been applied to various areas - the inelastic behaviour of concrete (Ortiz, 1985), organic wood based panels (Hoover, *et al*, 1992; Poblete, 1992; Mundy, *et al*, 1996) and in fibre reinforced cement mortar (Pakotiprapha, *et al.*, 1974; Nathan, *et al.*, 1977), to predict the mechanical properties. It was also found to be applicable to assess wave propagation (Benveniste and Aboudi, 1976).

In the application of the rule, a certain number of assumptions are made, and mathematical models are basically derived from Hooke's Law. Three geometrical arrangement models proposed to analyze concrete behaviour are illustrated in Figure 2.11 (Domone in Illston, *et al*, 1994). The experimental results confirmed that the predictions of models are good and apply for the full range of aggregate stiffness.

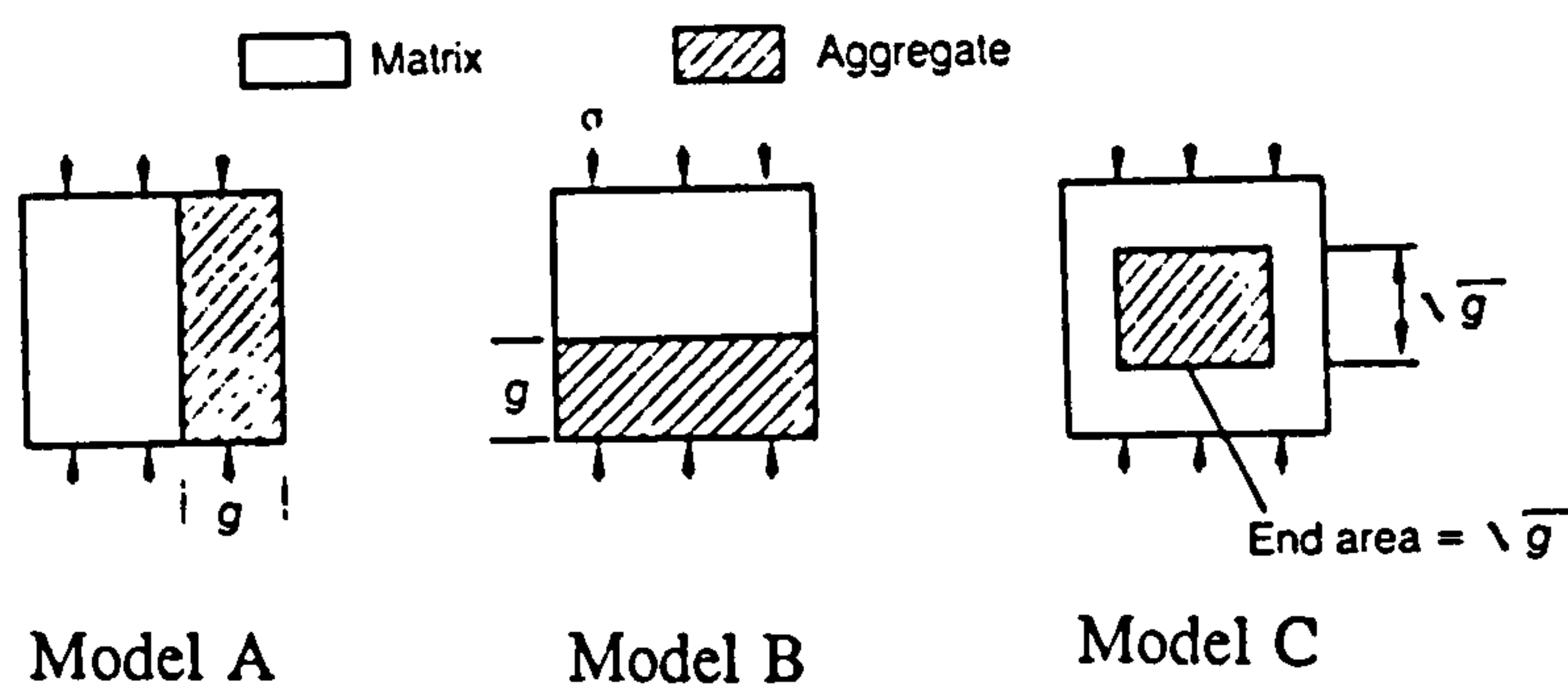


Figure 2.11 Simple two - phase models [From Domone (1994)]

In the application of these models to a short fiber composite, one of the main characteristics is that the stress in the fibre varies along the length of the fibre. The

fibre stress is zero at the fibre ends and builds up to a maximum value at the centre of the fibre as a result of shear at the fibre / matrix interface (Pakotiprapha, et al, 1974). The behaviour of this composite cannot be described, as can a long fibre composite, as having a significant effect of fibre length. A correction factor, Ψ , is introduced to account for the stress distribution at the end portion of the fibres of finite length (Broutman and Krock, 1967). In addition, the orientation of short fibres in a lamina is random. The fibre orientation distribution is taken into account by inclusion of an orientation correction factor η (Cox, 1952). The values of η (between 0 and 1) have also been calculated by Krenchel (1964) according to the fibre orientations.

2.8 Coatings

Coatings have for a long time been employed to protect against various physical agencies and also to decorate wood materials (Miller and Boxall, 1975; 1984; 1995; Roux, *et al*, 1988; Kaczmar, 1992; Rice, 1988). Generally speaking, products can be classified as 1) water borne coatings, which include water soluble system and emulsion systems (Worringham, 1996), and 2) solvent borne coatings.

Water borne coatings have several advantages, the chief of which being cheapness and availability. They also penetrate the wood well and reduce fire, explosion and health hazards. However the wood swells upon treatment, and the coating is of less protection against weathering.

The opposite to this is the solvent borne coating. This coating has a long history of traditional use and provides good durability. Unfortunately it is suffering from toxicological concerns at present and the threat of impending legislation on the emission of volatile organic compounds (Kelsey, *et al*, 1991; Miller and Boxal, 1992).

Since the real and imagined concept of concrete as an everlasting material was recently shattered, attention has been paid to the protection of concrete surfaces, especially for the prevention of the carbonation of concrete (Stanfield, 1996; Davies and Rothwell, 1989; Swamy and Tanikawa, 1993). Correspondingly the need for diversification in the paint industry has led to the production of finishes for a wide

range of substrates.

However, compared with wood, concrete surfaces have a restricted list of candidate coating materials. Chemical and physical characteristics preclude the use of certain coatings. Some primary coating properties that affect their compatibility with concrete surfaces include (Greenfield, 1994): 1) tolerance to alkalinity, 2) moisture sensitivity, 3) cure shrinkage, 4) elasticity, 5) viscosity, 6) permeability.

In addition, to meet the requirements above the functions of coatings should include chemical or mechanical bonding effects, such as the mechanical bonding, electro - static bonding and hydrogen bonding, to achieve the following functions: 1) to restore structural integrity, strength and aesthetics, 2) to provide long term protection against decay mechanisms *viz*: carbonation, chloride attack, acid gas attack, water penetration, alkali silica reaction, weather erosion and chemical and physical abuse (Stanfield, 1996).

2.9 The Relationship between the Properties of CBPB and the Parameters of Production

The properties of CBPB vary according to their constituents and methods of manufacture. An increase in the cement proportion in CBPB has been reported to reduce the thickness swelling and water absorption of boards after 24 hours water soaking (Hann, *et al*, 1963; Lehman, 1970; Moslemi and Pfister, 1987; Oyagade, 1988; Fuwape, 1992). Since there exists a considerable variation in manufacturing techniques and raw materials, only a few of the most important factors will be discussed below.

2.9.1 Density Profile across Thickness

The densities reported in reports are usually the average resultant board densities. The density of wood based panels arises by two main factors, that is, the raw material density and the compactness of the mat in the hot press (Kelly, 1977). The density gradient in particleboard, fibreboard and hardboard arising in the smooth or screen faces, is thoroughly documented (Suchsland, 1962; Winistorfer, *et al*, 1986).

The density of successive layers in the board can be controlled and it is normal for boards to have high face densities and low core densities with a few exceptions, probably most notably in very thin boards where the reverse type of density profile can be found. Actually this technique is used to control the density gradient of materials for various purposes of products. A positive relationship exists between the movement of wood based panels and their densities due to higher constituent content in unit volume.

2.9.2 Dimensions and Orientations of Particles

The board performance is to some degree controlled by particle geometry. This includes the mechanical properties, board surface characteristics, behaviour in machining operations and moisture responses such as moisture absorption and corresponding changes in dimensions, mechanical properties and surface characteristics (Maloney, 1977). Therefore an ideal ratio of length of chip to its width (diameter) is required for different types of panel products.

Particle orientation plays an important role in the properties of the material. Most particleboards have their fibres oriented randomly in the plane of the board, producing better properties in this plane. Particleboards with increased bending strength and stiffness in one direction are obtained by orienting the particles within the board, such as OSB. However this practice would sacrifice strength in the transverse direction (Lehmann, 1974). Dimensional stability of the board is directly related to the orientation and distribution of particles by virtue of the anisotropic characteristic of wood chips.

2.9.3 Wood Extractives

Extractives are the non - structural constituents of wood, generally comprising of a heterogeneous group of aliphatic and aromatic compounds which include sugars, starches, fats, oils, resins, waxes, gums, pectin, tannin, dye stuffs, organic acids, very small amounts of amino acids and proteins (Wangaard and Granados, 1967) and a small quantity of inorganic salts (Browning, 1968). Extractives occur in the cytoplasm

within the cell lumens of living parenchyma [where it is generally considered they are formed (Hillis, 1971)], intercellular spaces in the lumen cell walls of empty dead cells (vessels tracheids, fibres and rays) and to a varying extent within the cell wall (Bosshard, 1968; Choong 1969), deposited in the microcapillaries present (Hillis, 1971).

Extractives are known to have an enormous effect on the properties of wood, such as on the permeability and the bulking effect on wood shrinkage within the cell wall (Bosshard, 1968), etc. In CBPB, all hydration characteristics are substantially affected by sugar, tannin, hemicellulose as well (Moslemi 1983, Biblis, 1968, Fan, 1989 and 1992), with tannin and hemicellulose having the greatest effects (Miller and Moslemi, 1991).

Chapter 3

METHODOLOGY

3.1 Environmental Chambers

Three scales of chamber were prepared for the experiments. One group were large scale chambers existing at the Building Research Establishment, Watford, U.K. The second group were small scale chambers and the third were medium size chambers. Both of these were constructed by the author.

3.1.1 Control of the RH and Temperature in the Large Chambers

Three large chambers were used, each of dimensions 6000 x 3000 x 3000 mm, the first conditioning at 20 °C / 35 %RH, the second at 20 °C / 65 %RH and the third at 20 °C / 90 %RH.

The environmental conditions in each chamber were principally controlled by an air - conditioning unit (Tempbath Ltd.) which contains a heating and cooling system, a steam producing and condensing systems and a series of sensors. To supplement and fine tune the RH, an atomizer (Defensor Ltd.) was built in the chamber with conditions 20 °C / 90 %RH, and a room humidistat (Munter Ltd.) was employed in the chamber with 20 °C / 35 %RH.

3.1.2 Small Scale Environmental Test Chambers

In order to control the environmental conditions in which tests on the small size of chip samples [about 0.35 x (1-3.35) x 35 mm] could be carried out, a special test chamber was built, a diagram of which is presented in Figure 3.1.

For small size of chips, an important criterium when developing the system, which greatly influenced the results, was the positioning of the chips, and the starting and ending measuring points: the samples must be kept in one position and

measuring points can be ensured over the whole period of exposure. Therefore, the chemical solutions, which were changed (moved in or out of the chambers) to produce the desired RH, were held in a separate RH producing chamber, which was connected to the chip chamber. The air of the required RH could be circled between the two chambers through a pump. Another advantage of including the RH producing chamber is to shorten the duration of RH recovery on changing it from one level to another.

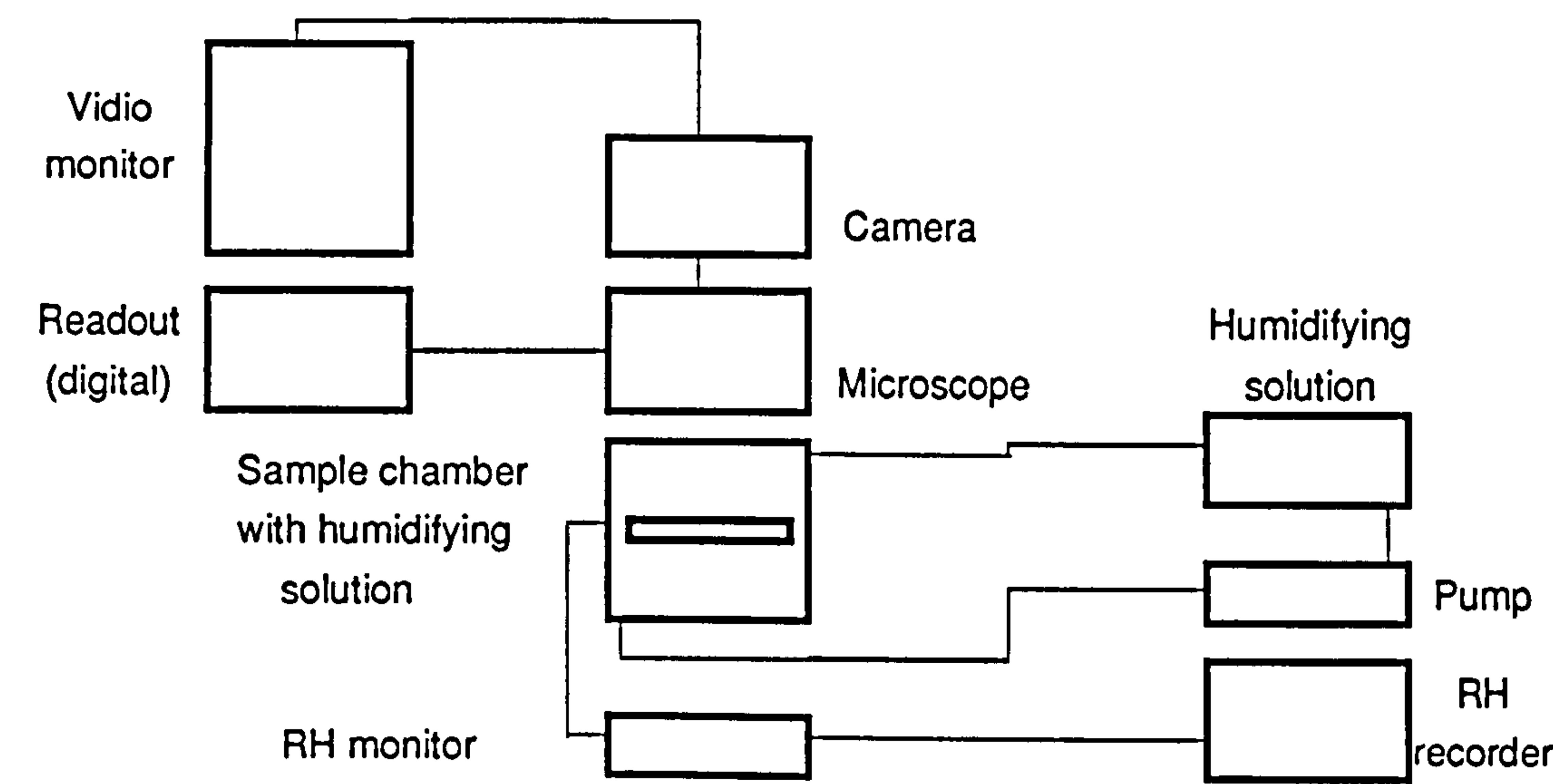


Figure 3.1 Diagram of apparatus used to exposure wood chips to required RH environments and to measure their dimensional change

The RH of the air within the environmental testing chamber was kept at its required setting by (de)humidifying salts. The salts selected for the cyclic RHs are included in Table 3.1. The values in brackets are the actual RHs.

Table 3.1 The saturated salt solution used in the experiments (20 °C)

Saturated salt solution	RH
Magnesium chloride	35% (33%)
Sodium nitrite	65% (65 %)
Potassium acetate	90% (93%)

To enable the chips to be measured from the same angle and at the same points in each measurement, the sample was placed and pin - point - glued on the slide which was fixed on the flat bottom surface of the chamber.

The RHs for various levels were supplied from the producing chambers. When the RH (the chemical solutions) needed to be changed from one condition to another, the cycling of the RH air was stopped, the connection between two chambers was cut and the chip's chamber was sealed to maintain the previous RH condition until the new required environmental condition was achieved in the producing chamber (about 2 hours), when the system was re - started.

From commissioning tests, it was found that the RH within the chip's chamber could be kept constant at the required values (i.e. 35 %, 65 % and 90 %RH). The consistency of the RH from the bottom of one side of chamber to the top of opposite side of chamber was guaranteed. In case of "corner effect", the sample was placed in the middle of the chamber.

After a change in RH during cyclic exposure, the new RH level around the sample had reached about 80 % of the required value after 1 hour, 90 % after 2 hours and 100 % after 4 hours.

3.1.3 Testing Equipment in the Small Chambers

The testing equipment consisted of two main parts. One part is for chip measurement, including trace, transfer and measurement, the corresponding instruments being a travelling microscope, TV monitor and digital recorder. The main instruments are briefly described as follows:

A) *Single axis measuring microscope* This instrument consists of a carriage which travels in one axis over a distance of 250 mm, a microscope tube controlled by a rack and pinion focus mechanism and CCTV camera with graticule adaptor inserted into the tube (Figure 3.2).

B) *Video monitor (VM 906)* A Hitachi VM-906 (solid state 9 inch video monitor) is connected to display the video signal from the camera. Outstanding performance

and reliability could be achieved by this monitor due to including an IC and silicon transistors (Figure 3.2).

C) Readout system This readout system, the Quick - Chek, QC - 1000, is a digital measuring device that displays measurements corresponding to the movement of viewing head (Objective) transferred through CCTV (Figure 3.2).

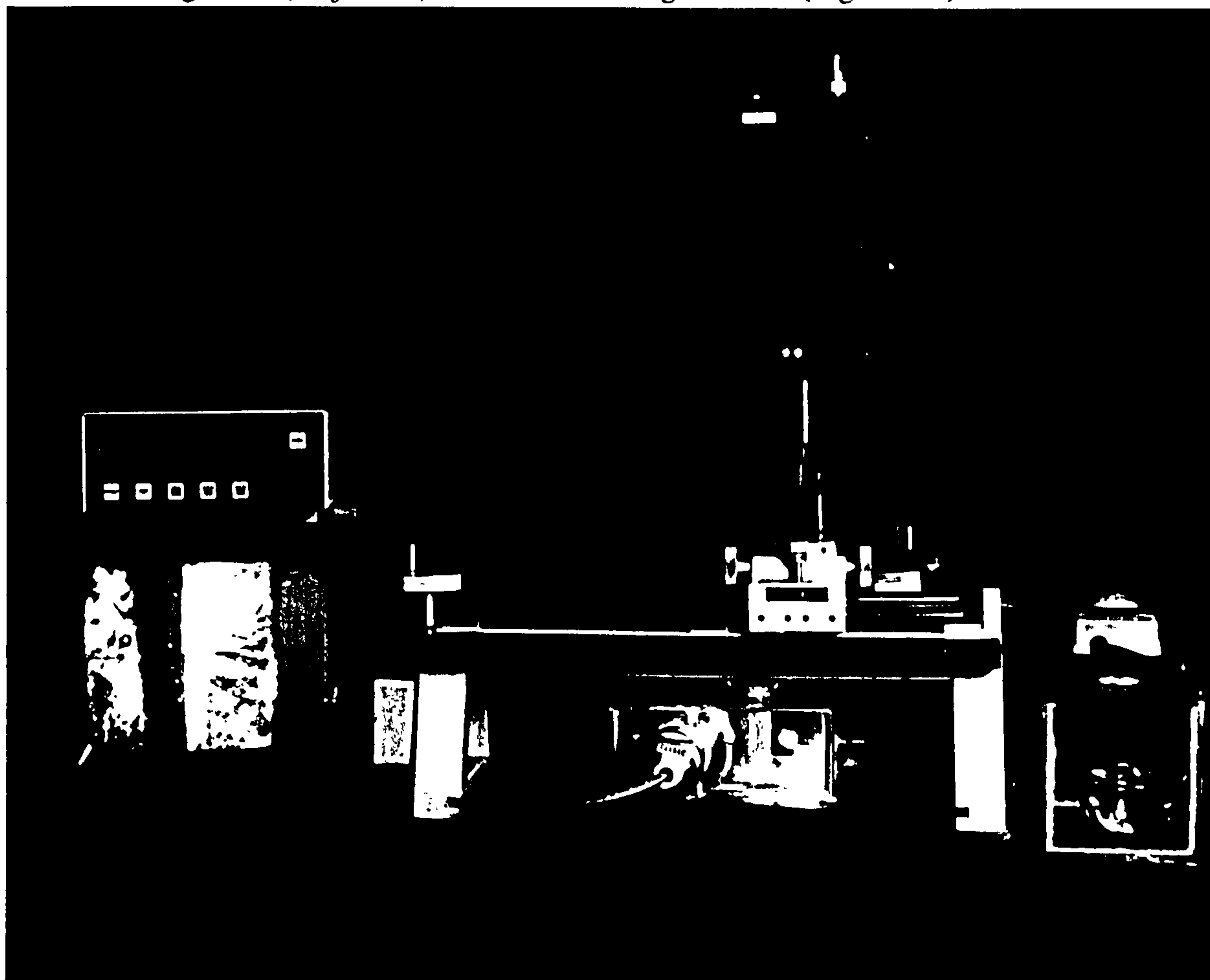


Figure 3.2 A photograph of the travelling microscope used in measuring the dimensional change of wood chips

3.2 CBPB Boards and Testing Methodology

3.2.1 Sampling of CBPB

Conventional methods of evaluating the physical and mechanical properties of a commercial CBPB necessitate the use of a certain size of samples, which must

inevitably represent only local features. Consequently the resulting data sometimes is not representative of the whole. Therefore, large size of samples was employed to assess the behaviour of CBPB.

Two groups of CBPB were selected for evaluation of the behaviour of CBPB and the application of sealers. One was 12 mm CBPB, which was chosen for the study of cyclic RH exposure. The material used for this study came from France (Viroc) and had been stored at BRE for about one year. Samples were divided into two groups, one was used as uncoated to evaluate the behaviour of CBPB, and the other was coated with different sealers in order to evaluate the applicability of coatings to stabilize the dimensions. More details of the coatings will be included in a following separate section. Another group was 18 mm CBPB which came from Cape Boards Ltd. The history of the samples was traced from manufacture.

3.2.1.1 Raw Materials

The CBPB used was made of ordinary Portland cement (OPC) and softwood chips. Specific details for 18 mm boards are included as Appendix I.

3.2.1.2 Machining of Samples

According to a previous investigation conducted at BRE (Dinwoodie and Paxton, 1980), no difference could be found in movement between the length and width directions of CBPB (Figure 3.3). Therefore no specific attention was paid to the sample orientation although all samples were cut with the edges of the samples parallel to those of the whole sheet of CBPB (Figure 3.4). The samples were visually inspected and those with distortions (bend) were discarded. In addition to the large size of samples, smaller samples were also selected for some experiments.

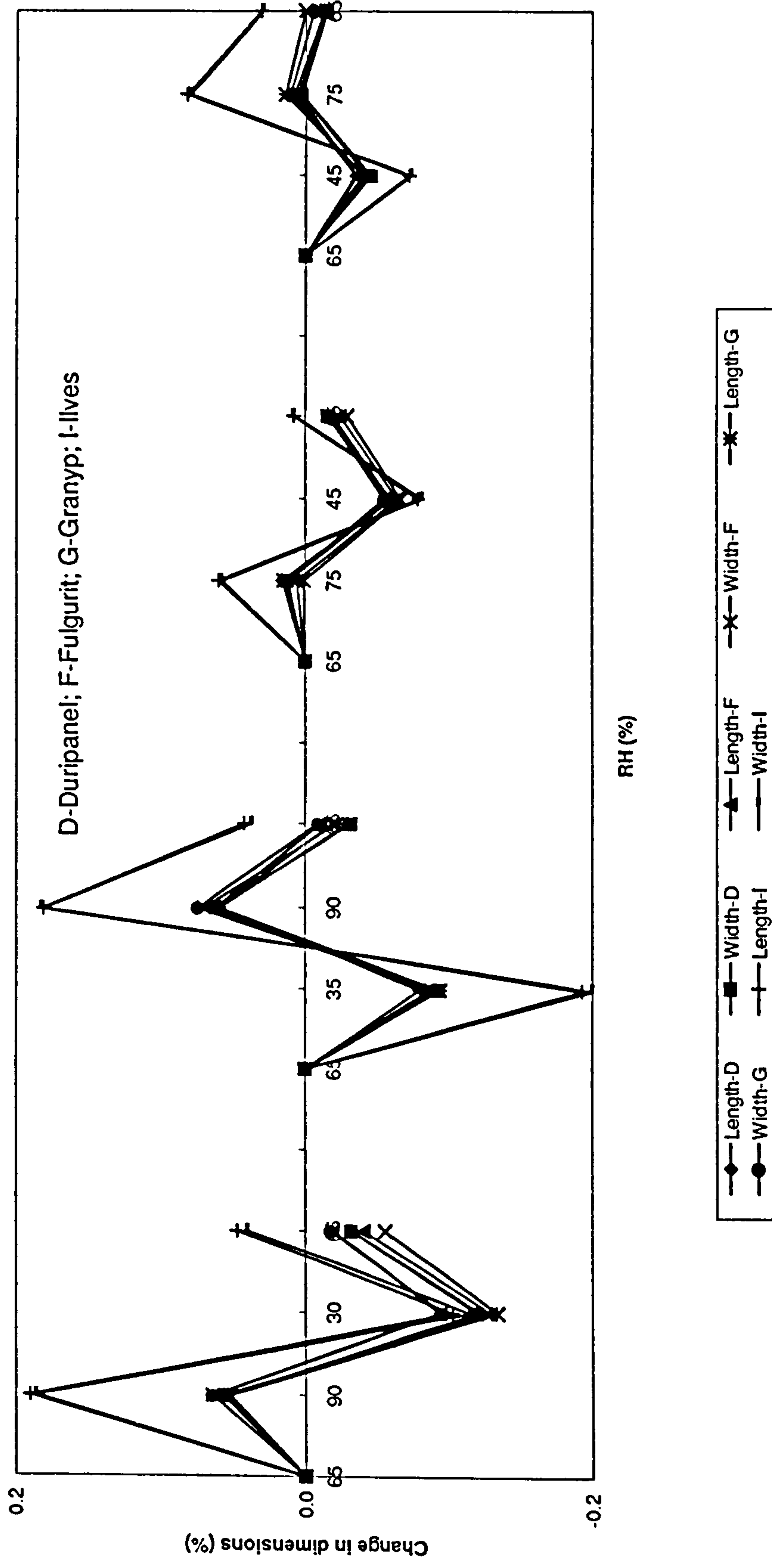
The dimensions of CBPB samples used were:

100 × 100 × 12 mm

600 × 600 × 12 mm

600 × 300 × 18 mm

Finally the edges of each sample were sanded to ensure an unique surface when



measuring.

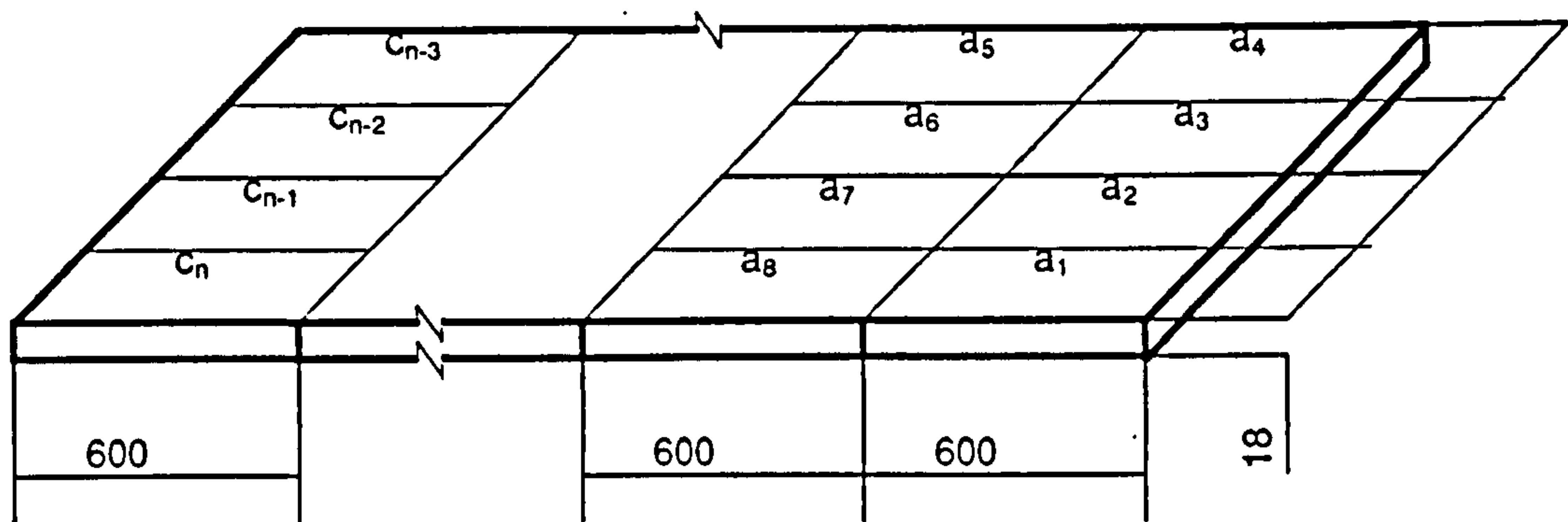


Figure 3.4 Matching and allocation procedure of 600 x 300 (600) x 18 (12) mm

3.2.2 Allocation of Samples of CBPB to Different Experiments

Both 12 mm and 18 mm panel samples were carefully selected and arranged for the following experiments: constant RH, a single change in RH, cyclic RH, free-CO₂, liquid water soaking, water vapour diffusion, oven drying, RH level change, sealer application test, and different pretreatment tests. The numbers were allocated as in Table 3.2.

Because of the need for replication and the variability in the properties between the samples, neither of the following two conventional methods of selecting sample replicates and comparative controls were considered suitable:

- 1) cutting consecutively the total numbers of CBPB required and thereafter subdividing them randomly into several sets including one set denoted as controls;
- or
- 2) cutting consecutively the required numbers of CBPB sample replicates one by one and then a group of control CBPB,

A reliable method of sample allocation was essential to enable:

- 1) an estimation of the raw material properties (CBPB samples) to be assessed for each replicate which would be exposed to various conditions;

Table 3.2 The allocation of samples of CBPB

Experiment	Sample size (mm)	Sample number	Number of cycles
Pre - study	100 x 100 x 12	3	1
Constant RH	600 x 300 x 18	3	
Single change in RH	600 x 300 x 18	12	
Cyclic RH	600 x 300 x 18	3	6+
As above	600 x 600 x 12	3	10+
CO ₂ - free	600 x 300 x 18	9	
Liquid water cyclic	600 x 300 x 18	3	3
Long-term liquid water soaking	600 x 300 x 18	3	
Oven-drying cyclic	600 x 300 x 18	3	3
Limited range of RH	600 x 300 x 18	6	3
Different storage prior to test	600 x 300 x 18	15	3
Different pretreatment	600 x 300 x 18	9	3
Sealer application	100 x 100 x 12	27	1
As above	600 x 600 x 12	18	3
As above	600 x 600 x 18	18	3
SEM, image analysis	600 x 300 x 18		
Density profile	600 x 300 x 18		
Chip isolation	600 x 300 x 18		

2) a comparison between replicates to be taken such that a mean effect of dimensional and mass change for each of the various exposure conditions could be

evaluated;

3) a relationship between the severity of treatment and resultant effects on CBPB to be assessed, thereby enabling interpretation of the mechanisms for the whole products.

Consequently a special method of sample selection for each of the various tests undertaken was adopted, as Figure 3.4. That is, CBPB samples of dimensions $600 \times 300 \times 18$ mm, were cut consecutively from pre - selected CBPB sheets, and labelled to indicate positions $a_1, a_2, a_3, \dots, b_1, b_2, b_3, \dots, c_1, c_2, c_3, \dots$. Samples a_1, b_1 and c_1 were allocated as controls, samples a_2, b_2 and c_2 were allocated for constant RH exposure, and so on.

This allocation procedure allows the results of each exposure condition to be compared to those of the two adjacent samples, that is, samples a_2, b_2 and c_2 could be compared to immediately preceding and following samples a_1 and a_3, b_1 and b_3, c_1 and c_3 respectively, and so on throughout. The results between replicates or between the various exposure conditions could be evaluated. Hence, this effectively eliminates variability caused by the raw materials.

3.2.3 Storage of Board Samples

Between the preparation of CBPB samples and subsequent exposure to the required condition, it was known that there would be, to a varying extent, a lapse of time, especially for experiments on the different storage periods prior to the cyclic RH exposure. Therefore, to ensure that all sets of samples, including controls, were in an equivalent physical condition when exposed to the various environmental conditions, all samples were moved immediately after cutting to a constant environmental chamber at $20^\circ\text{C} / 65\% \text{RH}$.

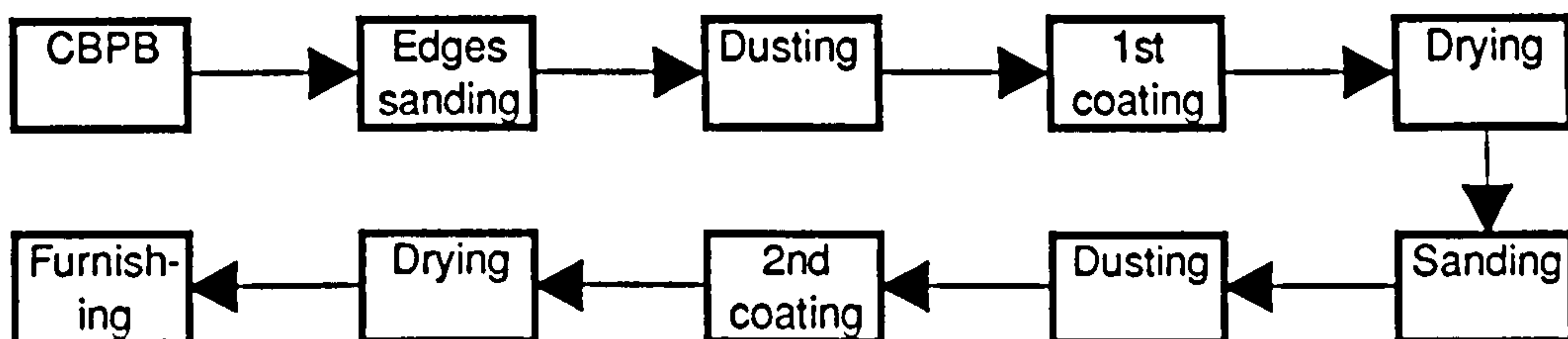
Additionally, in common with other cementitious materials under constant RH, hydrated cement paste may undergo consistent change. This change is related to the conditions of the surrounding environment. Therefore, to ensure that each remained equivalent during storage, all samples were carefully stacked, with each contacting the same CO_2 concentration and air circulation condition.

3.2.4 Treatment of the Edges of Samples

As noted earlier the permeability in the three principle axes of wood is considerably different: longitudinal permeability is about 10^4 times the transverse permeability (Dinwoodie 1987). The cement paste is isotropic. To understand the dimensional and mass changes of CBPB, the contribution of the edge effect must be evaluated. An investigation was carried out to evaluate this (chapter 17).

It will be seen from chapter 17 that unlike for wood, no difference was observed between the results produced for sealed and unsealed samples. Therefore the remaining investigations were only undertaken with the materials sealed on the edges to ensure an unidirectional flow during exposure and the uniformity of flow covering the whole area of the samples.

All the edges of samples were coated with two coats of epoxy resin. The procedure of sealing edges of CBPB is



A commercial epoxy resin was used, composed of an epoxy base and catalyst hardener. Before coating, the catalyst was mixed with epoxy (base : hardener = 4 : 1). The mixture was applied to the edges using a brush by hand. After applying the first coat, samples were dried for 24 hours, and then a second coat applied.

To eliminate moisture change during this procedure, and hence to shorten the subsequent reconditioning period, coating and film drying were carried out at 20 °C / 65 %RH which was the same as the preconditioning environments.

The sealed samples were moved back to original conditioning chamber.

3.2.5 Measuring Points on Samples

Points and lines were marked and numbered to facilitate the measurement of

subsequent changes of thickness and length in response to moisture. Details are given in Figure 3.5.

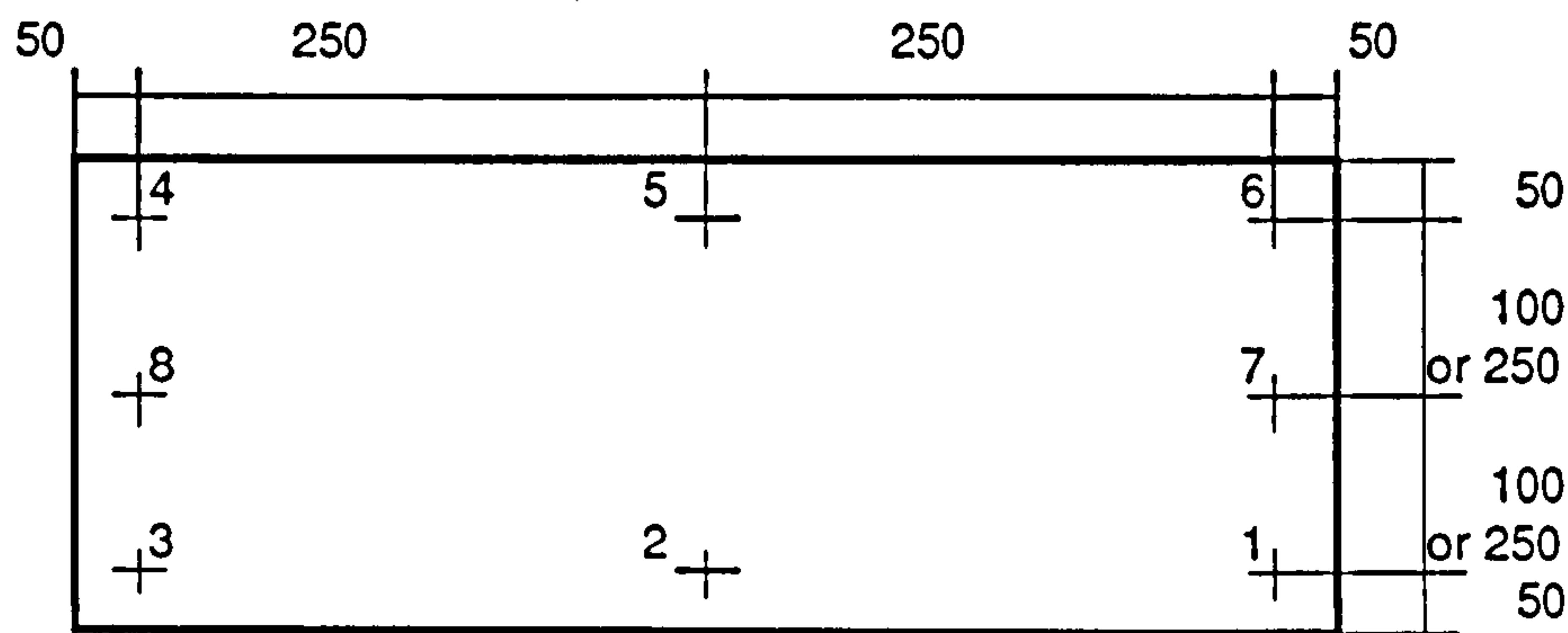


Figure 3.5 Measuring points and lines on test CBPB (600 x 300 x 18 mm) for determination of thickness and length change

For 600 x 600 x 12 mm panels, points 1 to 8 were for the thickness measurements and lines of the 1 - 6, 2 - 5, 3 - 4, 1 - 3, 4 - 6 and 7 - 8 for length measurements; for 600 x 300 x 18 mm panels, points 1 to 6 were for thickness measurements and lines of the 1 - 3, 4 - 6 and 7 - 8 for length measurements.

3.2.6 Pretreatment of CBPB

Three types of pretreatment were carried out in this investigation: different storage periods, a drying treatment and coating.

A) *Storage of CBPB* Four sets of CBPB were stored at 20 °C / 65 %RH after the edges were sealed. After two months, the first set was subjected to cyclic RHs. Two months later, the second set was started, and then after 2 further 4 month periods, the third and fourth sets were exposed to the same cyclic programme. Mass and dimensions were monitored immediately after cyclic exposure.

B) *Drying Pretreatment* Three groups of samples were prepared for this programme. One was stored at 20 °C / 65 %RH before testing, another was pre -

stored at 20 °C / 35 %RH and the third underwent an oven drying pretreatment. Three groups of samples were treated at the same time and stored for the same duration prior to the cyclic RH exposure.

C) Coating Pretreatment A number of samples were coated with different sealers to detect the applicability and efficacy of coatings to CBPB. The details will be described in a later section.

3.2.7 Exposure of Samples

To obtain a better understanding of the instability of CBPB, a series of experiments were carried out in addition to the different pretreatments given above. Several exposure procedures were employed to affect the CBPB to enable the mechanisms of dimensional and mass changes to be interpreted from various aspects. The summary of the procedures and objectives are given in Table 3.3.

A) Constant RH The treatment of these samples was unusual in terms of the wood chips remaining constant under constant environmental conditions. However, the most significant carbonation of cement paste was found to occur under this condition. The treatment of these samples was effected by simply exposing to 20 °C / 65 %RH for a long time. Mass and dimensions were measured once per month.

B) Single change of RH An exposure program consisting of exposure to a single change of RH, to which four sets of samples were subjected, was achieved by initially conditioning samples at 35, 90 or 65 %RH (two sets), and then transferring the first set to 90 %RH, the second set to 35 %RH and the third and fourth to 90 %RH and 35 %RH respectively.

The temperature and RH of the chamber were firstly calibrated and monitored continuously. The behaviour of the samples was traced throughout the whole testing period of about 600 days.

C) Cycling of RHs This program was devised to simulate extreme environments

over one year, as follows:

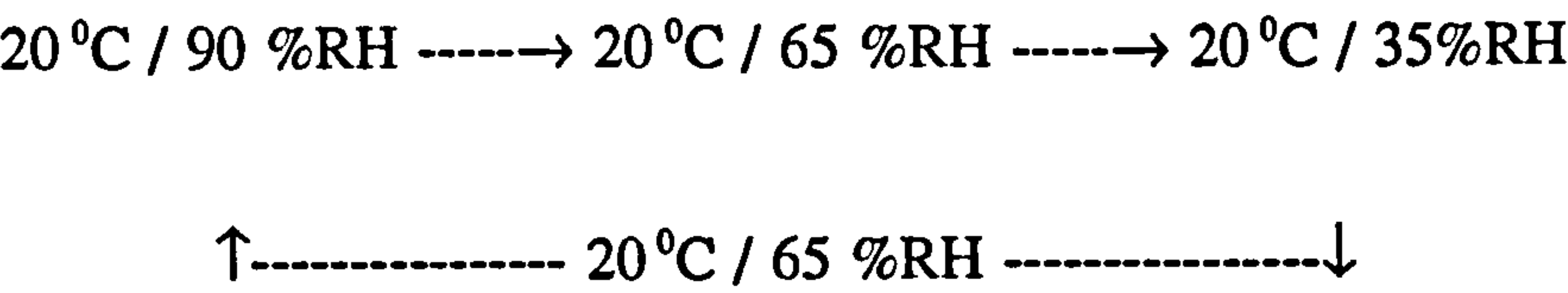


Table 3.3 Summary of various exposures and objectives

Exposure	Condition	Objective
Constant RH (long - term)	20 °C / 65 %RH	Evaluate carbonation of cement paste and deterioration of wood chips
Single change in RH (long - term)	20 °C / 65 %RH; 20 °C / 90 %RH; 20 °C / 35 %RH	Examine the applicability of moisture diffusion; develop mathematical models for sorption and dimensional changes
Cyclic RHs	20 °C / 35 %RH - 20 °C / 65 %RH - 20 °C / 90 %RH	Evaluate the behaviour of CBPB under serviceable environments
Limited range of RHs	20 °C / 35 %RH - 20 °C / 90 %RH ; 20 °C / 35 %RH - 20 °C / 65 %RH - 20 °C / 90 %RH	Examine the reaction of the material to moisture; change in structure / path of flow
Cyclic immersion	20 °C / 65 %RH - water soaking	Examine permeability and dimensional change under liquid water; interpret sorption
Cyclic oven drying	20 °C / 65 %RH - oven drying	Detect change in structure / path of flow; interpret mechanism of sorption
Long-term liquid water soaking	20 °C / water soaking	Evaluate the permeability; interpret mechanism of sorption.

The samples were moved from one condition to another after constant values of mass or dimensions were achieved at the preceding condition.

D) *Limited range of RHs* The treatment of these samples was effected by exposure to environments of between 35 and 90 %RH. The controls were subjected to the normal cyclic RHs. The duration for half a cycle was the same for both sets of samples to ease the evaluation.

E) *Cyclic immersion* These samples were exposed to water. The distance between individual specimens in the water bath was about 25 mm all round. Extra water was added to the bath to maintain the water level. The bath was placed in the chamber having conditions of 20 °C / 65 %RH.

F) *Cyclic oven - drying* A set of samples was placed in an oven at 105 ± 5 °C as part of the cyclic programme between 65 %RH and oven drying. The samples were kept in each stage until constant conditions were achieved. The mass and dimensions were monitored throughout the exposure.

G) *Long term water soaking* The water permeability of CBPB was studied by a long term water soaking program, to which one set of samples were subjected. The water bath was set in the chamber having conditions of 20 °C / 65 %RH. The intervals between measurements were 1, 3, 4, 30 or 60 days, depending on the different stages of exposure.

3.2.8 Measurements Taken on Board Samples

3.2.8.1 General Measurements before Exposure

It is known that the dimensional change of CBPB is rather slight (BS EN 634), and small deviation in the basis dimensions could make a significant effect to the final analysis. To avoid this, measurements were repeated three times, and the mean values taken into the data processing. That is,

$$M_0 = \frac{(M_0^1 + M_0^2 + M_0^3)}{3} \quad 3.1$$

$$L_0 = \frac{(L_{013}^1 + L_{013}^2 + L_{013}^3 + L_{046}^1 + L_{046}^2 + L_{046}^3 + L_{078}^1 + L_{078}^2 + L_{078}^3)}{9} \quad 3.2$$

$$T_0 = \frac{(T_{01}^1 + T_{01}^2 + T_{01}^3 + T_{02}^1 + \dots + T_{06}^3)}{18} \quad 3.3$$

Where M_0 , L_0 and T_0 are the mean nominal values of mass, length and thickness respectively; M, L and T denote mass, length and thickness; subscripts "0" mean initial measurement and subscripts after "0" represent the measuring positions; superscripts "1", "2" and "3" mean the numbers of repeating measurements.

3.2.8.2 Measurements of Dimensional and Mass Change

To ensure accurate results, the measurements of thickness were taken following European Standards EN 324 - 1 (1993); while measurements of the length (width) were carried out using special equipment (Figure 3.6) constructed with regard to the large size of samples involved.

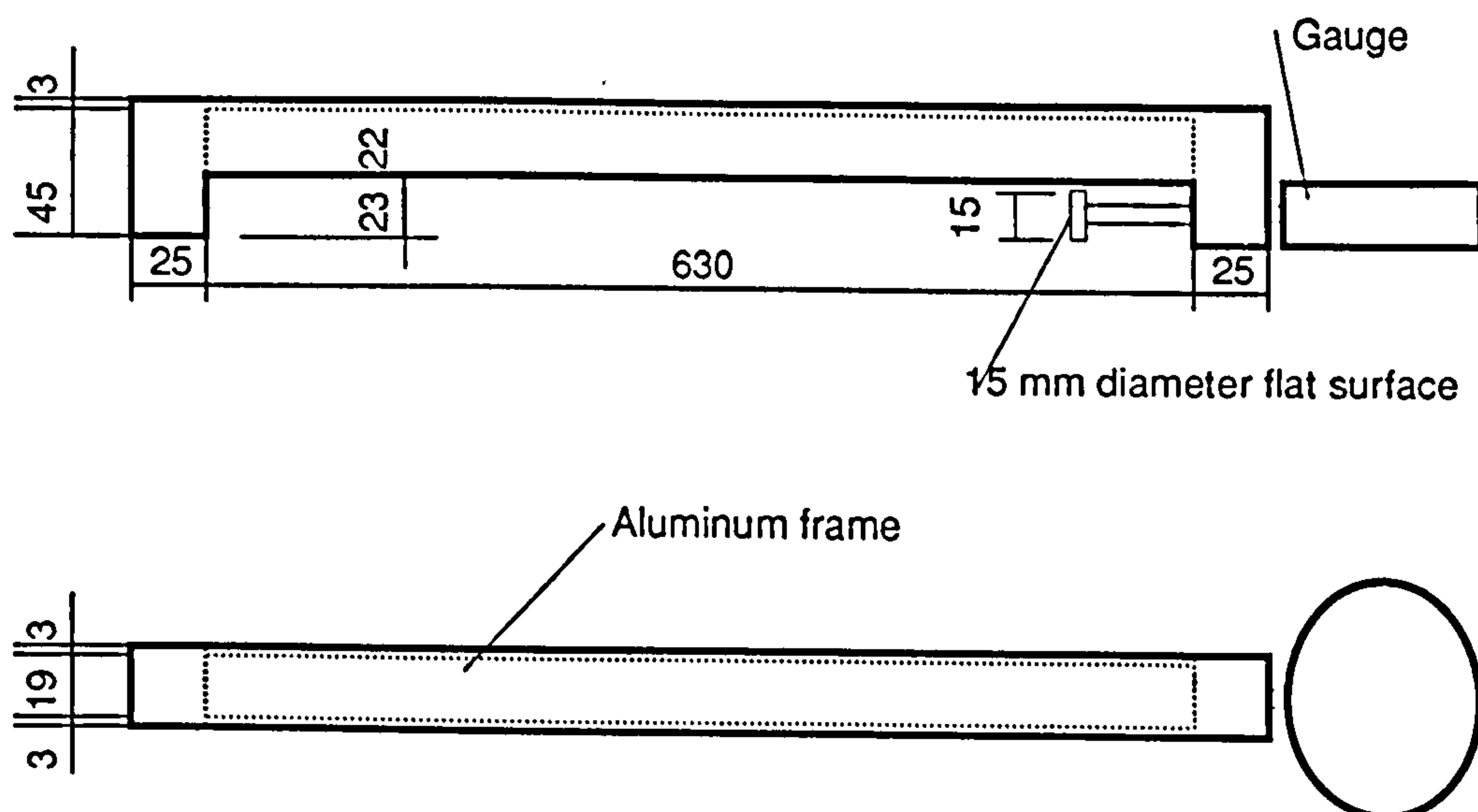


Figure 3.6 Jig for use in the measurement of change in length (width)

The changing values in mass, length and thickness were converted into percentage changes of mass and dimensions with respect to the original values:

For length,

$$\Delta L (\%) = \left(\frac{L_n - L_0}{L_0} \right) 100 (\%) \quad 3.4$$

For thickness,

$$\Delta T (\%) = \left(\frac{T_n - T_0}{T_0} \right) 100 (\%) \quad 3.5$$

For mass,

$$\Delta M (\%) = \left(\frac{M_n - M_0}{M_0} \right) 100 (\%) \quad 3.6$$

where

$$L_n = \frac{L_{13} + L_{46} + L_{78}}{3} \quad ; \quad T_n = \frac{T_1 + T_2 + \dots + T_6}{6} ;$$

M_0 , L_0 and T_0 are from equations 3.1; 3.2 and 3.3.

Percentage change data for each specimen was plotted against time. The deviation in a group was assessed, and finally the mean percentage change of the replicates against time was used.

3.3 Preparation and Testing of Chips

3.3.1 Sampling of Chips

3.3.1.1 Introduction

If a CBPB was obtained from a commercial supplier, absolute control over the types of chips and its associated properties was not possible. Indeed, often the specific furnish data was not freely available (such as the properties and type of additives used). Because of these unacceptable circumstances, a CBPB was requested from the

manufacturer with the procedure of processing this board being recorded.

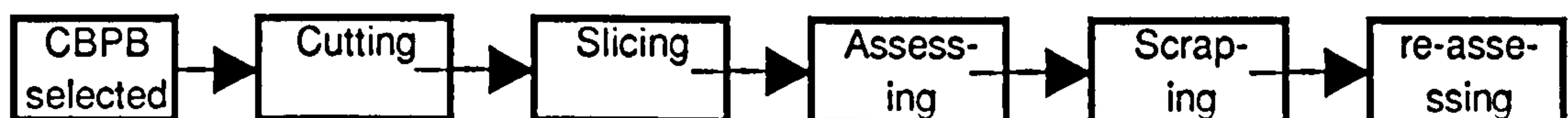
The experiments on chips were carried out for the evaluation of:

- 1) the contribution of wood chips to the dimensional and mass changes of CBPB;
- 2) the effect of the processing parameters on the properties of CBPB.

The former evaluation was satisfied by the results from the experiments on the chips isolated from the CBPB, while the different types of chips collected from various stages of production (namely unconditioned chips, chips from edges of the board after first "boosting", furnished chips and raw wood chips) produced results representing the properties of wood chips within CBPB after being processed.

3.3.1.2 Procedure of Sampling of Chips

A) *Chips isolated from final products or unconditioned CBPB* The procedure of sampling these two types of chips is the same and can be described as:



Boards of $600 \times 300 \times 18$ mm CBPB were prepared and cut to smaller sample sizes of $50 \times 50 \times 18$ mm. This dimension was chosen so that the full variation of possible sizes of chips could be obtained.

After slicing the small square of CBPB to yield 2 to 3 mm thicknesses, the surfaces of the slices were assessed, those chips with the surfaces undamaged were scraped and those damaged were scrapped. Three important criteria were considered when selecting chips:

- 1) the whole chip must not be damaged, in order to represent the true nature of chips within the CBPB;
- 2) the chips chosen must not be limited in size to enable a truly random distribution within the whole group of test samples to be obtained;
- 3) the shapes of chips isolated should not be specific.

A re-assessment was carried out after isolation. Damaged chips were discarded

and undamaged ones were gently dusted (cement paste) with gas. A final assessment was required before proceeding with the experiment.

B) *Chips from the edges of board* The procedure for obtaining this type of chips was much simpler. When panels were coming out from the first curing oven (70-80 °C), chips were taken from the edges of panels. Final assessment was also required to ensure whole undamaged chips were tested. Other considerations taken were as above.

C) *Furnished chips* No special procedure was required for these chips but treatment afterwards was needed. After removing from the forming tank, the chips were wet, and consequently the moisture content had to be measured. Then chips were placed in the 20 °C / 65 %RH conditioning room before testing.

D) *Raw wood chips* The chips of this type were prepared at the same time as the control samples.

There are a number of foreseeable limitations though all the chips were carefully isolated and selected:

1) variation in the chips with respect to heartwood, sapwood, earlywood, latewood and the grain orientation of chips. These would respond differently to the moisture effect;

2) no guarantee of the uniformity of the structure of the chips resulting from processing;

3) chips inside the CBPB might be under stress restraint. As soon as they were taken out of the cement paste, stresses may partially be released.

3.3.2 Types of Chips

Different types of chips produced from various stages of procedure are presented in Table 3.4.

Table 3.4 The types of chips used

Type	Name	Stage	Source
1	Raw wood chip	After flaking	Collected from storage tank
2	Furnished chip	After mixing	Collected from mixing tank
3	Chip from edges of board	After 70-80 °C "boosting"	Collected from edges of board coming out of boosting oven
4	Chip isolated from un - curing board	After 70-80 °C curing, cooling	Isolated from board without final oven drying
5	Chip from final product	After all procedures	Isolated from final (commercial) products

3.3.3 Exposure of Chips

To obtain the consistency between panel and components, chips were exposed to a series of environmental conditions adopted from those used for the panel experiments. A summary of conditions and purposes is presented in Table 3.5.

Table 3.5 Exposure of chips and their objectives

Procedure	Objective	Measurement
Constant RH	Detect deterioration of wood chips.	Mass
Single change in RH	Evaluate the contribution; examine the applicability of the theory of mixtures, develop mathematical models.	Mass, dimensions
Cyclic RHs	Evaluate the contribution under service environments; examine effect of processing parameters.	Mass, dimensions

3.3.4 Measurements Taken on Chips

3.3.4.1 Mass Measurement

All types of chips to be assessed were held in small, thin aluminum cups matching the relatively small amount of chips. To increase the degree of accuracy a handful of chips was included to produce a larger level of change rather than small amount of mass change of a single chip.

In the first hour of exposure, some turning over of the chips was carried out to ensure that relative uniform diffusion (in three directions) occurred. Immediately prior to exposure, three replicates of the measurements were carried out. This is critical bearing in mind the small changes measured during experiments.

The samples (about 1 - 2 g in total) were weighed within 1 hour after exposure and then at 1 - 2 hour intervals until constant, using an analytical balance with an accuracy of 0.001 g. All measurements were replicated three times, and the mean values were used.

The measurement facilities were positioned in the corresponding environmental rooms to ensure no change occurred during transferring or measuring. A pair of pincers were used to move samples between the chamber and balance.

3.3.4.2 Measurements of the Length and Width (Thickness) of Chips

3.3.4.2.1 Positioning the Chips to be Measured

Six samples of the same type, three for the length, and the others for the thickness (width), were first stuck onto the same microscope slide which was fixed to the bottom of the chamber.

To ensure a minimal effect of the pin on restraint of movement of chips during exposure for the chip for which length change was measured, only one sticking point was used, in the centre of the chips, whilst two points, on both ends of the chips, was used for the chip for which thickness (width) was measured. The location of pin sticking is presented in Figure 3.7.

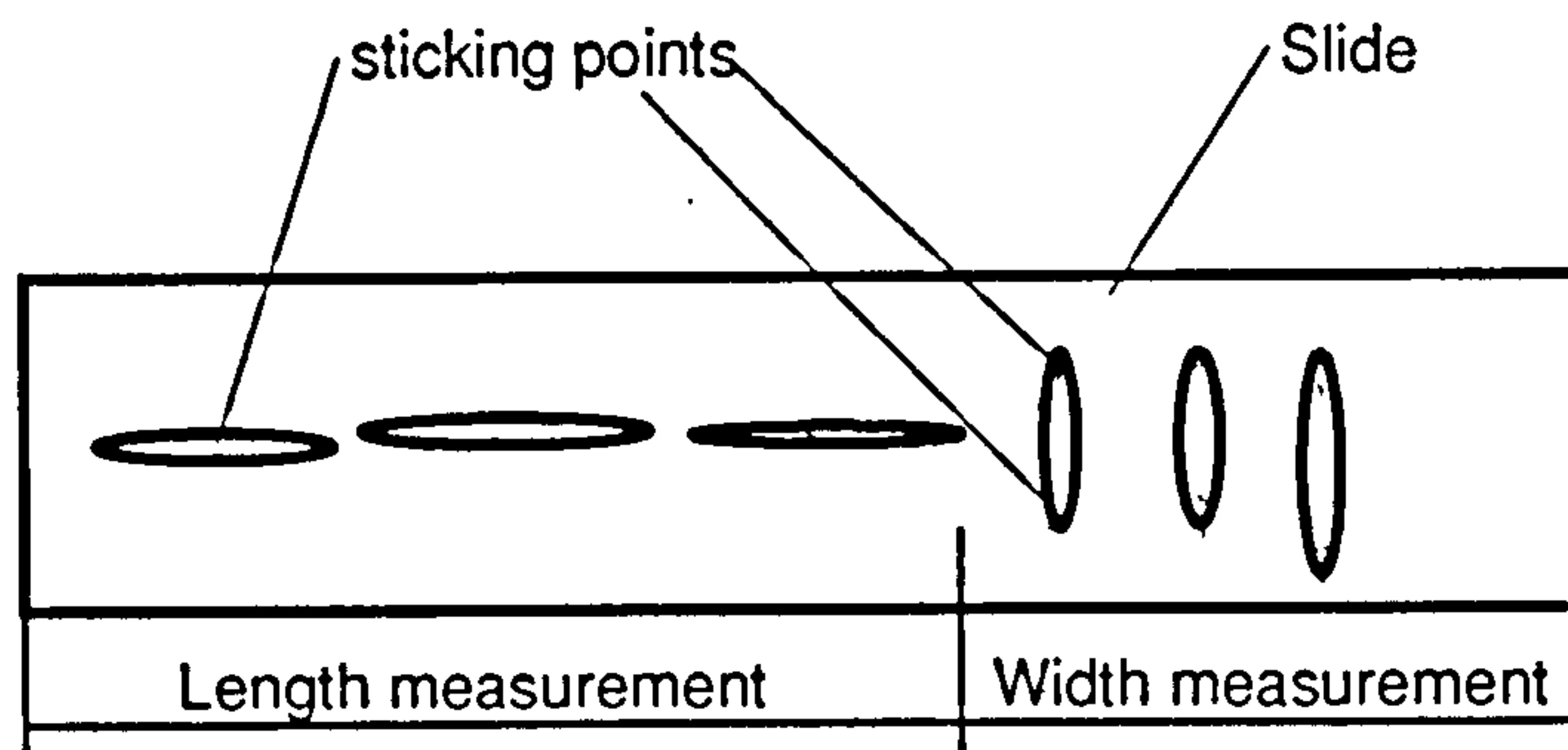


Figure 3.7 Positioning of chips for measuring length and width (thickness) change under various RHs

3.3.4.2.2 Measurement of the Change in the Length and Width (Thickness)

To effectively assess the dimensional stability of chips on exposure to cyclic RHs or to a single change in RH, re - measurements are required. Additionally, unlike the CBPB, because the effect of RH on the movement of the chips is significant and simultaneous, the intervals between the measurements should be as small as possible to enable a more correct record of the behaviour of the chips to be obtained, especially at the beginning of exposure. For all the tests, the samples were measured after 1 hour and then at 1 to 2 hour intervals until constant.

Measurement was carried out under the travelling microscope, with the resolution being 0.0001 mm (see Figure 3.1 and 3.2 in section 3.1.3).

3.4 Preparation and Testing of Cement Paste

3.4.1 Manufacture of Cement Paste

3.4.1.1 Introduction

The objectives of this section of work were two-fold, namely to determine the degree of carbonation of cement paste under the conditions used in the CBPB exposure tests and to assess the contribution of cement paste to the behaviour of CBPB.

Because cement paste used in the manufacture of CBPB was not available for examination of its dimensional movement, an unique cement paste was moulded. The main considerations on production were:

1) the best representation of the cement paste in CBPB. Therefore the material and the parameters used in the manufacture of cement paste were as supplied from the same manufacturer;

2) the least defects (mainly cracking);

3) of size and form to enable an sufficient distinction to be achieved when evaluating dimensional and mass changes.

To meet 2) and 3), the unidirectional dimension was required based on the isotropic properties of cement paste and such a thin, narrow and long sample can be produced to avoid internal cracks as the cement paste cures.

3.4.1.2 Raw Materials and Additives

The content of fresh OPC, sodium silicate and aluminum sulphate, was the same as used in manufacturing CBPB panels.

3.4.1.3 Fabrication of Cement Paste

12 neat cement paste samples were fabricated, each 300 mm in length, 15 mm in width and 5 mm in thickness. The ratio of water to cement was 0.35, this being based on the formula used in the manufacture of CBPB. The equation is:

$$\text{Water requirement} = 0.35W_c + (0.3 - M_c)W_w$$

where: W_c is the weight of cement paste, M_c is the moisture content in wood chips (based on absolutely dry chips) and W_w is the weight of absolutely dry chips.

In this instance, the formula $W / C = 0.35$ was employed in the neat cement paste manufacture, where W is the weight of water and C is the weight of cement.

The furnish was prepared by measuring accurately sufficient OPC, aluminum sulphate, sodium silicate and water in the desired ratio, to yield almost the same quality cement paste as it is in CBPB, into a large aluminum open topped container. Mixing (electrically), initiated immediately on the addition of additive, was

undertaken until an even distribution of the cement paste, chemicals and water was produced (about a 7 minute mixing period). This was the same as that in the factory for manufacturing CBPB, Figure 3.8.

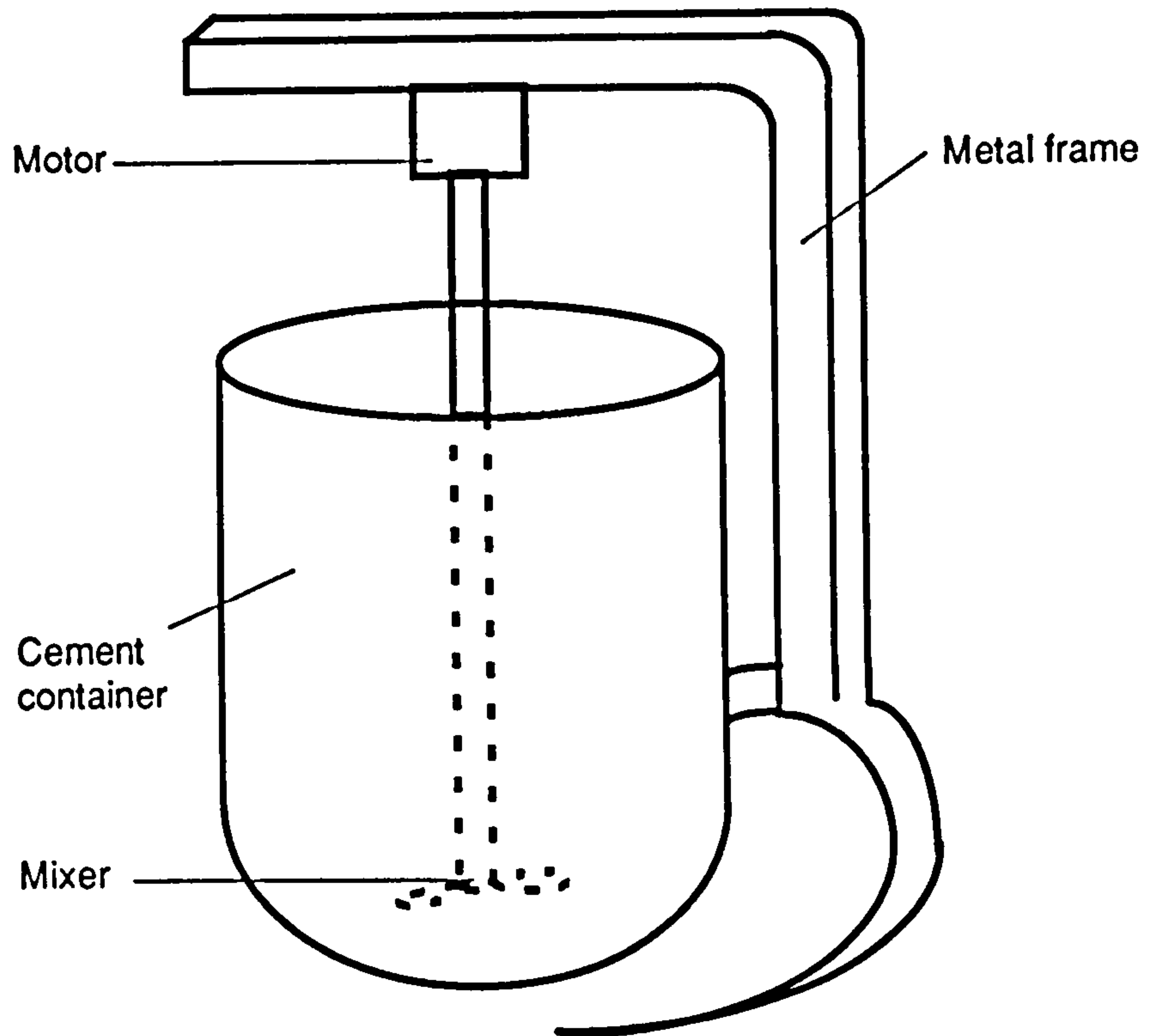


Figure 3.8 Diagram of apparatus used to mix neat cement paste

A wet cement mattress was then immediately formed by evenly spreading a small quantity (approximately 20 %) of the pre - mixed furnish onto a specially designed mould of dimensions 300 mm x 52 mm x 35 mm. A top plate was then placed directly above the mattress. Sufficient load (including the top plate) was transmitted through the top plate to meet the required pressure as in the factory manufacture of CBPB, Figure 3.9.

After 6 to 8 minutes pressing, the mattress was clamped and the filled mould was transferred to an oven, at about 70 °C, to give the mixture a "boost" (pre - curing). The "boosting" lasted 7 to 8 hours and then the constraint was released.

Further curing of the compressed mattress was carried out in two consecutive stages:

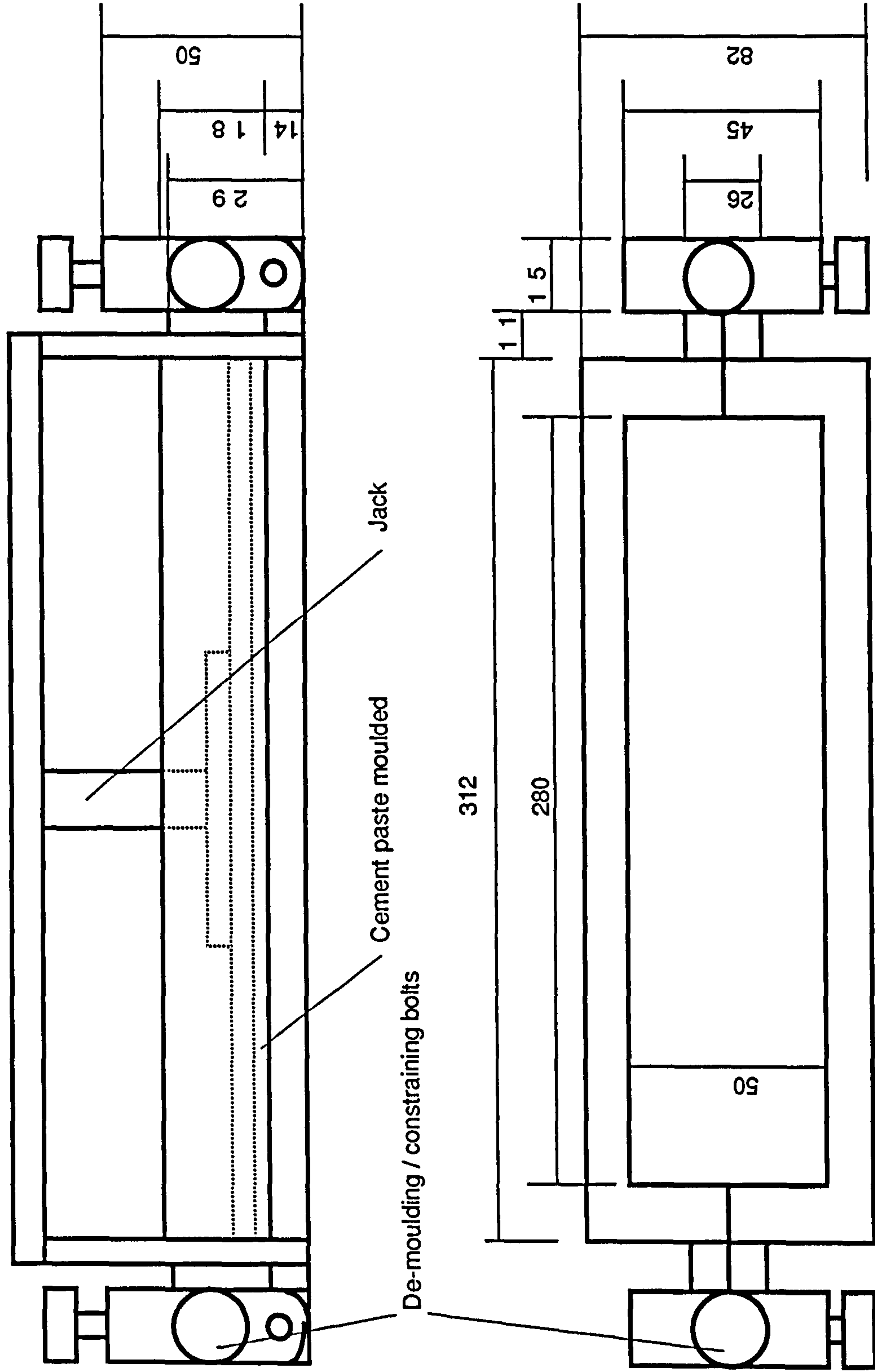


Figure 3.9 Press and mould used for neat cement paste formation

1) Immediately after temperature boosting the cement paste was removed from the mould and the paste (with some strength) was transferred to a conditioning room at 20°C / 65 %RH for 7 to 8 days;

2) After conditioning under an environment of 20°C / 65 %RH, the cement pastes were moved back to the oven at $110 \pm 5^{\circ}\text{C}$ and kept there for about 3 hours, thus ensuring the required strength and moisture content of cement paste had been produced.

3.4.2 Sample Preparation

3.4.2.1 Sampling of Cement Paste

Individual samples for testing were prepared by two methods:

A) From panels CBPB After compression, the brittle cement paste was broken into fine particles. The wood chips were separated. The sample of the cement paste in this case could best represent the nature of cement paste in CBPB, but inevitably small amounts of wood powder were included in each portion of cement paste powder sample. This type of sample can only be used to examine the behaviour in the mass of cement paste.

B) From the laboratory cement paste Samples were cut into dimensions 140 x 14 x 5 mm, and then furnished and assessed. Those with an uniform surface condition were forwarded for exposure.

3.4.2.2 Allocation of Samples of Cement Paste

To compare the dimensional change and mass change of the cement paste to those of the chips and CBPB, the samples of hydrated cement paste were divided into several groups. The allocation of samples is shown in Table 3.6.

The method of individual sample allocation for subsequent exposure to the different conditions was the same as that used to determine the change of CBPB

associated with the corresponding exposure conditions.

Table 3.6 Summary of cement pastes used and their objectives

Test	Type of cement paste (number)	Measurement	Objectives
Constant RH	Cement paste particle from CBPB	Mass	Evaluate its carbonation and contribution to CBPB
As above	Neat cement paste made (3)	Mass, dimensions	Evaluate carbonation; develop mathematical models for sorption and dimensional changes
Single change in RH	Cement paste particle from CBPB	Mass	Evaluate its contribution to CBPB
As above	Neat cement paste made (6)	Mass, dimensions	Evaluate its contribution; examine the applicability of the theory of mixtures or develop mathematical models
Cyclic RHs	Cement paste particle from CBPB	Mass	Examine its contribution to CBPB
CO ₂ - free	Neat cement paste made (9)		CO ₂ - free test

3.4.3 Examination of Cement Paste

3.4.3.1 Exposure of Cement Paste

A) *Cement paste particles* The samples of cement paste particles isolated from the CBPB were exposed using the same procedures adopted for the wood chips (see section 3.3.3).

B) *Neat cement paste* The sets of samples for normal air exposure were treated by subjecting to the corresponding environmental conditions used for the CBPB exposure, that is, the constant RH 20 °C / 65 %RH; from 20 °C / 90 %RH (precondition) to 20 °C / 35 %RH or from 20 °C / 35 %RH (precondition) to 20 °C / 90 %RH exposure. However, the duration of exposure of cement paste varied from that of CBPB, depending on the time to reach constant dimension. This control was thought to be important due to the time-dependence of carbonation of cement paste on CO₂ level.

The sets of samples for CO₂ - free air exposure were separately placed in the controlled chambers (see Figure 3.11). The CO₂ - free air supply and control system is described in a later section.

3.4.3.2 Measurement of Mass and Dimensional Changes of Cement Paste

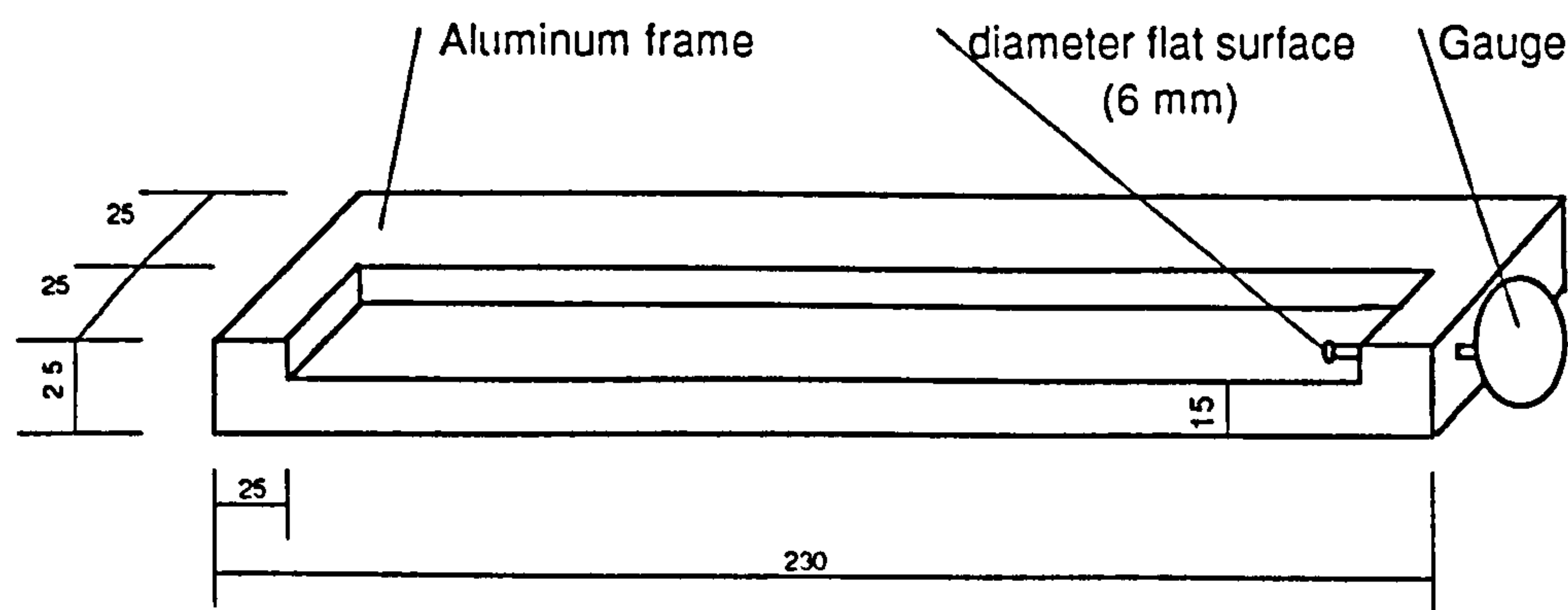


Figure 3.10 Jig for use in the measurement of change in length of cement paste

To enable the small change of the cement paste to be assessed, certain dimensions of samples are required. In terms of the isotropic characteristics of cement paste only one dimension was measured. Therefore the dimensions of the samples were 140 x 14 x 5 mm. The equipment constructed to suit the samples used is shown in figure 3.10.

Both mass and length change of cement paste were monitored until constant for all tests. A analytical balance was used to measure the mass, with an accuracy of 0.001 g, and the dimension gauge read to 0.001 mm.

3.5 Testing in a CO₂ - Free Atmosphere

3.5.1 Introduction

As has been reviewed earlier (section 2.6.3) carbonation of cement paste occurs when in contact with carbon dioxide, even at the low concentration in the atmosphere. It can be assumed, with confidence, that when CBPB is exposed to the air, the cement paste in the CBPB will present the cation calcium, forming CaCO₃, consequentially resulting in a volume and mass change. Therefore, a CO₂ - free test was developed so that the results could be used, in conjunction with the results from the exposure of CBPB to the normal environment, to:

- 1) test the degree of carbonation by normal air;
- 2) evaluate the contribution of CO₂ and moisture when CBPB is subjected to service environments;
- 3) guide the stabilization of CBPB.

3.5.2 CO₂ - Free Test Chamber

In order to control the CO₂ - free conditions in which studies of dimensional and mass changes of CBPB and cement paste were carried out, two special test chambers were built. The equipment has three main parts. An air tight conditioning chamber was made which consisted of an exposure volume 650 mm long by 150 mm wide by 350 mm height. A gas handling system provided a stream of gas (mixed gases)

through a series of pumps. The gases, comprising of a wide range of RH levels, were produced using two stages of humidifying solutions before and after CO₂ trapping. The CO₂ was removed from the air supply by using a chemical trapper or gases were replaced with N₂. The detailed apparatus used is presented in Figure 3.11. In the Figure, only the equipment for carbosorb is detailed. The one for N₂ addition was the same, with the N₂ cylinder replacing the carbosorb producer.

3.5.3 Preparation and Allocation of Samples

3.5.3.1 Samples of CBPB

Samples of CBPB were prepared as described in section 3.2.1 and 3.4.2. Additional samples were prepared to be used as controls. The type and storage duration of CBPB (18 mm made of OPC and Sitka spruce) was primarily selected or decided for the following reasons:

- 1) Consistency with the rest of the investigation undertaken in this treatise;
- 2) UK commercial popularity;
- 3) Less carbonation at beginning of the experiments;
- 4) Size requirement, referring to the carbonation depth of normal cement paste.

3.5.3.2 Samples of Cement Paste

The samples of cement paste were the same as those used in the normal air environmental conditions (see section 3.4.2). The selection conformed to the criteria used in selecting CBPB. Additionally consistency between the cement paste and CBPB was required to ensure the comparability of the results of studying both materials.

3.5.3.3 Allocation of Samples

The allocation of samples of CBPB and cement paste for the CO₂ - free tests is presented in Table 3.7.

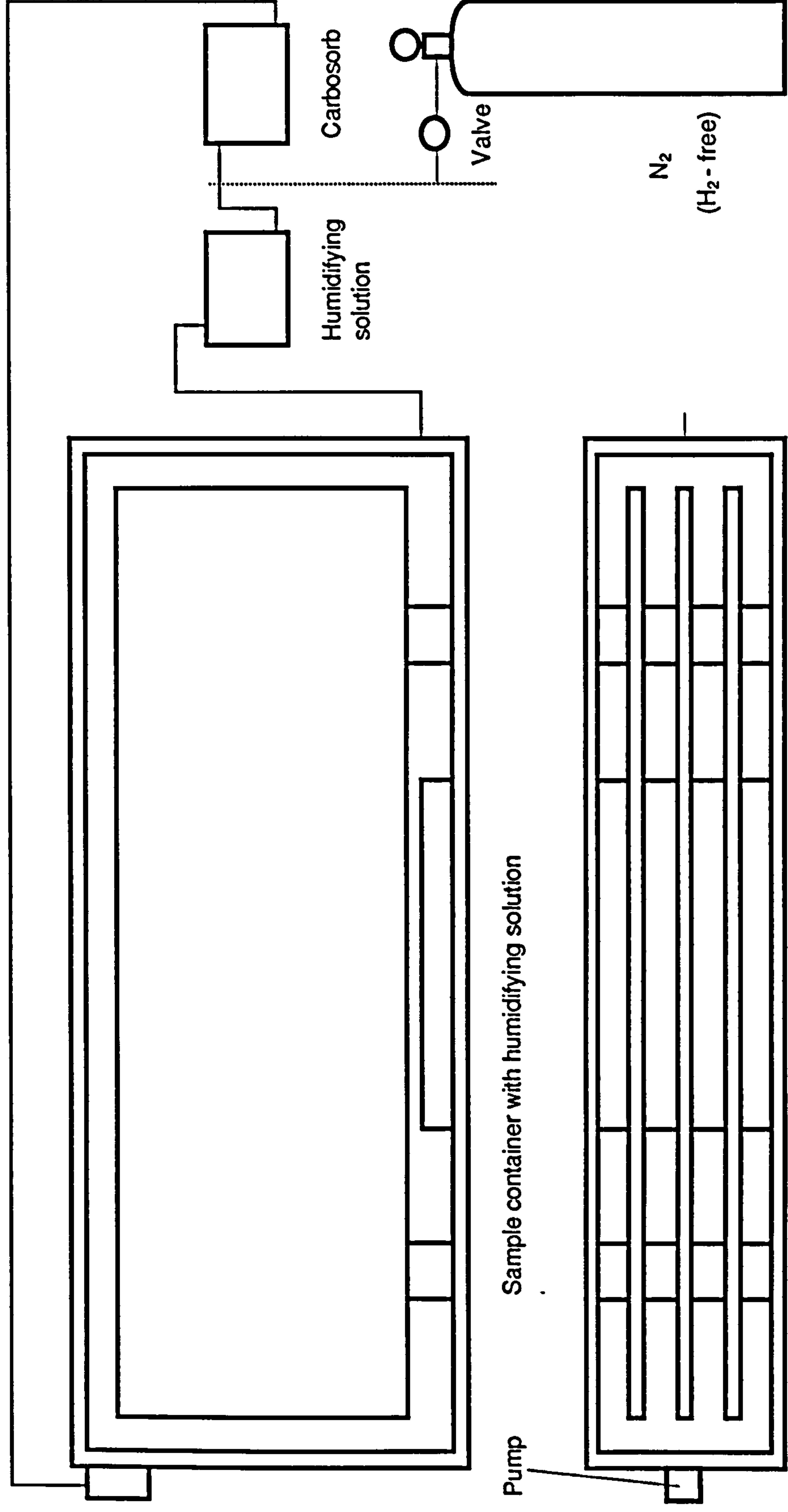


Figure 3.11 Diagram of apparatus used to expose cement paste and CBPB to air without carbon dioxide (chemical trapper or N₂ replacement)

Table 3.7 Allocation of samples for CO₂ - free test

Exposure	Material	Size	Number	Objective
Constant RH: 65 %RH	Cement paste	140 x 14 x 5	3	Evaluate carbonation of cement paste, deterioration of chips
	CBPB	600 x 300 x 18	3	
Single change in RH: 35 to 90 %RH 90 to 35 %RH	Cement paste CBPB	140 x 14 x 5	3	Evaluate and interpret contribution, examine the applicability of the theory of mixtures, develop mathematical models
		600 x 300 x 18	3	
	cement paste CBPB	140 x 14 x 5	3	
		600 x 300 x 18	3	
Control	Cement paste	140 x 14 x 5	3	Comparison
	CBPB	600 x 300 x 18	3	

3.5.4 Exposure and Measurement of Samples

The CO₂ - free environmental exposure was achieved using the following methodology:

- 1) Chambers preconditioned and saturated (about 5 hours);
- 2) After weighing the required CBPB and cement paste replaced in the chambers containing a rack to support the CBPB;
- 3) Vacuum pumps applied and held for about 5 hours;
- 4) Sufficient N₂ or CO₂ - free air passed over the humidifying solutions and added to the chambers to immerse the samples;
- 5) For experiments on N₂ replacement, N₂ supply maintained for several hours

on and several hours off;

6) Using the chemical trapper, CO₂ - free air maintained all the times;

7) The air was supplied parallel to the samples from the bottom side or the top side, based on the molecular weight of the gas;

8) CBPB or cement paste, saturated with N₂ or CO₂ - free air, transferred from the conditioning chamber to the measuring equipment and the dimensions and mass were measured at regular intervals throughout the test.

Several samples were exposed to a normal air environment of a certain RH. The dimensions and mass of all the samples were monitored at the same time. Further details of the procedures of measurement of CBPB are given under sections 3.2.8.1 and 3.2.8.2.

3.6 SEM Investigation

Preparation of SEM samples

To prepare the CBPB samples for SEM, two factors must be considered. Firstly, the samples should be of sufficient size and of a form to enable the full size of particles to be included, the chip orientation to be identified and the distribution of wood cement interfaces to be viewed. Secondly, various sizes of wood particles have to be included in one sample to ensure a true random distribution is represented. Consequently to satisfy these two constraints, a form of CBPB specimens was chosen as the best means of investigating orientation and distribution within a bulk system. The 50 x 50 mm square samples were cut vertically from the CBPB. The samples were ground from one top surface to produce surfaces at various depth into the thickness of the boards along the thickness direction. The thicknesses of the remaining squares, with the different features of horizontal surfaces, were 18, 17, 15, 13, 11 and 9 mm, Figure 3.12. The layers were designated as L0, L1, L2, L3, L4 and L5 respectively from surface to core layers.

To assess the distribution of wood particles / cement paste on side faces (within the thickness of the board), three matched samples, of the dimensions of 50 x 18 x 10 mm (length by width by thickness), were also prepared, Figure 3.13, namely T1, T2 and T3.

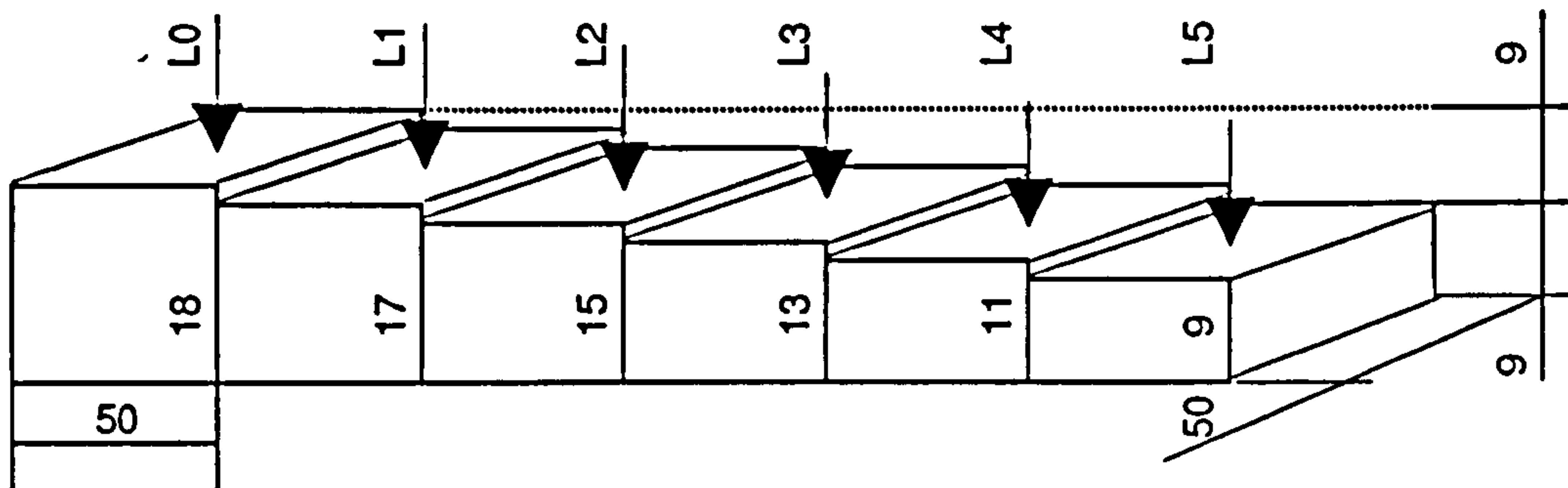


Figure 3.12 Sectioning of CBPB along thickness for SEM examination

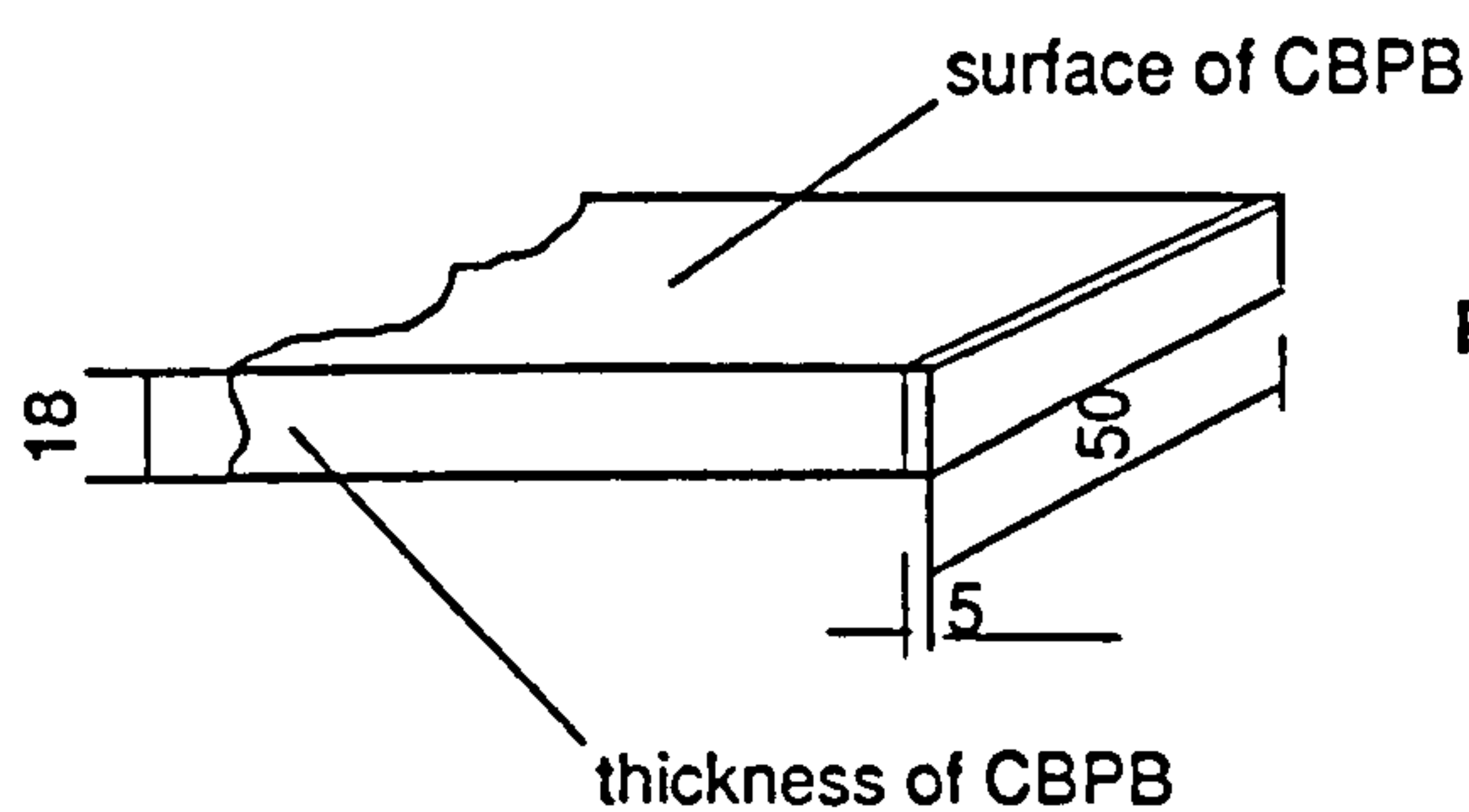


Figure 3.13 Sectioning of CBPB along length for SEM examination

After the samples were prepared, all the samples were vacuum impregnated with resin to provide strength and fill in any air pores with an electron opaque medium so that they could be polished.

3.7 Additional Testing

A number of additional tests were carried out, including assessment of proportions of materials (necessary for the analysis of the rule of mixtures), producing the density profile (which is essential for analysing the distribution of cement paste or wood chip through the thickness of CBPB, and hence assessing the contribution of cement paste or wood chips to the behaviour of CBPB); moisture and density measurements.

3.7.1 Measurement of the Moisture Content and Density

To measure the moisture content and the density of the cement paste, CBPB and wood, firstly the test pieces were placed into RH rooms at 35 %, 65 % and 90 %RH until constant mass was reached. The mass and dimensions of each of test pieces were then measured. Then the materials underwent oven drying to determine the oven dried mass and their dimensions. The percentage moisture content and the density of the materials were calculated according to BS EN 322 (1993) and 323 (1993) procedure. Three replicates were taken for each material under each condition.

3.7.2 Material Property Testing

The properties of wood were taken from previous data (Dinwoodie, 1981) in view of the identical wood chips (Sitka spruce). At moisture content of 12 %, e_L , e_R , e_T , v_{LR} , v_{LT} , G_{LT} and G_{LR} of Sitka spruce are 11600, 900, 0.029, 0.020, 720 and 750 N / mm² respectively.

It was found that the elasticity of wood increases by 1.5 % per % decrease in its moisture content within the range of moisture content 6 and 20 % (Gerhards, 1982). Such the values of the elasticity can be converted to those at moisture content at 8.53 % and 19.59 % at exposure RHs of 35 % and 90 % respectively.

Three test pieces of cement paste were selected from the samples exposed at 20 °C / 65 %RH for about 2 months (using the samples used for dimensional and mass change tests). The test piece dimensions were 140 x 14 x 5 mm, with a testing span 130 mm. The maximum load (bending test) sustained and deflection at the middle of the test piece were recorded. The MOR and MOE were then calculated using formulae in BS EN 310 (1993).

3.7.3 Density Profile of CBPB

It is well know that the quoted density of wood based panels represents only the overall density of products, the density at various depth in the panels varies, depending on the types of the materials, and the parameters of production, especially

the pressure and duration in the early stage of pressing.

However, the density of CBPB was intended to be similar throughout the thickness by virtue of the nature of manufacture. However, in the author's opinion, the density of CBPB along the thickness could in reality be very different because of considerable differences between the density of wood and that of cement and the high variation between the size of cement particles and those of wood chips which could cause the considerable variation in the distribution of cement or wood chips between the core and the surface of CBPB because of the mechanism of forming the mat during manufacture.

In common with the testing of other wood based materials, a total of 6 samples of CBPB (3 months storage), each of dimensions 300 x 20 x 18 mm, were cut from two oversized, preselected samples of CBPB. The allocation of samples is presented in Figure 3.14. Samples 1, 2 and 3 were used for the measurement of density of the upper side of CBPB, and samples 4, 5 and 6 for lower side.

The same samples and allocation were employed for measuring the density of CBPB with 2 year - storage periods.

After conditioning at 65 %RH, the mass and dimensions of each sample were measured, and then one by one thin layers were cut off from surface (from both sides) to the core of the samples, using a fine toothed saw. After each cut, the mass and dimensions of the samples (the part remaining) were immediately re - measured, and the density at various points calculated by following equations:

after 1 cut,

$$\rho_1 = \frac{M_0 - M_1}{LB(T_0 - T_1)}$$

and corresponding positions are:

for one side,

$$a_1 = \frac{T_1 + T_0}{2}$$

or for opposite side,

$$a_1' = T_0 - \frac{T_1 + T_0}{2}$$

after 2 cuts,

$$\rho_2 = \frac{M_1 - M_2}{LB(T_1 - T_2)}$$

and corresponding positions are:

for one side,

$$a_2 = \frac{T_2 + T_1}{2}$$

or for opposite side,

$$a_2' = T_0 - \frac{T_2 + T_1}{2}$$

.....

after n cuts,

$$\rho_n = \frac{M_{n-1} - M_n}{LB(T_{n-1} - T_n)} \quad 3.11$$

and corresponding positions are:

for one side,

$$a_n = \frac{T_n + T_{n-1}}{2} \quad 3.12$$

or for opposite side,

$$a_n' = T_0 - \frac{T_n + T_{n-1}}{2} \quad 3.13$$

Where

ρ_n = the density of board at nth cut;

a_n = the distance from top surface;

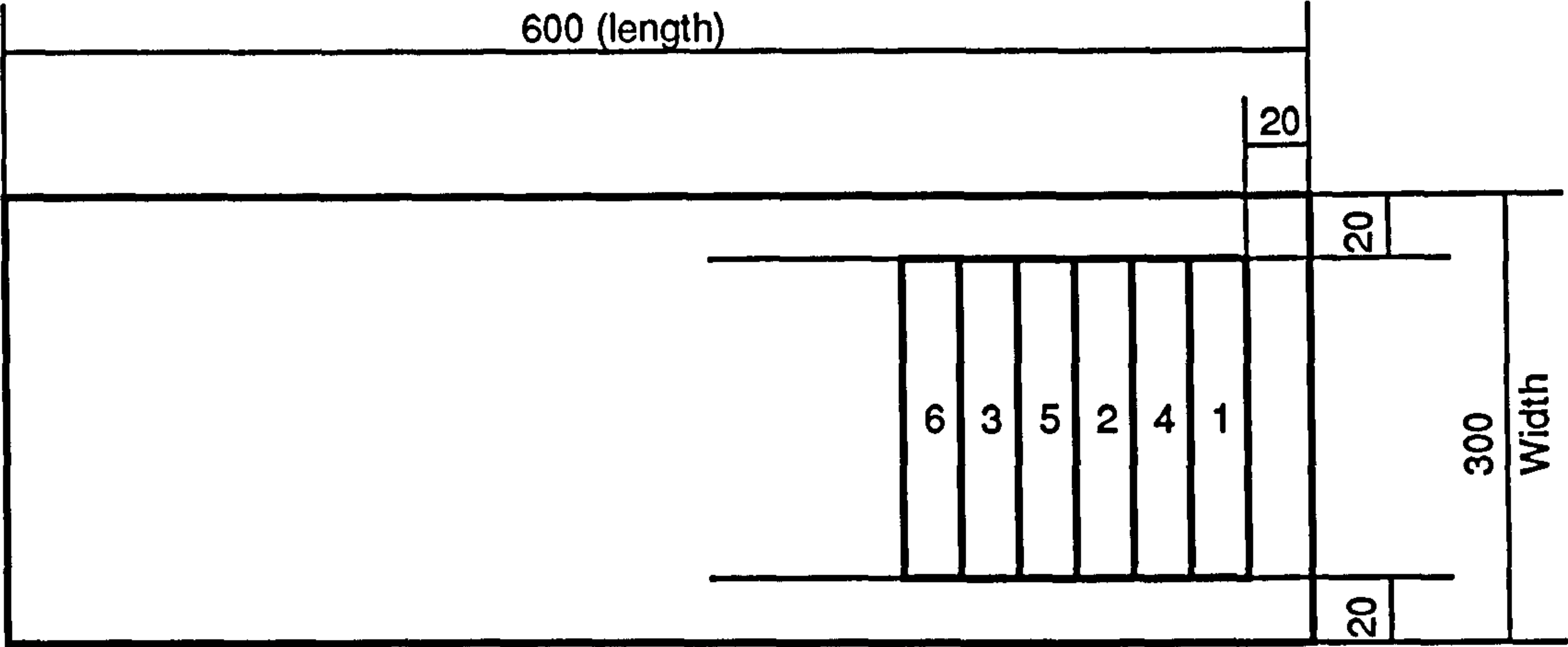


Figure 3.14 Allocation of CBPB samples for density profile examination

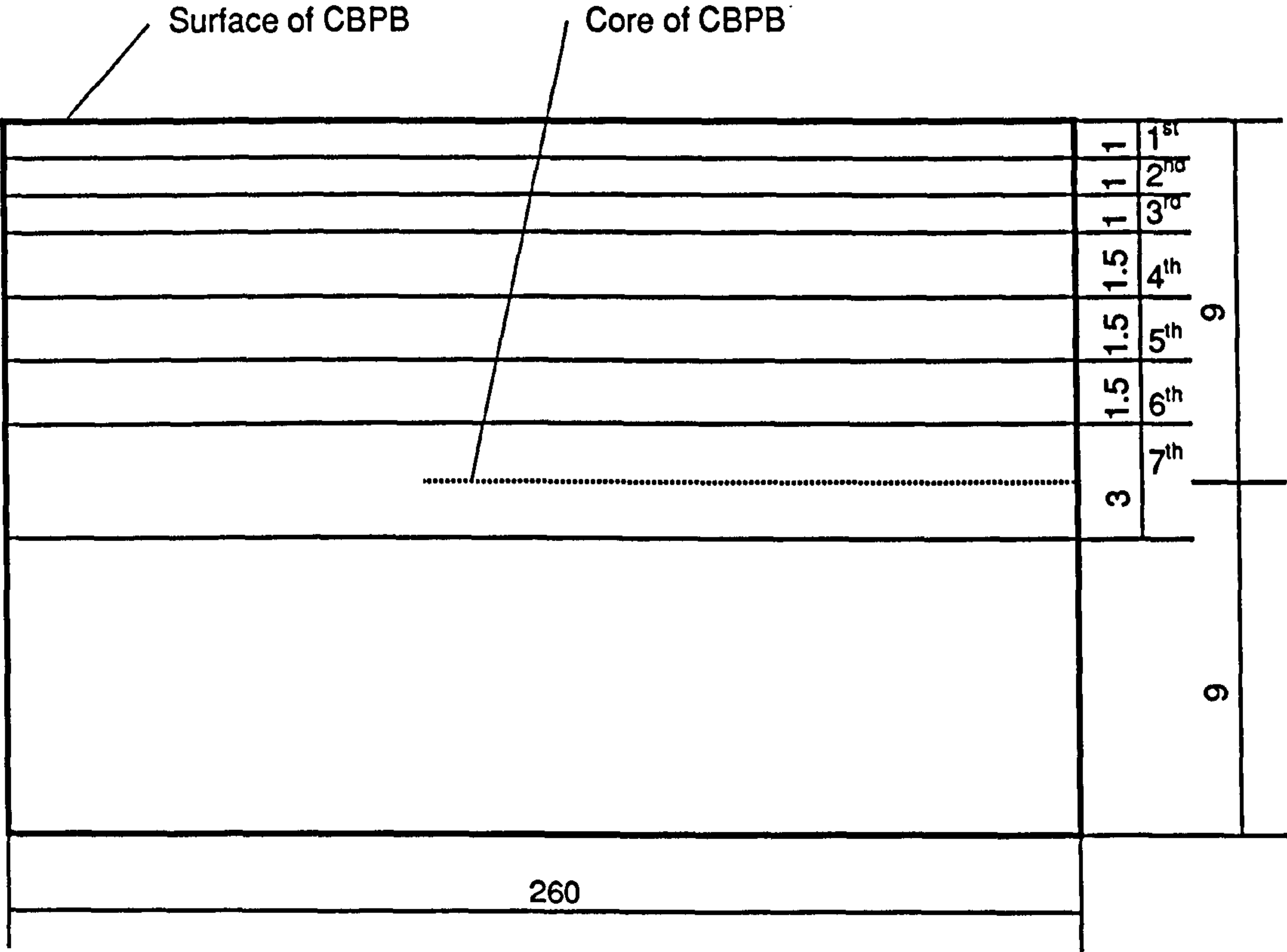


Figure 3.15 Layer cutting of CBPB along the thickness for density profile measurement

a_n' = the distance from top surface of symmetrical layer;

M_0, T_0 = the mass and thickness of samples before cutting;

M_1, T_1 = the mass and thickness of samples after first cut;

M_n, T_n = the mass and thickness of samples after nth cut;

L, B = the length and width of samples respectively.

The thickness and profile of layer cutting are displayed in Figure 3.15 according to the symmetry of panel products.

3.8 Application of Coating

3.8.1 Introduction

CBPB, like concrete, is a porous material. Microcracks and micro - pores will always exist on the outer surfaces, and these localized surface defects will harbour and provide a transportation route for aggressive agents, such as water. This results in a movement of CBPB. One way of protecting and stabilizing the CBPB is through the application of surface coatings thereby preventing the ingress of aggressive agents.

3.8.2 Selection of Types

Prior to testing, it was necessary to select a suitable coating. Compared with steel or wood, CBPB surfaces have a restricted list of possible coating materials. The chemical and physical characteristics of CBPB preclude the use of certain coatings. Firstly CBPB surfaces are inherently highly alkaline which may adversely react with a variety of coatings; secondly the surface of CBPB (as concrete) is comprised of numerous mini pores, which invariably contain some degree of moisture. This porosity can cause bubbling and pinholing of an applied coating due to the displacement of air or the expansion of trapped vapours; thirdly CBPB surfaces exhibit relatively low tensile strength when compared to steel and wood surfaces, and a result is that excessive forces may fracture the CBPB surface and un - bond the coating from the CBPB; fourthly CBPB experiences dramatic dimensional changes due to forces of expansion and contraction and settlement. Therefore, a suitable

coating should be one that is able to resist the alkaline nature of CBPB, is tolerant to high moisture content when coating (and be highly moisture resistant on exposure) has elasticity to accommodate anticipated movements in CBPB, is stable on exposure and is resistant to carbon dioxide. In addition to these, a suitable coating must be one that coats CBPB surfaces uniformly and which is easily handled when applied to CBPB surface.

Four model and three proprietary sealers were chosen for small scale trials based on material availability, estimated cost or previous experience in use for wood materials.

3.8.2.1 Model Formulations

Four model systems were prepared in the laboratory. The sealers were formulated from selected water-borne emulsion resins that potentially offered the required low moisture permeability and alkali resistance. For comparative purposes all sealers were prepared at solids content of 30 % (by weight), using simple solution/mixing procedures.

All the sealers were prepared by adjustment of the solids content with water to the required 30 %. The rheology and stabilisation of the sealers was controlled by the use of hydroxy-propyl-methyl cellulose added at a constant 1.0 % (by weight) to each of the formulations; the grade used was Methocel J12-MS ex Dow Chemicals.

Each sealer was prepared by slowly adding the cellulose thickener to the water using a high speed stirrer. Stirring was continued until dissolution and thickening had occurred; this took about 30 minutes. The emulsion resin was then slowly added and stirred at a low shear for a few minutes to ensure complete mixing. Each sealer was then stored in a glass container. The formulations are in Table 3.8.

3.8.2.2 Proprietary Sealers

1. Panellakk, ex Jotun Decorative coatings. A water-borne acrylic varnish of similar solid content to the model formulations; included as a control by which to judge the model formulations

Table 3.8 The model formulations of sealers

Formulation	Types of emulsion bases	Emulsion resins (% wt)	Cellulose thickener (% wt)	Water (% wt)
1	Polidene 33-075, ex Scot Bader Ltd: A polyvinylidene chloride copolymer, supplied at solid content 55 %	53.5	1.0	45.5
2	Vinacryl 4000, ex Vinamul Ltd: A pure acrylic copolymer, supplied at 50 % solid content	59.0	1.0	40.0
3	Technimul DC1112, ex Dussek Campbell Ltd: A styrene acrylic copolymer, supplied at 50 % solids content	59.0	1.0	40.0
4	Haloflex 2025, ex ICI Mond Division: A terpolymer of vinyl chloride, polyvinylidene chloride and acrylic resin, supplied as 58 % solids content.	51.5	1.0	47.5

2. Cito, ex Jotun Decorative Coatings. A solvent-borne masonry sealer based on styrene butadiene resin of known low water vapour transmission characteristics, and

included as a control.

3. CPB sealer, ex Nicobond Ltd. A solvent-borne sealer based on an undeclared resin system. Included as a representative of a material produced for the specific purpose of sealing cement particleboard. This product contained a inert filler material, presumably to moderate absorption of the applied coating into the substrate, and to reduce moisture transmission by pore-blocking.

3.8.3 Panel Preparation

For laboratory trials, the boards were cut up to produce samples $100 \times 100 \times 12$ mm, and for large scale tests to dimensions of $600 \times 600 \times 12 / 18$ mm. The edges of these large size samples were coated with 2 coats of epoxy resin.

The sealers were firstly all applied as single coat treatments onto the small sized samples for comparison of effectiveness, and then onto the quarter-sized samples. To assess the effects of film thickness, sealers were applied as two coat systems, and the most promising CPB sealer was also applied as a three coat system.

3.8.4 Assessment of Sealers

The preliminary trial centred on the assessment of candidate sealers. The result of the preliminary tests was the basis of the selection of a particular coating with which to test the hypothesis of the stabilization of CBPB.

The overall experimental approach may be outlined as follows:

1. Formulate and select a variety of coatings for preliminary trials;
2. Coat and subject all CBPB to 90 %RH and evaluate the results;
3. Eliminate coatings which are clearly of very low efficacy;
4. Apply the remaining coatings to large scale samples and subject them to cyclic humidity (see section 3.2.7.3);
5. Choose the best coating and subject it to further testing in order to examine its durability with time under the environmental cyclic humidity;
6. Apply different thickness of sealers to CBPB surfaces to assess its permeability.

7. Quantitatively assess the results of the test.

Mass, thickness and length of CBPB boards were monitored at 24 h, 48 h, 72 h and 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.

PART 2

THE BEHAVIOUR OF

CBPB AND ITS

COMPONENTS

Chapter 4

THE NATURE OF THE CBPB TESTED

4.1 Equilibrium Moisture Content of CBPB

The moisture content of CBPB is the quantity of moisture present expressed as a percentage of the oven - dry weight. The equilibrium moisture content (EMC) is the moisture content of a specimen which is in equilibrium with the surrounding air. Its value increases with RH at constant temperature and decreases with temperature at constant RH. For wood it is also affected by mechanical stress and previous history. Furthermore the moisture content on adsorption is normally lower than that on desorption.

The values of EMC of CBPB and its components at the various RH used in this thesis are presented in Table 4.1.

Table 4.1 EMC of CBPB and its components at various RH regimes used (%)

Regime	CBPB	Cement paste	Wood chip
20 °C / 35 %RH	4.24	3.83	8.53
20 °C / 65 %RH	8.10	5.27	14.39
20 °C / 90 %RH	12.68	7.40	19.59

It is apparent that the moisture in wood chips at the RHs tested (35 %RH, 65 %RH or 90 %RH) is "bound" water. When CBPB is transferred from one condition to another, the change in the properties of wood chips is inevitably related to movement of this "bound" water, and this is one of the considerable influences on the volumetric change of wood.

Compared to the EMC of wood chips, the cement paste under corresponding conditions has a lower EMC. Moreover, the differences in moisture content of

cement paste between the conditions (i.e. 35 %RH, 65 %RH and 90 %RH) are much less than those of wood chips. The values measured at 90 %RH is slightly lower than those given in literature and this may be attributable to the effect of the lower pressures imposed during pressing cement paste (CBPB) in this study.

The EMCs of CBPB lie between those of the cement paste and wood chips under the same conditions. The relationship between the moisture in CBPB and its components will be discussed more comprehensively later.

It should be noted that the values of EMC measured result from oven drying at 105 °C. Under this condition a considerable amount of non - evaporable water remains in the cement paste, and it was assumed that mature cement paste could combine with 23 % of non - evaporable water.

4.2 Density and Density Profile of CBPB

4.2.1 Density

The density of a specimen is its mass per unit volume, with both values being measured at the same moisture content. In all composite boards, the density of the materials is a reflection of properties such as the porosity of the materials, which is closely related to the capability of adsorption / permeability of materials or stiffness. An exception is the dimensional stability after water soaking and exposure to high RH (eg. for particleboard, due to more wood in the higher density board thickness swelling and linear expansion can be increased by absorption). The density of CBPB and its components at the various RHs used are presented in Table 4.2.

Table 4.2 Density of CBPB and its components (kg / m³)

Regime	CBPB	Cement paste	Wood chip
20 °C / 35 %RH	1342.08	1906.79	376.75
20 °C / 65 %RH	1366.33	1955.68	391.47
20 °C / 90 %RH	1430.39	2123.21	425.32

Table 4.2 shows that the density of CBPB is related to the densities of cement paste and of the wood chips. Under the same RH, the density for CBPB lies between that for the cement paste and wood chips. In contrast to the order of the values of moisture content, the value of density for cement paste is much higher than that of wood chips. The numerical modelling of density of the CBPB will be carried out in chapter 15.

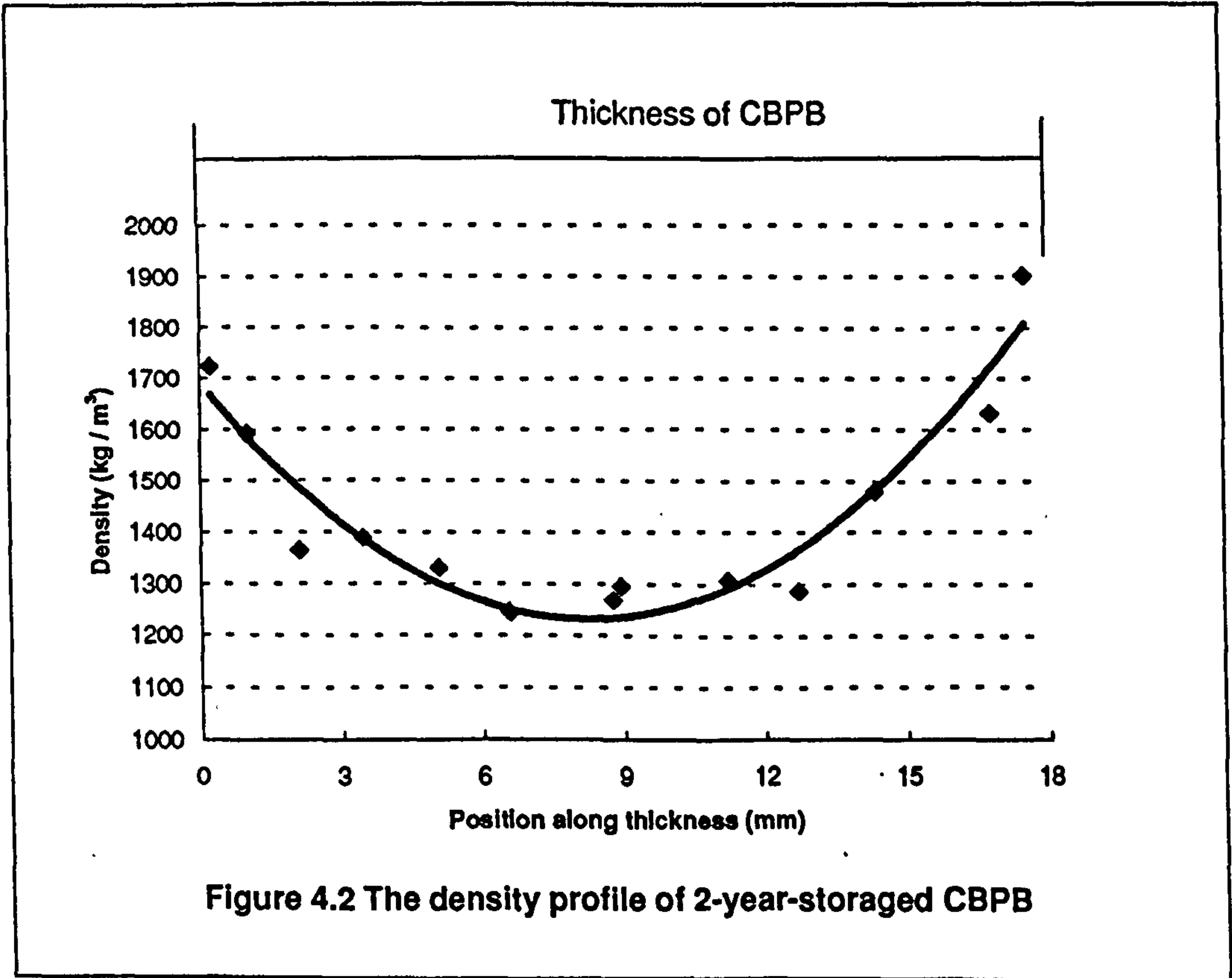
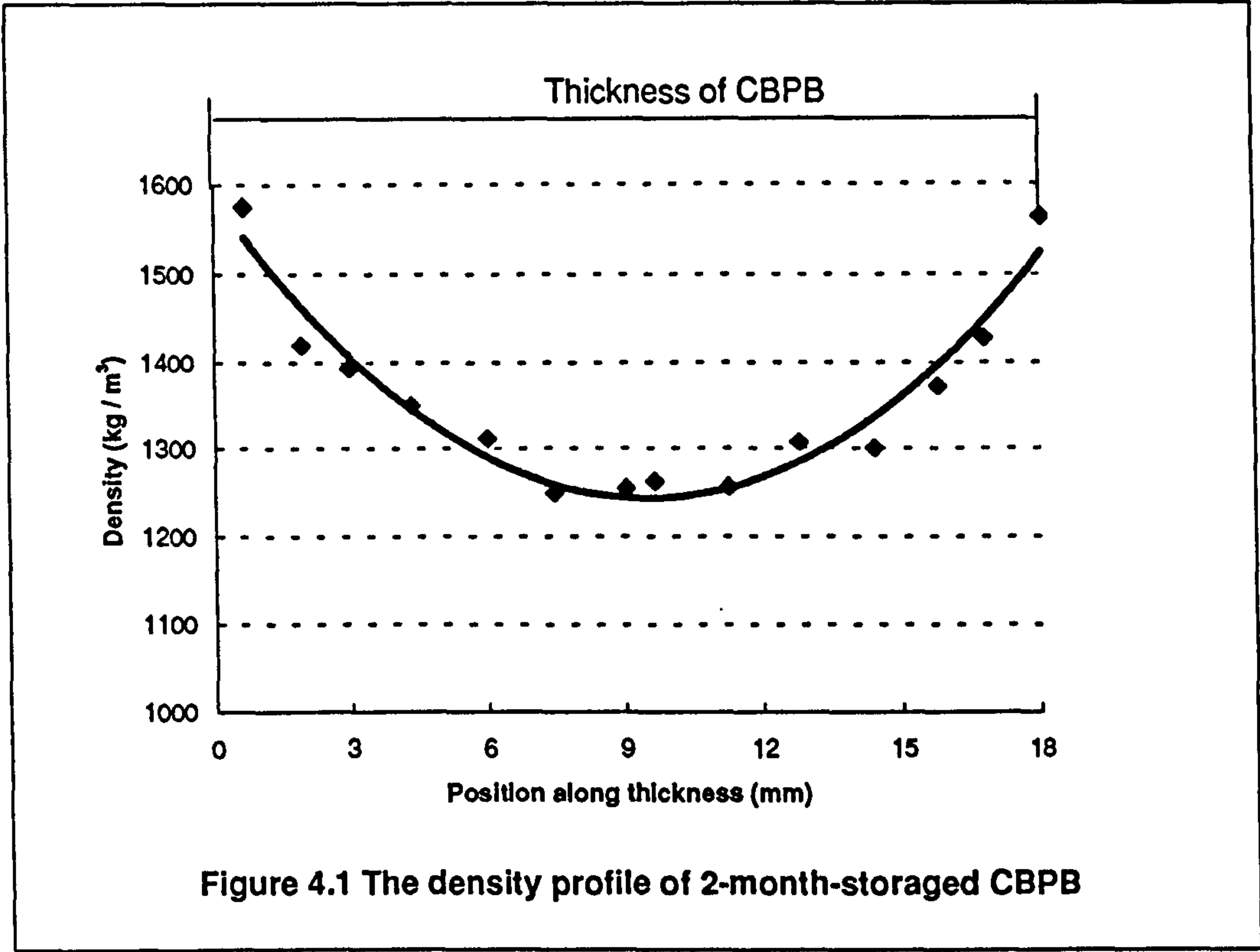
4.2.2 Density Profile of CBPB

A density profile shows the density of CBPB from one face to the other. The density profile for the CBPB used are presented in Figures 4.1 and 4.2.

These Figures illustrate that the board has high face densities and low core densities. Newly made CBPBs have 300 kg / m^3 higher density at the face; and 2 - year - stored CBPBs have 430 kg / m^3 or 600 kg / m^3 higher densities for the top or bottom faces, compared to core densities of 1250 kg / m^3 , for both newly made and stored materials.

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

In addition to this, of great importance are the differences existing between newly made and old materials, with a symmetrical distribution being found in the newly made CBPBs but a great deviation is observed between the top and bottom in the 2-year-stored CBPBs. This unexpected finding superimposed the explanation of the accumulated change in the mass of CBPBs with the number of cycles or the



exposure duration. It is because the CBPB undergoes carbonation under normal atmospheric conditions.

The degree of carbonation in cement paste is affected by its accessibility to carbon dioxide. The sample of CBPB for the density profile testing was chosen from the top of the stack. Thus one face of this sheet was in contact with a lower sheet of CBPBs while the other face was exposed to the normal air (20 °C / 65 %rh). It is inevitable that this will result in a greater degree of carbonation on the layers near the face exposed to normal air than those near that face contacting the other sheet of CBPB. Therefore, the higher density was produced at the side corresponding to the exposed face of the CBPB.

4.3 Interim Conclusions 1

1 EMCs of the CBPB lay between those of the cement paste and wood chips.

2 Moisture in the dissected chips under all RHs exposed was present as "bound" water.

3 The density of CBPB lay between that of the cement paste and wood chips. The value of density for the cement paste was much higher than that of the wood chips.

4 The shape of the density profile for CBPB was similar to that of other chipboard, but the mechanisms of their production was very different.

5 Newly made CBPB had a symmetrical distribution of density across the thickness of board but older material had an asymmetrical one due to the different degree of carbonation in both faces. This unexpected finding supplemented the explanation of accumulated change of CBPBs with exposure.

Chapter 5

BEHAVIOUR OF CBPB UNDER CONSTANT RH CONDITIONS (20 °C / 65 %)

5.1 Introduction

It is well known that the mass and dimension of wood remain constant under constant RH. However, alkaline and thermal degradations of wood, which occur in the manufacture of CBPB, have historically been two of the subjects considered in wood science (section 2.4). In addition to these, adverse effects, such as chemical decomposition and dissolution of alkali soluble substances on the properties of cement paste is also well documented (section 2.6). The question thus arises as to whether an alkali environment after the complete hydration of cement paste has any further effects on the wood physical properties, for example, volumetric decrease, and how does cement paste respond in a certain, constant environment, and what is their combined effects on the CBPB?

To answer these questions, CBPB samples were subjected to 20 °C / 65 %RH, i.e. normal air environments.

5.2 Mass Change

The rate of change in mass of CBPB under normal air (constant) RH is presented in Figure 5.1. Specimens for the test had been stored for 4 months prior to their exposure.

The mass response was to significantly increase over the duration tested. The increase in mass seems to be consistent - samples after exposure of 35 days and 350 days in normal air condition showed increases of 0.29 % and 1.77 % respectively.

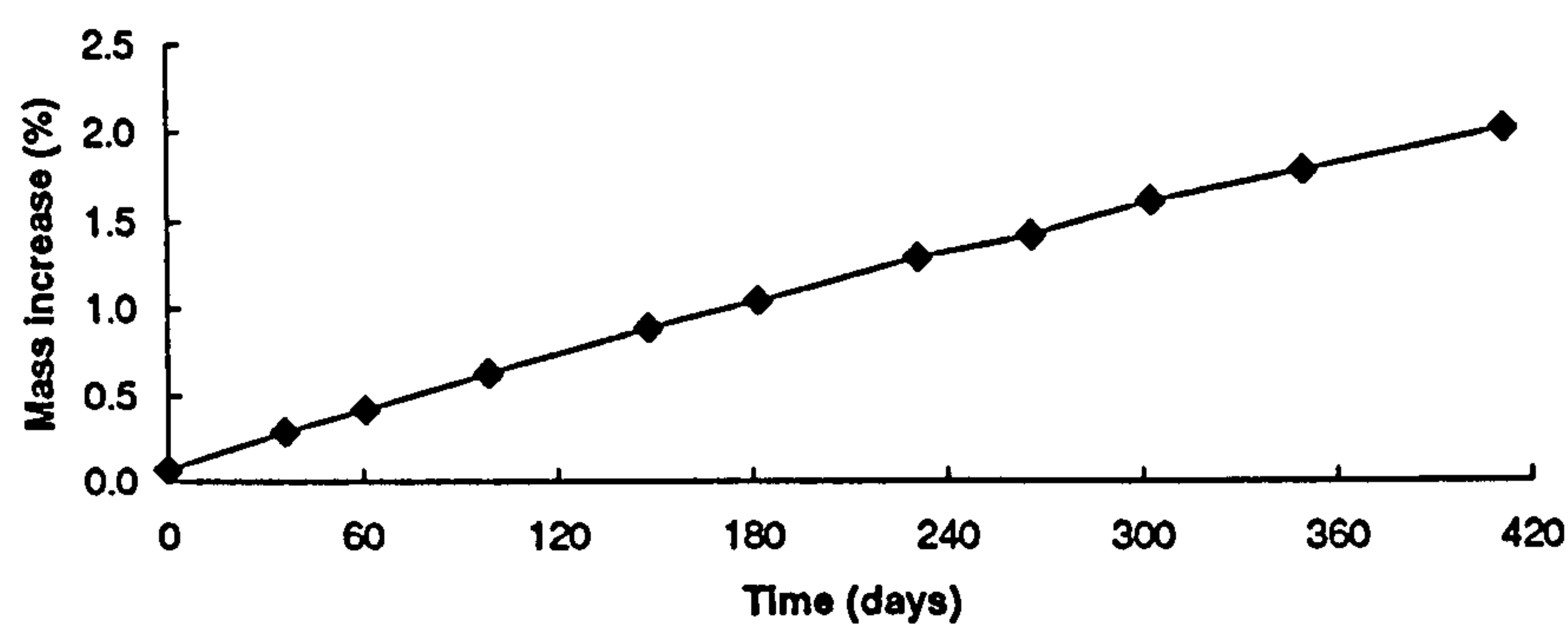


Figure 5.1 Mass change versus time on exposure of CBPB under constant normal environment of 20 °C / 65 %RH

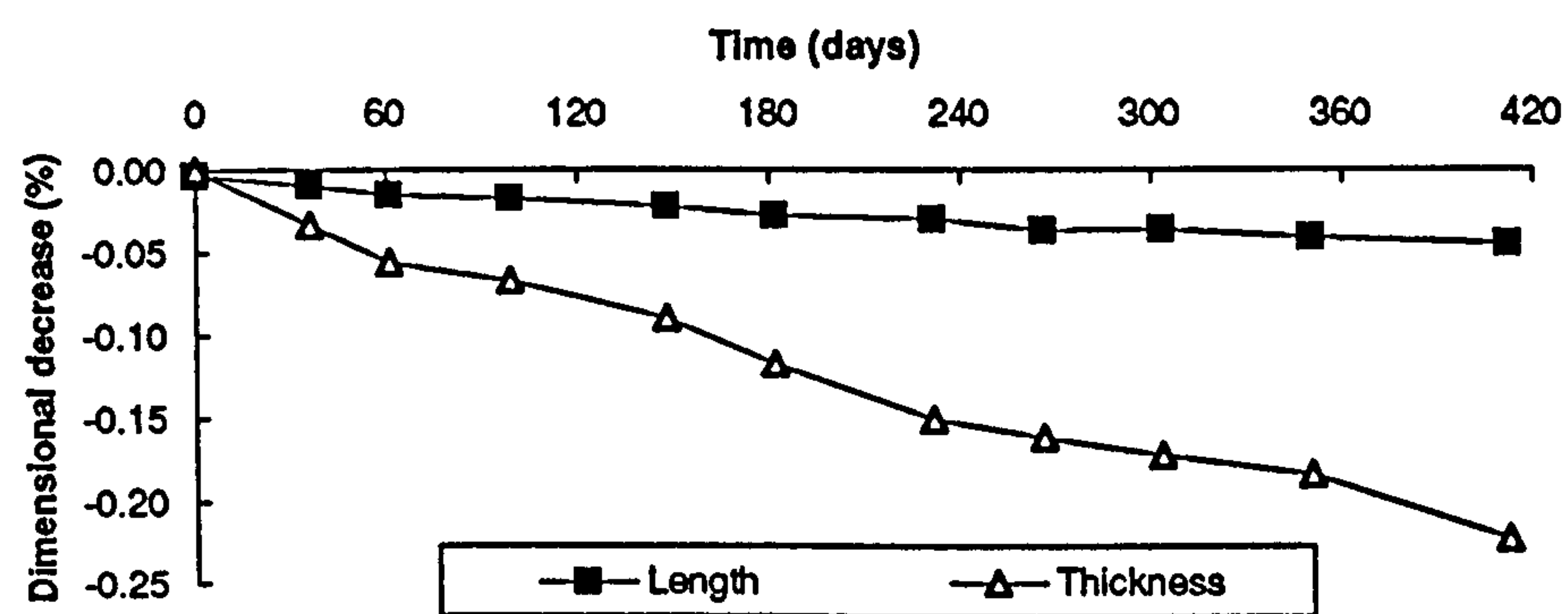


Figure 5.2 Dimensional change versus time on exposure of CBPB under constant normal environment of 20 °C / 65 %RH

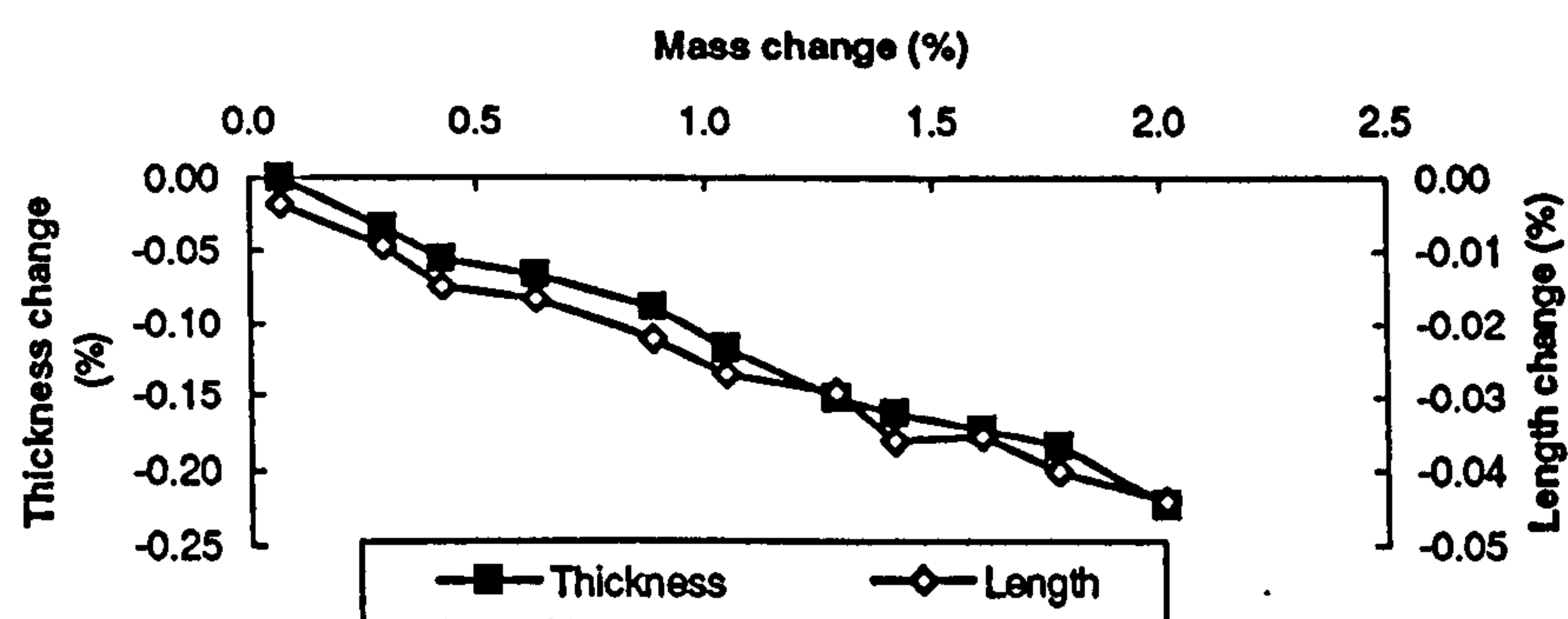


Figure 5.3 Relations between dimensional decrease and mass increase of CBPB under constant normal environment of 20 °C / 65 %RH

5.3 Dimensional Change

Three measuring positions for length change and six for thickness change were taken on each of the 600 x 300 x 18 mm samples. The mean changes in both length and thickness of CBPB are presented as percentages of the original values. The results are shown in Figure 5.2.

It is clearly demonstrated in Figure 5.2 that the dimensions of CBPB under normal (constant) air exposure decreased instead of increased. Over the period tested, changes in both length and thickness were approximately linear with time, with dimensional change producing a negative gradient in contrast to the positive gradient for mass increase.

A comparison of rate of change in length with that in thickness shows that the decrease in thickness was considerably greater than that in length. The exposure after 35 and 350 days resulted in decreases of 0.009 % and 0.040 % in length, but 0.033 % and 0.184 % in thickness respectively.

5.4 Relationship between Mass and Dimensional Changes

Figure 5.3 shows the length and thickness change versus mass change of CBPB under constant RH (20 °C / 65 %RH). Essentially the same trends were found between the relationship of length and mass change and of thickness and mass change but the ratio of thickness to mass change was about 5 times higher than that of length to mass change. Both length change and thickness change to mass change appear to be linear over whole exposure duration.

5.5 Discussion

The implication of the results above is that even under constant RH, CBPB undergoes mass change and dimensional movement and even normal air has a significant effect on the behaviour of CBPB. The impact of normal air to the cement paste in CBPB was illustrated in the Figures which may be supplemented by the alkali influence.

The explanation for the pronounced effect of normal air on the mass change of CBPB can be discussed primarily in terms of chemical activity of calcium hydroxide in the boards. Very dilute carbonic acid, resulting from the low concentration of carbon dioxide in the atmosphere, can significantly attack most of the components of the hardened cement paste in CBPB. Thus water is released and there is an increase in mass of the CBPB. The details of this will be discussed in chapter 11.

A second reason likely to account partly for the relatively small effect on the mass increase during the exposure of CBPB is the further hydration of cement paste in CBPB. Hydration of cement paste increases the solid content of the cement paste and consequently the mass of CBPB.

Previous workers (section 2.4.2) have discussed the possibility that the alkali solution reacts with components of wood, dissolving considerable quantities of the hemicelluloses. The consequence of this is that a chemically heterogeneous extract is formed. Test on CBPB under CO_2 - free atmospheres carried out in this work confirmed these findings. However, it should be noted that the effect of a hydrated cement paste on the wood chips probably brought about the mass decrease of CBPB, in contrast to an increase if the alkali soluble products were removed.

Compared to the increase in the mass of CBPB, the mechanisms of changes in the dimensions of CBPB are more complex. The decreases in the dimensions are attributable to several factors. Movement of the chips in CBPB, possibly due to the high alkalinity present as aforementioned, resulted in the movement of CBPB. When considerable quantities of the hemicelluloses and some of lignin were dissolved, the soluble substances may migrate from the CBPB and if the stiffness of the chips is not enough to withstand the internal stresses which normally exists in materials, substantial changes will take place in the structure of CBPB.

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

Thirdly, when cement paste shrinks incompatible strains probably appear,

producing residual stresses. These stresses are of long duration, and consequently result in the creep of material elements which could be reflected in further dimensional decrease of CBPB. However, it should be noted that the creep causes some relaxation and redistribution of internal stresses, a process which is beneficial to the structural performance. Thus, one of the functions of the chips is to reduce cracking and microcracking of the CBPB.

The ratio of $\Delta T / \Delta W$ to $\Delta L / \Delta W$ (the slopes of the lines to the thickness and length decrease) was about 5 : 1 (see Figure 5.3). The considerably different contractions between thickness and length are thought most likely to have been caused by the distribution of the cement paste. It is possible that at constant environment (20 °C / 65 %RH) the relatively large isotropic shrinkage of the denser cement paste present on both faces of CBPB is restrained by a delay in the shrinkage of the chips in the thickness of the board. Furthermore the anisotropy of wood may promote the difference between the change in the thickness and length (width). Based on fundamental considerations, the hemicelluloses are usually intimately associated with the cellulose, effectively binding the microfibrils which have similar orientations of 10 - 30 ° to the longitudinal axis. Like those due to the moisture or thermal effects, when the hemicelluloses are dissolved and soluble products are moved out, the cellulosic microfibrils do not change their orientations, and thus the anisotropic movements of wood chips should qualitatively follow the behaviour of the same species of normal wood - that is, the transverse change is much greater than the longitudinal change. Additionally because most of chips lie flat in the CBPB (as in chipboard), the change across the thickness is greater than that in the length (width) direction.

5.6 Interim Conclusions 2

1) Under a constant (normal) air environment, certain chemical or physical changes occurred in CBPB resulting in mass increase and dimensional decreases. The mass increase with exposure time was closely related to the carbonation of cement paste and further hydration, while the dimensional decrease was possibly associated with the degradation of wood chips, carbonation and resultant effects.

- 2) The rates of changes between mass and dimensions were considerably different. The mass increase was about 47 times the length decrease and 10 times the thickness decrease.
- 3) The contraction of thickness was about 5 times higher than that of length (width) due to the specific structure of CBPB, anisotropic characteristics of wood chips and the distribution of cement paste and wood chips across the thickness and width (length) of CBPB.
- 4) Both mass increase and dimensional decrease with exposure time appeared linear over the period tested.
- 5) Regardless of the adverse change between the mass and dimensions, there was the same trend between the relationship of length and mass and that of thickness and mass but with a considerably different ratio.

Chapter 6

BEHAVIOUR OF CBPB UNDER A SINGLE CHANGE IN RH

6.1 Introduction

Several sets of CBPB samples were subjected to different, single changes in RH. The changing levels were from 35 to 90 %RH, 65 to 90 %RH, 90 to 35 %RH, 65 to 35 %RH. All experiments were conducted at 20 °C. Mass, length and thickness were recorded for about 400 days. The combined effects of moisture on wood chips and cement paste, of alkali on chips, and of normal air on the cement paste were assessed.

6.2 Results

6.2.1 Adsorption

The curves above the X - axes of Figures 6.1, 6.2 and 6.3 show mass, length and thickness plots associated with the adsorption of moisture by CBPB after 400 days exposure during a single change in RH from 35 to 90 % or from 65 to 90 %. Solid lines represents the results when the samples had been initially conditioned at 35 %RH whilst the dotted lines represents the data produced by the samples initially conditioned at 65 %RH prior to moving to 90 %RH.

The adsorption curves are similar but with different rates for the solid and dotted curves. The rates of mass change were markedly different to those of dimensional change. There is a consistent increase in mass of CBPB, but the dimensions changed very slightly after a certain period. Over the period of exposure (400 days) the resultant curves can be divided into two parts: curves OA_1 / OA_2 represent the behaviour of the samples up to 76 days, with the subsequent exposure resulting in curves A_1B_1 / A_2B_2 .

6.2.2 Desorption

The curves below the X - axes of Figures 6.1, 6.2 and 6.3 represent the behaviour of CBPB on drying. Again the solid lines represent the data of the samples initially conditioned at 90 %RH and the dotted lines, initially conditioned at 65 %RH prior to moving to 35 %RH. The same trend of changes on desorption allows similar demarcation for the desorption curves as that of adsorption curves, but with only 36 days for the first stage. A significant mass decrease is shown between O to C_1 / C_2 . Beyond C_1 / C_2 , however, only a little change can be observed. Desorption resulted in a significant length change in the first instance (Figure 6.2) and showed a continually marginal contraction after C_1 / C_2 (in contrast with those in adsorption). The contraction in thickness was exhibited in a similar manner as the corresponding part of the curves describing length changes (Figure 6.3).

6.2.3 Long - Term Water Immersion

The behaviour of CBPB under long - term water soaking is presented in Figure 6.4. As for those on adsorption and desorption under RH exposure, a rapid increase in both mass and dimensions occurred at the beginning of immersion. Changes in dimensions significantly decreased after about two weeks exposure, and further soaking resulted in only a very slight increase. In contrast with this is the change in mass, which consistently increased over the whole period of immersion (400 days).

A similar demarcation of the rates of the change of CBPB under water immersion was observed.

6.2.4 Relationship between Dimensional and Mass Change

Once the dimensional and sorption changes with respect to exposure periods are established, the most useful relationships, in terms of interpreting data, is the mass change versus dimensional change or dimensional changes versus mass change (Figures 6.5 to 6.8, 6.4 C). Again O, A, B, C, D, S and W represent the corresponding points as those on Figures 6.1, 6.2, 6.3 or 6.4. Here in desorption, OCs

are drawn linear, after which the plots are linear but completely different relationships exist (Figures 6.7 and 6.8). The region CD, where mass change occurs somewhat slightly with exposure time, shows a very great contraction for unit mass change.

A linear relationship does not occur in adsorption and water immersion. A decrease of slope occurs in curves OA or OS with exposing period. Curves AB or SW exhibit more significant decreases in slope and tend to be linear. For explicitness, the relationships are plotted in the mass change against the dimensional changes for adsorption rather than dimensional change against mass change for desorption.

6.3 Discussion

The results of changes in mass or dimensions of the CBPB are obviously not of the type usually observed in wood or other particleboards, but rather consist of not only significant changes in the early stages but also substantial increases under adsorption or slight increase under desorption in mass (A_1B_1 / A_2B_2 in Figures 6.4, 6.2 or 6.3) and a consistent decrease in the dimensions under desorption (curves C_1D_1 / C_2D_2 in Figure 6.2 and 6.3) at the later stages of exposure. These results confirm that the physical properties of CBPB are closely related to the properties of both wood chips and cement paste. Overall, the dimensional change of CBPB was due primarily to the interaction between the movement of moisture into or out of both the wood chips and the cement paste and the solid skeletal structure of the material. Internal volumetric stress varied in sympathy with the changes in moisture state, consequently causing volume change. A significant movement of wood chips, resulting from the moisture change, could induce a simultaneous deformation in the CBPB.

As in concrete, the presence of the aggregate can modify the magnitude of the volumetric strains and even cause some small degree of cracking in the paste because of the local stresses induced by the aggregate restraint. However, unlike concrete, the cement paste shrank or swelled around the wood chips to a much higher degree so that compensating tensile / compressive (in the cement paste) and compressive/tensile (in the wood chips) stresses are generated. This results in the overall volumetric

strain of CBPB lying between that of the cement paste and the wood chips.

There might be two further processes causing a gradual increase in mass and decrease in length with time. The first is the possibility of condensation, whereby the number of "mini pores" which exist in the cement paste could fill with water due to the high surrounding RH; the second reason is the certain occurrence of carbonation which, as will be detailed in chapter 11, could contribute to an increase in the mass of the CBPB and a corresponding reduction in dimensions.

The obvious break in the adsorption curves occurs at the points A_1 / A_2 (see Figures 6.5 and 6.6), which correspond to an exposure period of 76 days. Before these points, there was not only considerable mass increase but also dimensional increases due to moisture adsorption; after these points, exposure of CBPB under 90 %RH mainly produced consistent change in mass but only very slight dimensional changes. The points A_1 / A_2 distinguish the mechanisms of moisture reaction from other mechanisms. When dried CBPB are exposed to high RH, and like other porous materials, they absorb moisture from the surrounding air, causing mass and volumetric increase. After a certain period (76 days), an equilibrium is obtained, when further exposure should not bring about any effect in view of the mechanism of moisture reaction. However, the cement paste in CBPB, being composed of a number of "mini spaces", characterises another nature of CBPB, that is providing the potential for moisture condensation under high RH (90 %RH).

It may be concluded that under 90 %RH adsorption, the behaviour of CBPB is closely related to the surrounding moisture. The moisture adsorption mechanism for both wood and cement paste is dominant in the first stage (about 76 days), and moisture condensation in cement paste dominates the behaviour of CBPB on further exposure. It should be noted that this distinction between capillary water and gel water located in CBPB is arbitrary since the mechanism of adsorption may be the same. However the concept is helpful for the interpretation of the behaviour of materials.

Carbonation of cement paste may supplement the behaviour of CBPB, especially at the second stage of a longer term exposure. However, as discovered for other cementitious materials the degree of carbonation of cement paste under high RH is very low and the dimensional change arising from this cause could always be

neglected. The case in the behaviour of CBPB will be confirmed in chapter 11.

Comparisons of Figure 6.5 A with 6.5 B or Figure 6.6 A with 6.6 B show that mass and dimensional changes at the "inflection points" are dependent on the original moisture content of CBPB. Under adsorption, the higher the initial moisture content, the lower the mass or dimensional change. However, it is apparent that the time for CBPB to reach the equilibrium is independent of the initial moisture content but dependent on the RH (final moisture content). In the case studied, as mentioned above, the duration for the CBPBs (both from 35 and 65 to 90 %RH) is about 76 days and the duration for desorption (moving CBPBs from 90 or 65 to 35 %RH) is about 36 days.

A scrutiny of the rate of change between the mass and dimensions indicates that dimensional changes are more dependent on the initial moisture than mass change under adsorption. At the "inflection point", the change in length and thickness of CBPB (initially conditioned at 35 %RH) is about 2.13 and 1.80 times those of CBPB (when initially conditioned at 65 %RH) respectively, but only 1.41 times for mass.

The corresponding "inflection points" for the desorption curves are C_1 / C_2 . The time required to approach these points is much shorter, about 36 days, than that required for adsorption. There is a very significant decrease in both mass and dimensions during this period of exposure. After this the dimensional changes decline considerably, and there is a slight increase in the mass.

Unlike for adsorption, under desorption the higher the initial moisture content, the higher the mass and dimensional decreases; the mass change is more dependent of the initial moisture content than dimensional change. At the "inflection point", the change in length and thickness of CBPB (initially conditioned at 90 %RH) is about 1.67 and 1.81 times those of CBPB (initially conditioned at 65 %RH) respectively, but with 1.91 times for mass change.

Combining the mechanisms of wood - water with cement - water relationships, the curves OC_1 / OC_2 could be attributable to both moisture desorption and carbonation of cement paste, with the moisture reaction being thought to be the dominant factor. Curves C_1D_1 / C_2D_2 are most likely to be attributable to the carbonation of cement paste.

The plots of the relationship between dimensional and mass changes are more

explicit. Figures 6.5 and 6.6 confirm that the mass increase under adsorption is independent of the dimensional changes while the dimensional changes seem to be independent of both the mass increase and exposure duration after about 76 days. Nonlinear relationships for adsorption show that more than one mechanism is affecting the behaviour of CBPB in this case.

Figures 6.7 and 6.8 clearly represent the relationship between dimensional and mass changes due to the moisture reaction or other mechanisms. The linear relationship in the first stage could be produced by the behaviour of cement paste and wood chips using the rule of mixtures, which will be discussed in part 3. No condensation occurred in this case after the reaction between CBPB and water had terminated. Slight increases in mass and decreases in dimensions are thought to be due to the carbonation or degradation of wood chip.

A slightly different reaction existed between long - term liquid and vapour water exposure. When CBPB was immersed in water, water was firstly adsorbed in gel pores and cell walls, resulting in commensurate volumetric increases, which had happened in the first two weeks for the CBPBs tested (see Figure 6.4). Prolonged exposure allowed capillary water to fill some of the capillary pores and lumen, causing an increase in dimension. This process extended until point S. Beyond this, the water was located in lumen and larger capillary pores which are beyond the effect of capillary tension. Therefore, the mass gradually increases but with no dimensional change.

Under water immersion, carbonation was not a case in CBPB. However, prolonged immersion would induce tensile stresses in inter - solid bonds, which may disrupt some of the weaker links and permit further expansion.

The trends of changes in both mass and dimension of CBPB versus time for both water immersion and 90 %RH adsorption were very similar, but the amount of the changes, especially those of mass, were significantly different, about 5, 2 and 1.2 times higher in mass, thickness and length change for CBPB under water soaking than on adsorption at 90 %RH. This result manifests itself in the different reaction between porous materials with liquid water and with vapour moisture.

6.4 Interim Conclusions 3

- 1) Under the single changes of RH tested, the changes in mass or dimensions of CBPB with exposure times consisted of two distinct stages - significant changes at an early stage and consistent changes at the later stage of exposure, showing the close relationship between the properties of CBPB and its components.
- 2) The duration required to approaching the "inflection points" for both mass and dimensional changes of CBPB was independent of the initial moisture content, but was dependent on the final moisture content (exposing RH) and sorption history. This duration for desorption was about 36 days and for adsorption was about 76 days.
- 3) General moisture reactions dominated the behaviour of CBPB in the first stage of exposure (under both adsorption and desorption), exhibiting significant changes in both dimension and mass of CBPB.
- 4) Carbonation or condensation on the cement paste in the CBPB were thought to be the cause of the behaviour of CBPB in the second stage of exposure, producing a substantial increase in the mass of CBPB on adsorption at 90 %RH and a slight increase in mass, but decrease in dimensions of CBPB on desorption at 35 %RH.
- 5) The amounts of mass and dimensional changes at the "inflection point" (equilibrium) depended on the initial moisture content.
- 6) The dimensional change was more dependent on the initial moisture content than mass change under adsorption, but was less dependent under desorption.
- 7) After the "inflection points", the mass increase under adsorption was independent of the dimensional change of CBPB.
- 8) The trend of changes in both the dimensions and the mass of CBPB was similar for both liquid water immersion and 90 %RH adsorption, but significantly different

in the amounts of mass change, the former was about 5, 2 and 1.2 times the latter for mass, thickness and length changes respectively. The different reaction of CBPB with liquid water and vapour moisture was very clear.

9) The "inflection point" in the plots of the relationship between the mass and dimensional changes of CBPB under sorption clearly distinguished the general moisture reaction from other mechanisms. Under desorption, the relationship between the mass and dimensional change of CBPB followed the general (linear) relationship, however, this is only the case before equilibrium. After this, an abrupt change in the relationship occurs, suggesting that the influence of carbon dioxide was dominant. Under adsorption, mass increases were supplemented by the condensation of moisture, the relationship between the mass and dimensional increase did generally not follow the linear rule.

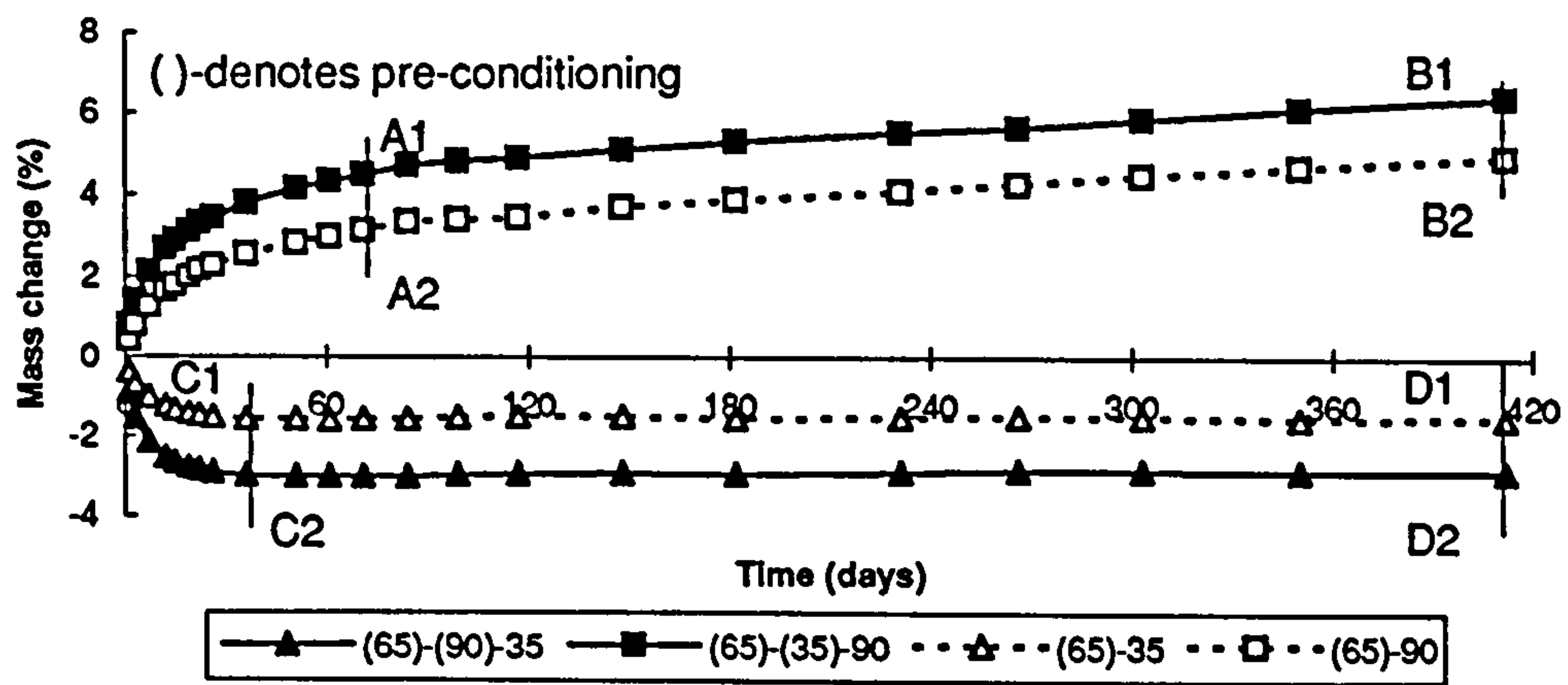


Figure 6.1 Mean mass change of CBPB under a single change in RH

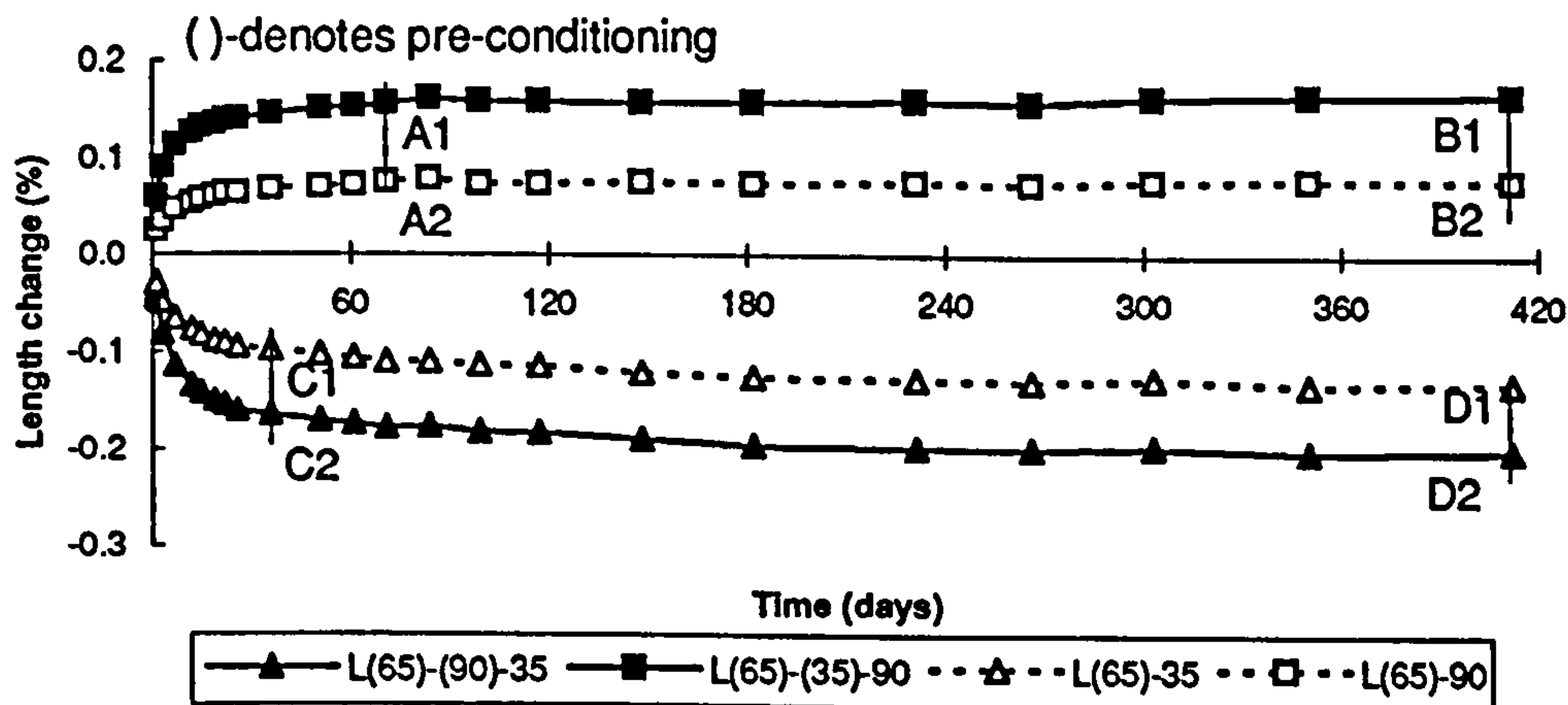


Figure 6.2 Mean length change of CBPB under a single change in RH

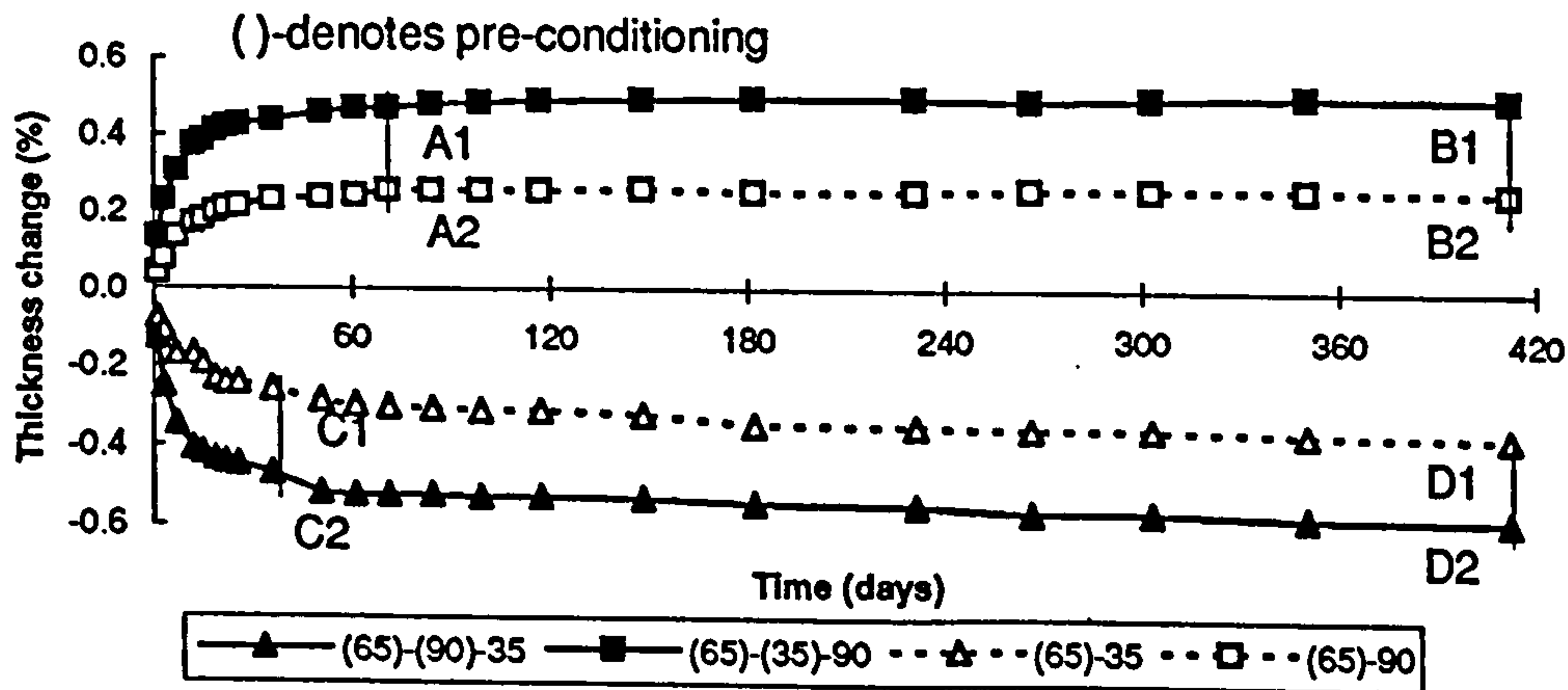


Figure 6.3 Mean thickness change of CBPB under a single change in RH

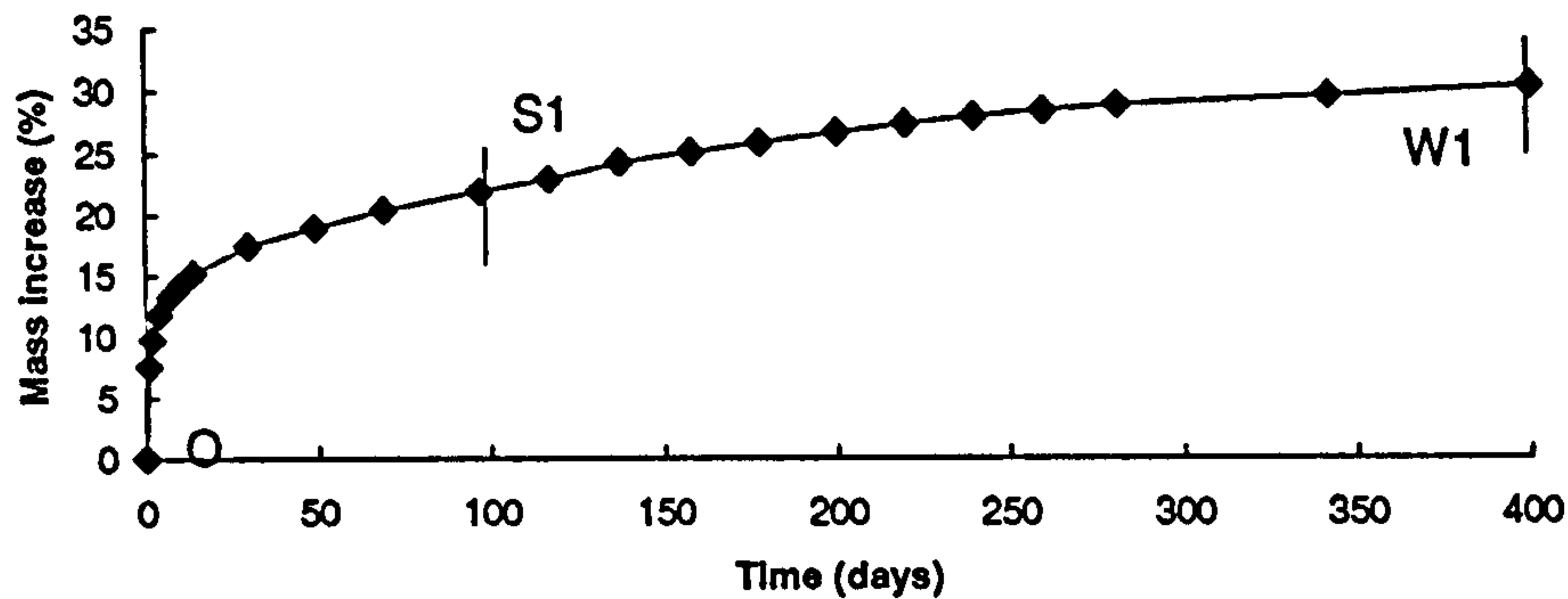


Figure 6.4A Mass change of CBPB under long - term immersion in water (20 °C)

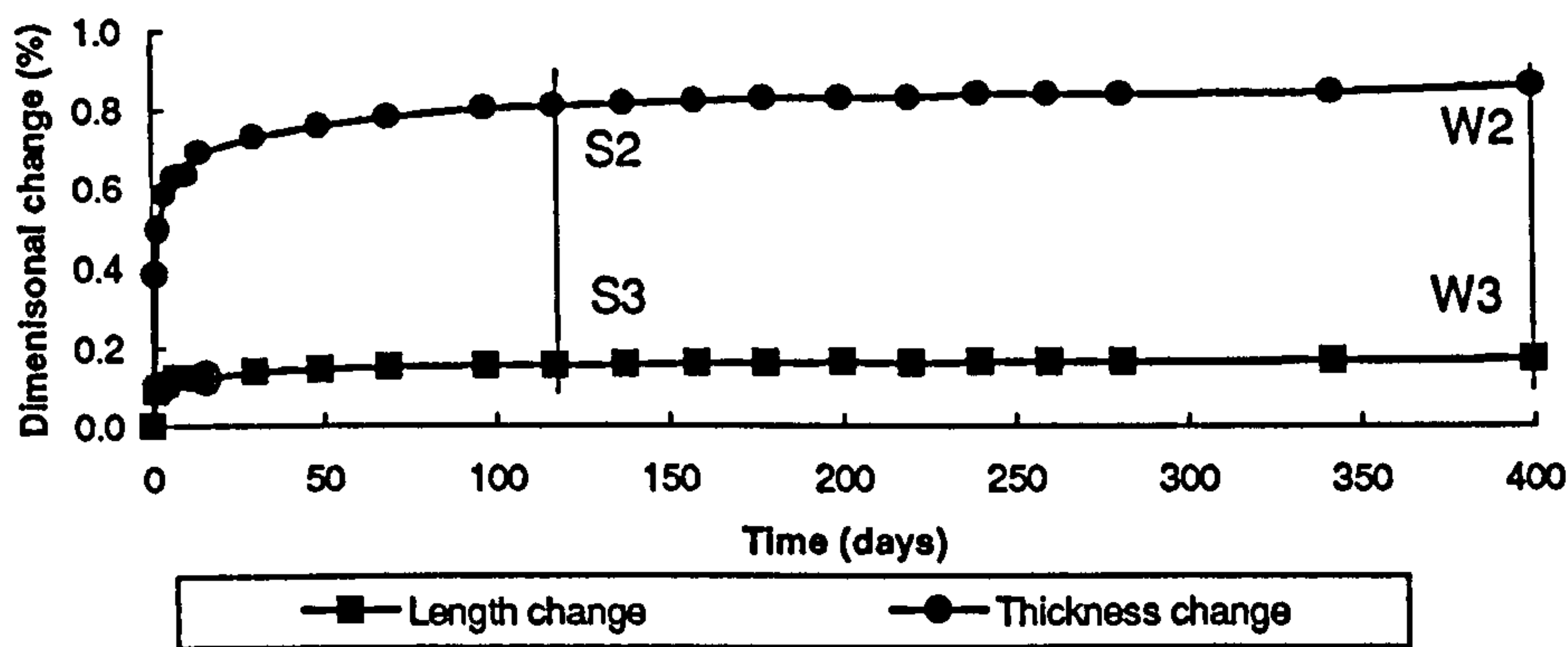


Figure 6.4B Dimensional change of CBPB under long - term immersion in water (20 °C)

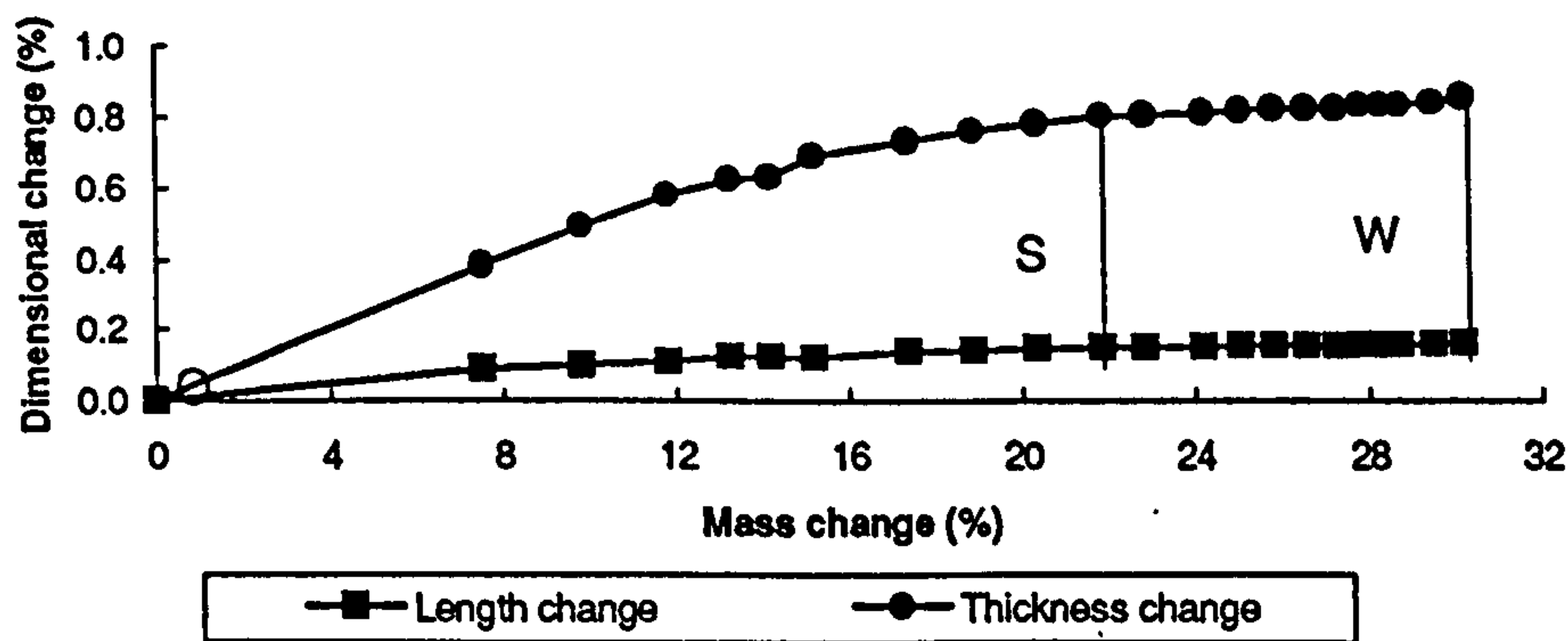
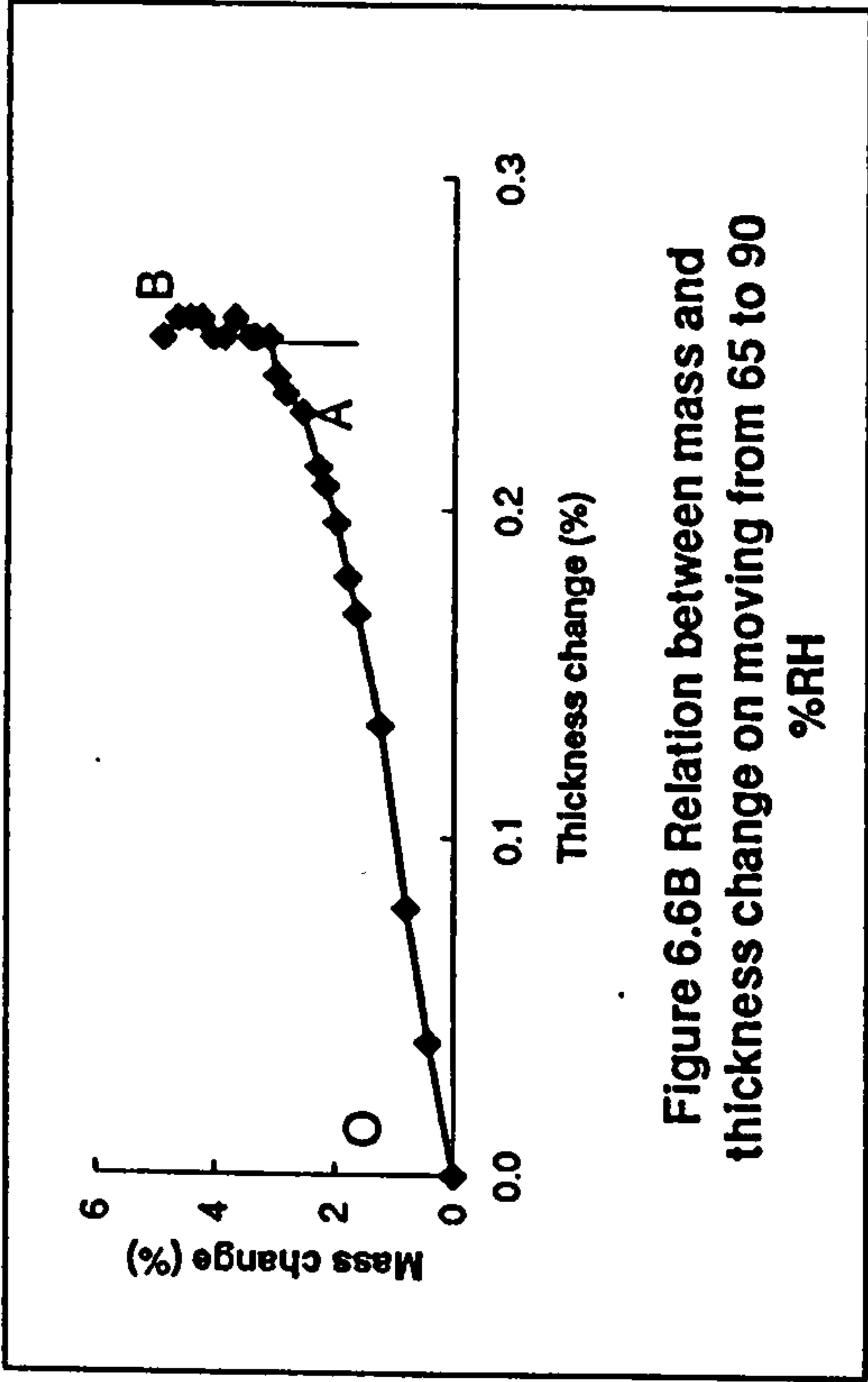
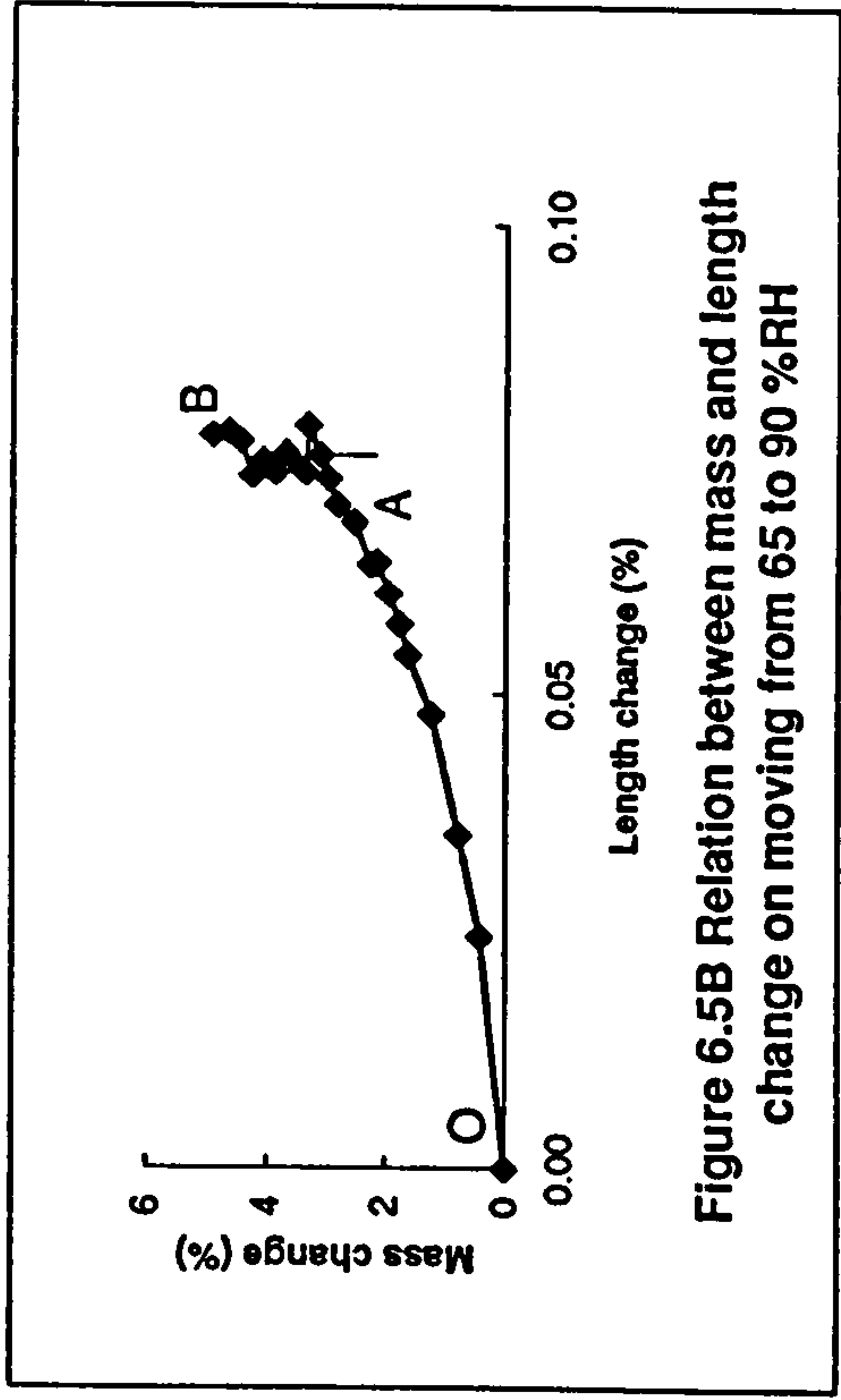
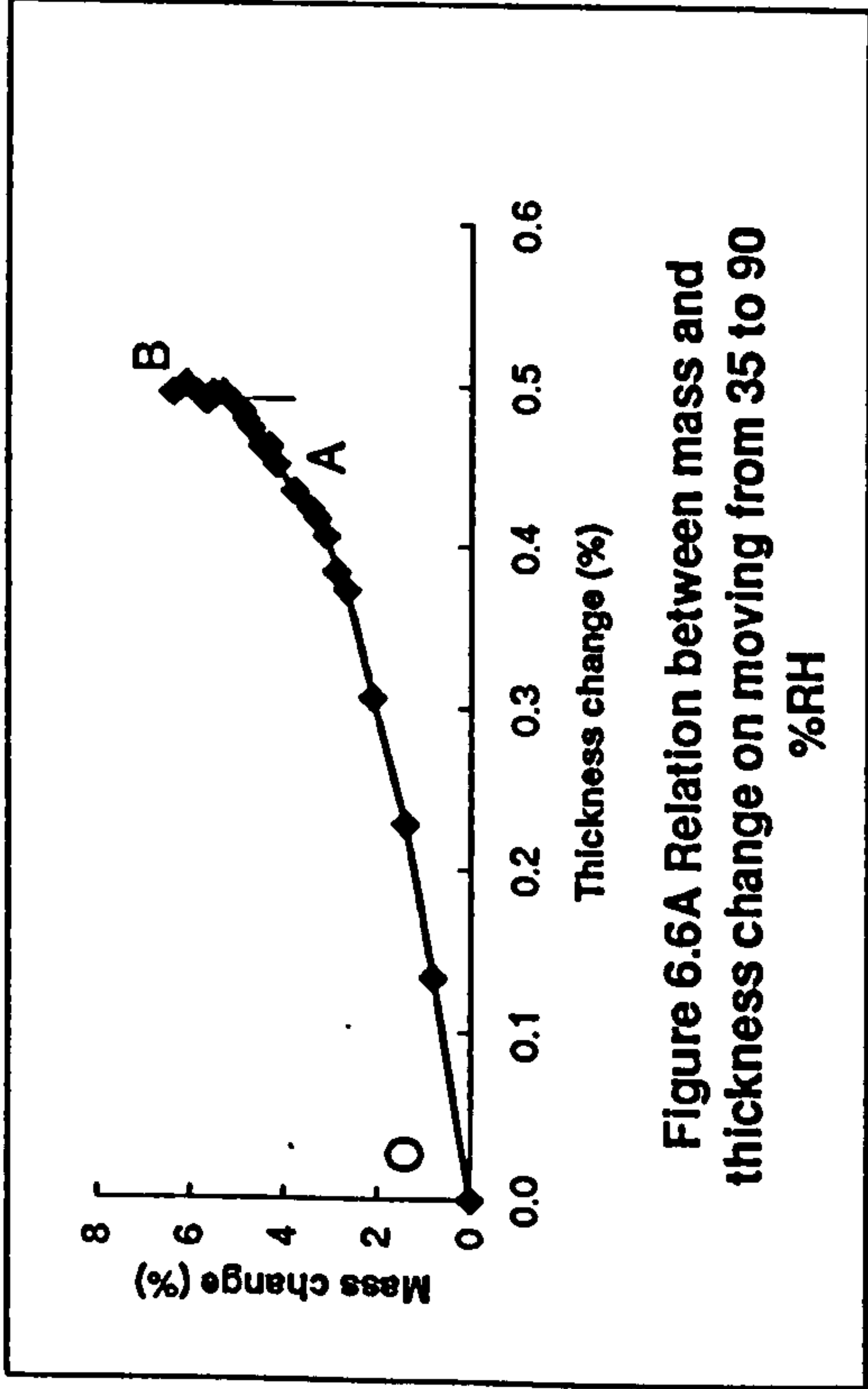
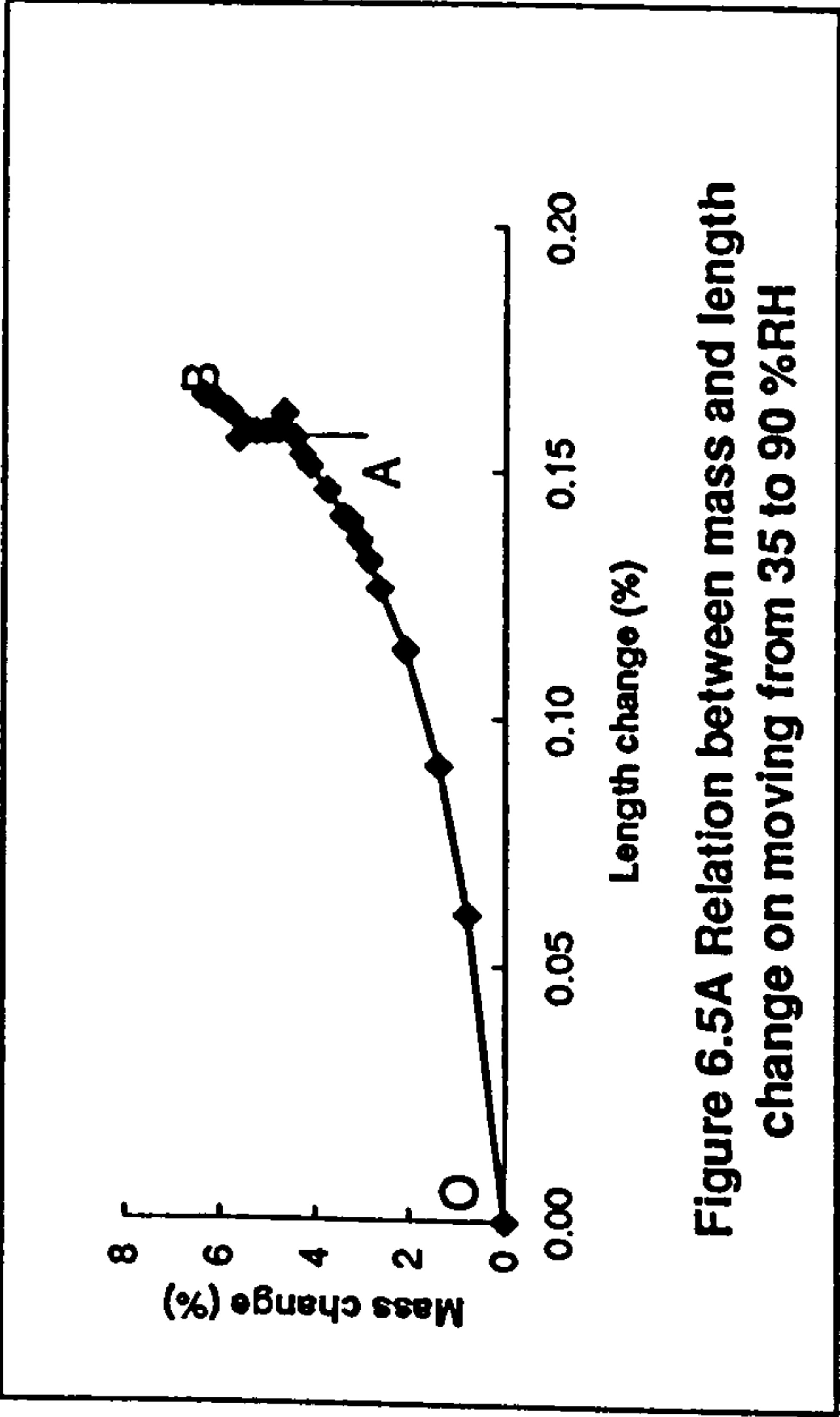
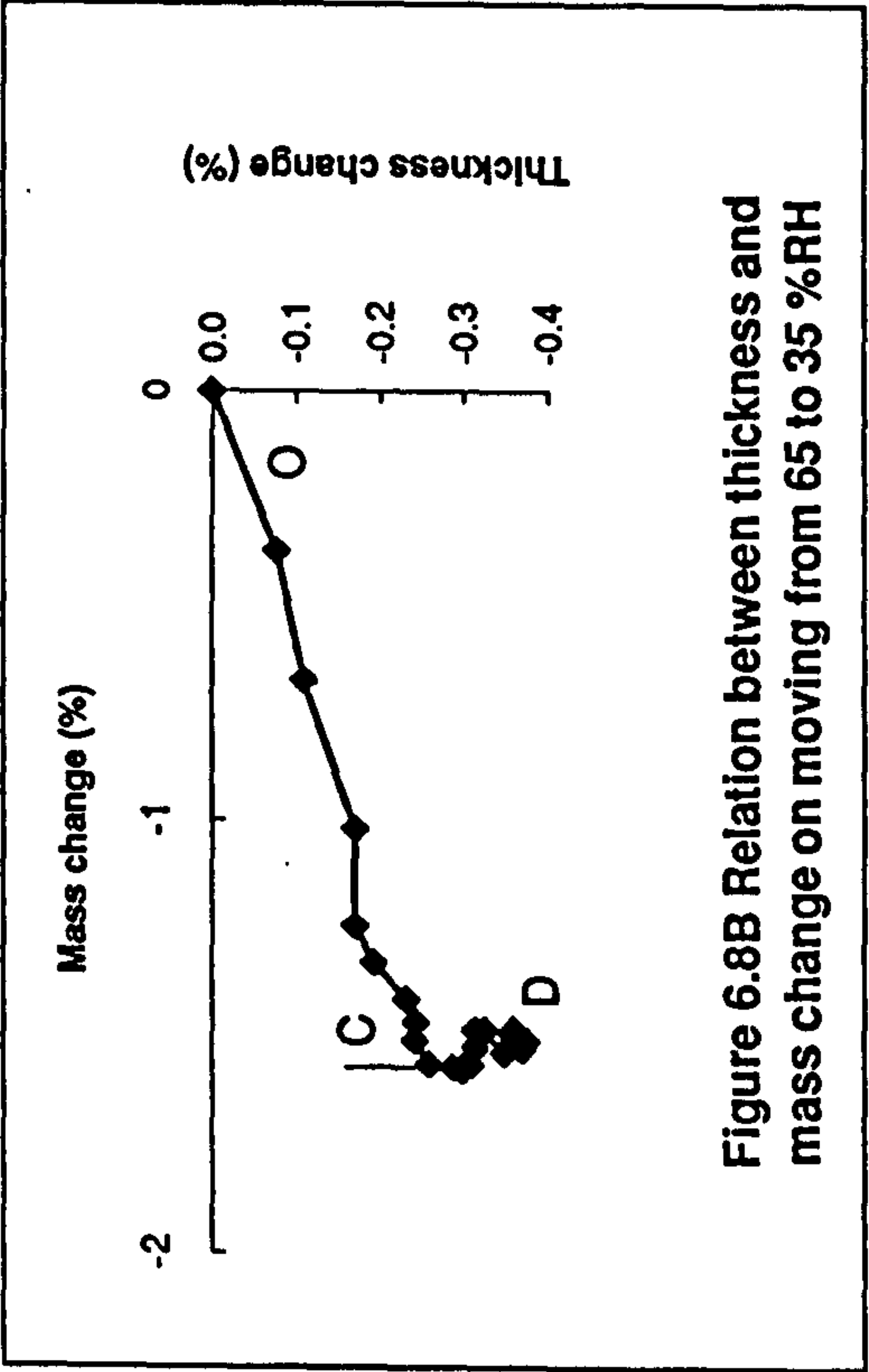
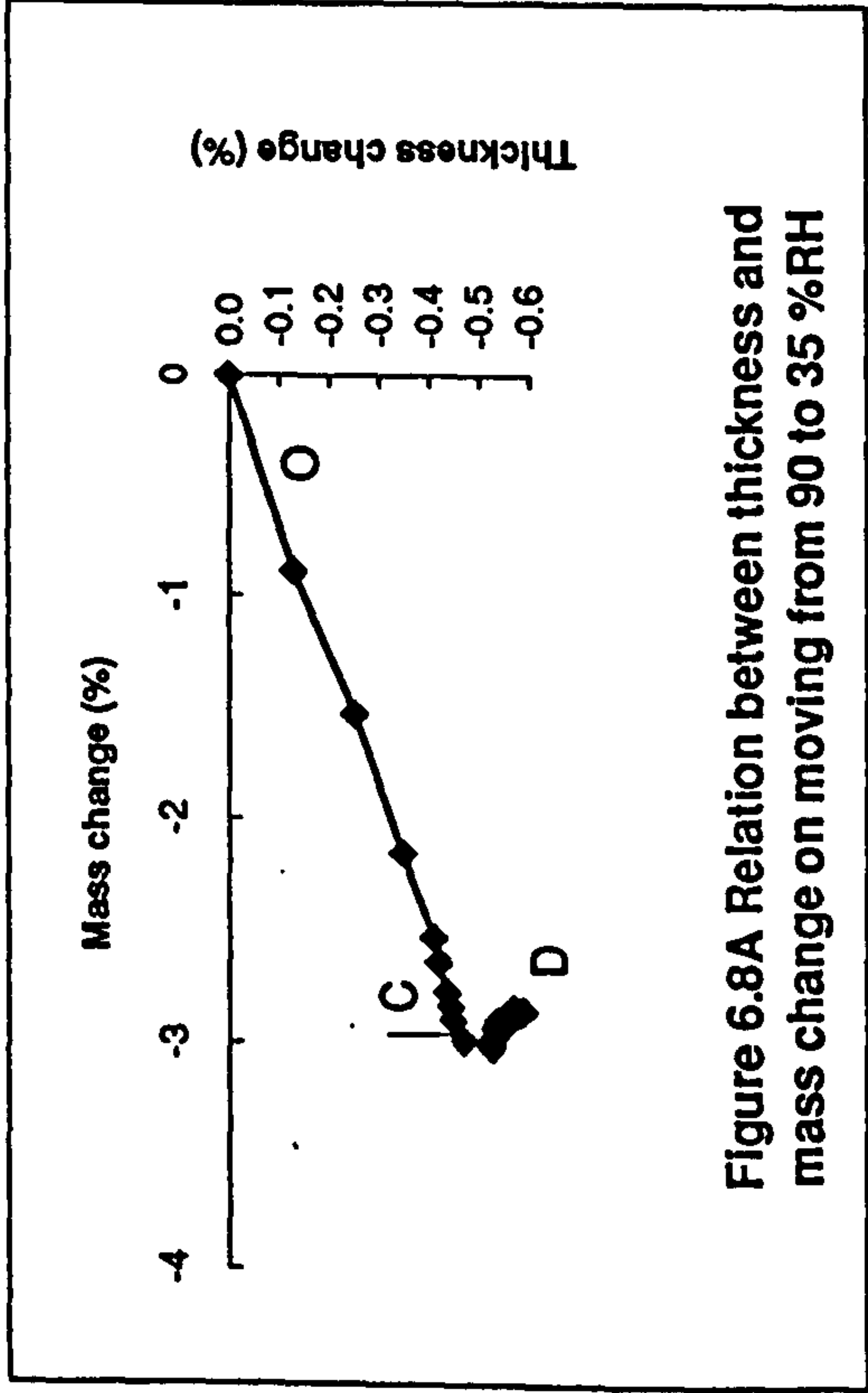
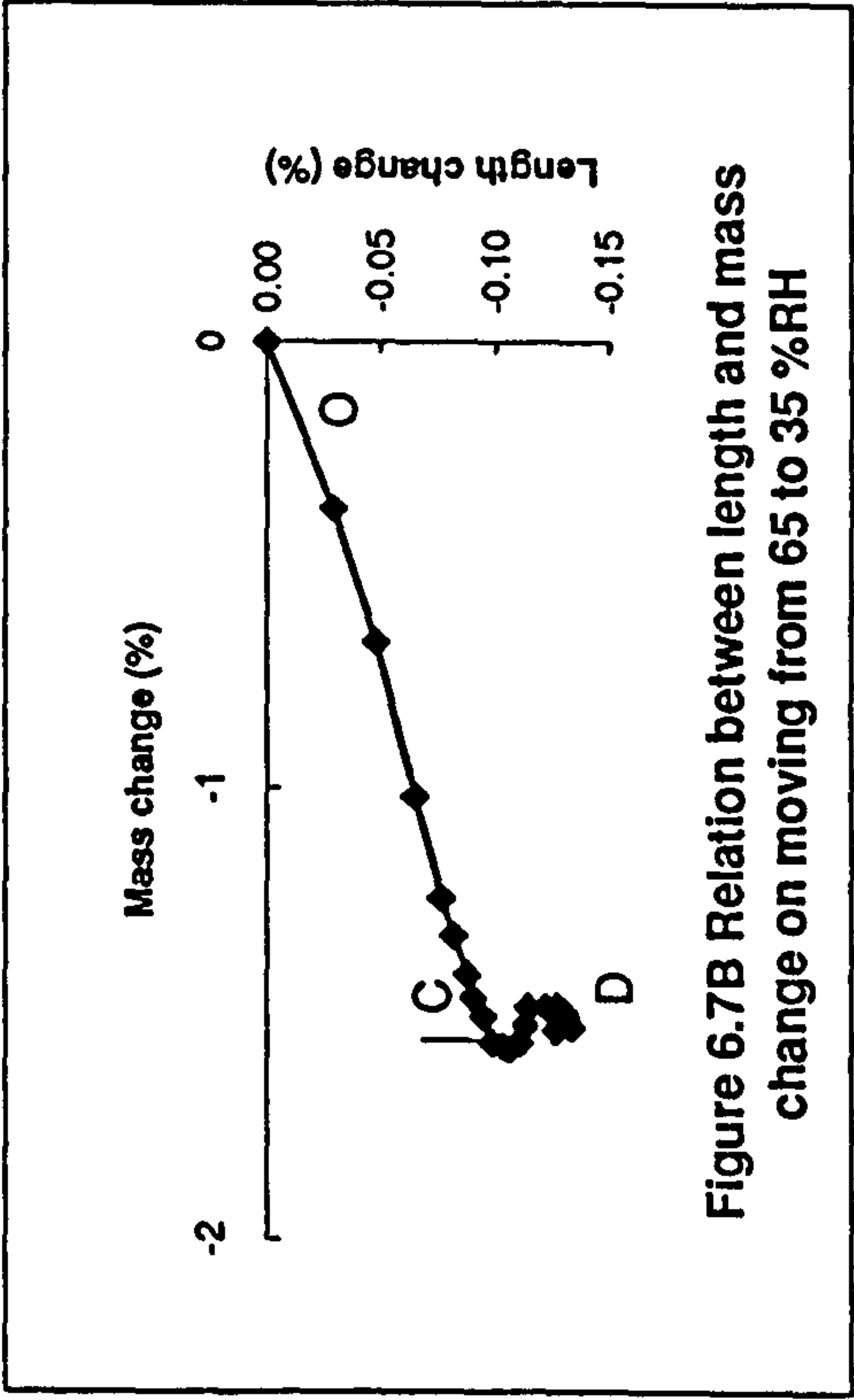
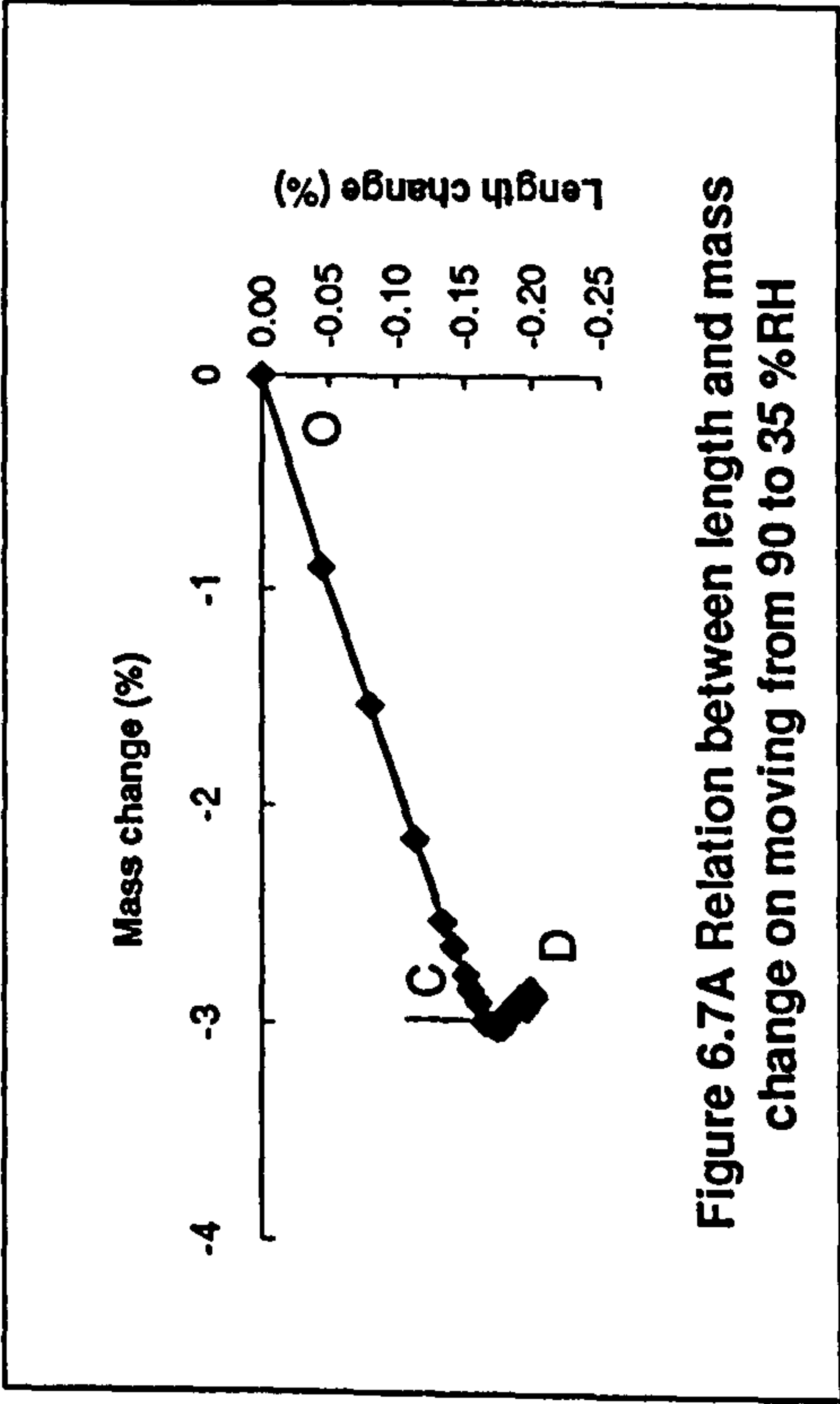


Figure 6.4C Relationship between dimensional and mass change of CBPB under long - term immersion in water (20 °C)





Chapter 7

BEHAVIOUR OF CBPB UNDER CYCLIC RH CONDITIONS

7.1 Introduction

Various applications of CBPB in industry and for home building expose the material to a range of different environments. CBPBs are affected by a repeated / cyclic thermal or moisture changes.

It is well known that when porous materials are exposed to a moist environment, dried materials will absorb moisture from, and wet materials will loose moisture to the surrounding air. A result can be volumetric change, i.e. shrinkage or swelling depending on losing or gaining moisture. However, studies on cement paste (Czernin, et al., 1980; Soroka, 1979; Swenson, 1968; 1967; Bazant, et al., 1991; Saetta, et al., 1993) observed that in addition to reversible shrinkage, hardened cement paste underwent carbonation and dehydration in an aging process that resulted in decreases in dimensions, i.e. irreversibility, and that the rate and degree of carbonation and carbonation induced shrinkage were related to the RH (moisture content) in the material. Moreover, shrinkage strains are incompatible with each other, and therefore residual stresses, called shrinkage stresses, develop, producing significant creep.

While determining dimensional change isotherms for wood, Kollman and Côté (1968) noted that there existed a well-defined inter-relationship between volumetric swelling and alkaline solution equilibrium pH. A result of cell wall hydrolysis and subsequent dissolution of the products resulted on drying in dimensional loss in both radial and tangential directions. In CBPB sufficiently alkaline conditions remained within the cell wall to induce additional alkali hydrolysis, causing further dimensional change with increased cycles (Steward, 1986). Restrained shrinkage was also reported by some authors (Kollman and Côté, 1968).

CBPB products in practical use are in general subjected to different ranges of RH from time to time. Being a hygroscopic material, it gains or loses moisture with the

frequently fluctuating atmospheric RH. It should exhibit different isotherms between the different ranges of RH. Studies on wood have shown that the 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. Intermediate sorption curves of hygroscopic materials are found to be formed 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 (Figure 2.9).

The purpose of this chapter is to examine the response of CBPB to cyclic RHs and the behaviour 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.

7.2 The Different Reactions of Mass and Dimensions to an Initial RH Change

The average values of mass and length change resulting from an initial exposure of CBPB to 90 %RH and subsequent increasing - and - decreasing cycles are presented in Figure 7.1. It may be seen that there was a pronounced influence of relative humidity on mass and dimensional change. The curves in the first part of Figure 7.1 indicate that the initial increase in length was extremely rapid. When comparing the change after 2 days with that after 42 days, when equilibrium was obtained in terms of the constant dimension, 78 % of the maximum length increase was made in the first two days, while only 34 % of the ultimate mass change occurred. The reasons for this can be interpreted from the behaviour of chips and cement paste (chapters 9 and 10). When looking at the second exposure to 90 %RH, 56 % of the total increase of length in this period occurred in the first two days, while only 39 % mass change occurred.

The first change in moisture content brought about large increases in both mass and length. For the same exposure period at 90%RH, the mass and length increased by 3.72% and 0.133% over the conditioned dimensions. For the second exposure the

values were 1.95% and 0.041% respectively. Most of this difference could be attributable to the physical and chemical process in cement paste. The movement of water on the first drying (or wetting) probably opened up interconnections between the capillary pores and the resulting changes in geometry were likely to reduce the area on which capillary tension can act during subsequent RH cycles; some new interparticle bonds were probably formed, providing some degree of irreversible consolidation of the surface, and the surface area of the solid particles were permanently reduced. The process of consolidation can also draw the original interlayer much closer together, and the formation of new bonds in the collapsed layers, or slippage between the layers, formed a consolidated and more stable structure (Illston, et al., 1979). In the presence of water, further hydration of cement paste could also have contributed this difference (Soroka, 1979; Powers and Brownyard, 1948; Powers, et al., 1959). For the whole panel, stress release cannot be excluded.

The trend of thickness change was similar to that of length, but the rates of change are very different, the former having double the amount of change.

7.3 The Behaviour in Mass and Dimensions within One Complete Cycle

Figures 7.1, 7.2 and Table 7.1 also show the different responses of mass and dimensions to fluctuations in RH. It may be seen that both mass and dimensions reflect changing RH.

In one complete cycle, there existed an obvious difference in mass and dimensional change at those parts of the cycle embracing high and low RH. When the first complete cycle was considered, the RH change from 90 % to 65 % resulted in only a small change in the mass, whilst changing from 65 %RH to 90 %RH caused an appreciable increase in mass under adsorption. By contrast, nearly complete recovery was found in length change on transferring CBPBs between 65 %RH and 90 %RH (whether adsorption or desorption), as also was found for both mass and length changes during RH changes from 65 %RH to 35 %RH and from 35 %RH to 65 %RH. 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 in CBPB. Capillary condensation above 80 %RH apparently was responsible for the dramatic increase in mass. Calculations from Feldman (1964) and Power's data (1948) have shown that the mass change of cement paste on adsorption between 35 %RH and 65 %RH was about 1.7 times lower than between 65 %RH and 90%RH, whilst 1.2 times higher for desorption. Double the rate of dimensional change on adsorption can also be found during lower RH exposure, and similar behaviour covered the whole RH range (35 % - 90 %) for desorption. Apparently the 65 %RH wood content (volume) also contributed to the different dimensional changes between lower and higher RH regions.

Much greater length movement occurred below 65%RH than above this RH. This coincided with the phenomenon of carbonation shrinkage 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 to be a consequence of cycles of induced drying shrinkage.

7.4 Differences in Thickness and Length Changes under One Complete Cycle

In addition to the considerably different behaviour in mass and length discussed above another significant characteristic of CBPB is the different behaviour between length and thickness. Figures 7.2 and Table 7.1 indicate the relative changes in length and thickness, especially at low RH, for CBPB in one complete cycle of RH changes.

It is well known that the degree of swelling or shrinkage is very different in the three principle axes owing to the complex structure of the wood; the longitudinal movement of wood is considerably smaller than transverse movement (less than 1/10), and the radial movement is usually about half the tangential movement over a given moisture range. This could be responsible for much of the recorded difference in length and thickness behaviour of CBPB, especially so in view of the isotropic nature of the cement paste. In Figure 7.2 the trend of thickness and length change is similar for both adsorption and desorption, but with significantly different

rates (change in length or thickness per percentage change in RH). Thus, $\Delta L/\Delta T$ is 1.0 : 3.1 for desorption and 1.0 : 2.9 for adsorption during the change from 65 %RH and 90 %RH cycle, and 1.0 : 2.0 and 1.0 : 1.9 during RH change from 35 % to 65 %. 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 due probably to the dominance of the considerably higher transverse movement of wood chips. The main questions are 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), and how much constraint occurred due to the cement paste? This will be studied in part 3.

7.5 Behaviour of Mass and Length in Successive Cycles

Most interesting results were obtained from a set of cycles. With the increase of the number of cycles, there was a consistent increase in mass and decrease in dimensions. This is shown in Figures 7.3 and 7.4 in which the values are expressed in terms of the original values at 90 %RH. Mass increase and dimension decreases can be anticipated. Total recovery cannot take place during cyclic RH change. The rate of change was very high at first, but damped down with time.

It is apparent that both reversible and irreversible deformations occurred in the CBPBs 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 were related to:

- 1) the carbonation of cement paste in CBPB. Carbonation, which will be discussed in chapter 11, not only increased the mass of the cement paste but also was accompanied by an irreversible carbonation shrinkage;

- 2) the stress and restraint on the wood chips. There are, at least, two types of stress - strain thought to be the case in CBPB subjected to cyclic RH, one of which results from moisture gradients (section 2.3.3.4). During the initial stages of normal drying (or wetting) some hygroscopic shrinkage (or swelling) of surface regions takes place first and this is resisted by the wet (or dry) core. As a consequence, the outer

and inner layers build up stress - restraint, causing delayed shrinkage or swelling. Another stress - restraint arises from the different properties of cement paste and wood chips. When wood chips and cement paste adsorb or desorb moisture under cyclic RH, the amount of shrinkage or swelling per unit volume is different in terms of different mechanical and physical properties, so establishing a stress - restraint situation. As mentioned in section 2.3.3.4, 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 shrinkage. The effect of mechanical stress on shrinkage 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;

3) alkali degradation of wood chips. The degradation of wood chips under alkalinity condition could result in mass loss, and consequently volumetric decrease (as discussed in the chapter 5).

The thickness change arising from a set of cycles followed the trend of length change of CBPB. However, the amount of the changes at various stages of RHs was different. This difference is thought to be related to the structure of CBPB (as discussed in the chapter 5). Additionally the moisture gradients due to the cyclic RH changes may bring about an adverse effect on the different change between thickness and length (width).

7.6 Relationship between the Mass and Dimensional Changes over One Complete Cycle

From the last section, it is apparent that the trend of mass and dimensional changes in the corresponding stage within each complete cycle was very similar. This suggests that the relationship between the mass and dimensional change of CBPB for all cycles should be in the same order. Therefore concentration was put on one complete cycle to evaluate whether the relationship is changed by the immediate step of exposure or the dimensional change is simply related to the mass change.

The dimensional changes / mass changes of CBPB in the first complete cycle are

plotted in Figures 7.5 and 7.6. Where the dots are densely accumulated is the final stage of the exposure, and those located around the middle correspond to the RH of 65 %. 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 (Figure 6.5 to 6.8): that is, under desorption, the relationship appears to be linear, under 65 %RH adsorption, the generally linear relationship is still reflected, but under adsorption at 90 %RH, there appears to be a decline in the slope of the plots due to moisture condensation. The scatter at the final stage of exposure is due to an excessive exposure which leads to carbonation or condensation processes.

The results imply that the dimensional change (length or thickness change) is only related to the mass change of CBPB. The relationship between the dimensional and mass change is independent of the immediate change in RH.

7.7 Sorption and Dimensional Change Isotherms (Hysteresis Loops)

Results

For CBPB the hysteresis loops as a function of RH are shown in Figures 7.7, 7.8 and 7.9 for a series of 10 cycles. It should be noted that, for each complete cycle, the higher curve was obtained by exposing the CBPB to successively lower RHs and permitting sufficient time for mass equilibrium to be reached (dimensions were constant). The lower curve was the adsorption line obtained when the sample regained moisture at the same RH to which it was exposed during desorption. The successive loops were obtained upon subsequent sorption after the sample had been allowed to come to equilibrium. For dimensions the "top" loops, in Figure 7.8 and 7.9, are the first loop; for mass the "bottom" loop (in Figure 7.7) is the first loop.

As was the case for the long term exposure of CBPB at 90 %RH, 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 other wood based materials: the maximum width of the hysteresis loop may not be found in the immediate stage but could be located anywhere depending on the changing range of RH. Table 7.2 presents the width of the hysteresis loop at 65 %RH (the

difference between the desorption and adsorption) for mass, length and thickness, whilst Table 7.3 shows the width at 90 %RH.

The history of change in both mass and dimensions has been re - plotted as the change percentage to the exposure duration instead of the RH assuming that each complete cycle is separated. These are included as Figures 7.10, 7.11 and 7.12 for mass, length and thickness respectively. In these Figures, the lowest curve is the first cycle and the highest one is the 10th cycle for mass change; for dimension plots (both length and thickness), the highest is the first cycle and the lowest is the 10th cycle.

The history of CBPB is re - plotted as the change in dimensions to the change in mass (see Figures 7.13 and 7.14).

Discussion

The hysteresis loop of mass change for the successive 10 cycles, in Figure 7.7 shows that a gradual mass decrease on desorption reflects as nearly a straight line, whilst the mass change on adsorption is closely associated with the level of RH, the adsorption curve was convex to RH axis. The regain in mass under lower RH was less significant and the regain under higher RH was 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 %. This indicates that the history of sorption of wood or other wood based materials is valid for CBPB only under desorption and adsorption at lower RHs, The critical point, dividing the lower and higher RH, relates to the upper level of pressure at which condensation can occur. Above this critical point, the CBPB produces a unique isotherm curve which is dominated by not only the reaction with water but also the condensation of moisture onto the CBPB. The ordinary laws of moisture reaction cannot be applied at this stage. This also reinforces the results on the long term performance (see Figures 6.5 and 6.6).

Besides the effects common to many materials, CBPB exhibits certain irreversible phenomena not found among some other types of materials. This is also shown in Figure 7.7, where the second or successive desorption and adsorption

curves for the sample are given.

Comparison of the first with the second hysteresis curves shows a marked difference between them. No explanation for this feature could be found from the viewpoint of wood unless the wood chips are produced from dried green wood which gives the highest EMC at a given RH (Skaar, 1972). However, the significant deviation between the successive cycles, especially between the first and second cycles, is believed to be due to two factors in view of the nature of cement paste, one of which is thought to be irreversible shrinkage of cement paste reducing the capacity of the sample for evaporable water. The irreversible shrinkage of CBPB manifests itself as discussed above. The other reason is thought to be the additional hydration of the cement paste which occurs while the sample is subjected to vapour pressures above about 80 %RH (Powers and Brownnyard, 1948).

As shown in Figure 7.7, after the first cycle, the curves produced by the successive cycles are practically similar. 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. In Table 7.2 it appears that the width of loop at 65 %RH decreases as the number of cycle increases (excepting that of the first cycle). However, the same width of the hysteresis loop is observed between the 9th and 10th cycle. The difference of change between adsorption and desorption at 90 %RH is presented in Table 7.3. Like the width of loop at 65 %RH, the difference between the successive cycles is reduced with the increase in the number of cycles. However in contrast the values arising from adsorption are higher than those derived from desorption. This suggests that the CBPB becomes "stabilized" after long term exposure: cyclic changes in moisture may result in a change in the structure of CBPB.

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. However, this was diminished with cycles: in Figures 7.7 and 7.10, the difference in the mass increase between first and second exposure is 1.12 % but only 0.09 % for the difference between 9th and 10th exposures. Without doubt it can be suggested that

the successive hysteresis loops of CBPB would coincide after a certain number of cycles.

Note that the continued hydration only has the effect of increasing the minimum weight of cement paste - moving upward of the successive loops could only, and very likely, be explained as the carbonation of cement paste in the CBPB due to atmospheric exposure.

Along with the measurements in the mass change described above, measurements were made on the dimensions (see Figures 7.8, 7.9, 7.11 and 7.12). The features pointed out in Figures 7.7 and 7.10 cannot be seen here. The dimensional changes produced curves concave to RH axis for both adsorption and desorption, with the more significant being observed in the length change (Figure 7.8). The adsorption curve is not intersected by the desorption curve. However, the values arising from desorption are higher than those arising from adsorption (Table 7.2). In contrast to mass change, as the number of cycles increased, the hysteresis loops moved lower and lower and the length gradually decreased. There were decreases of 0.038% and 0.053% after the fifth and tenth treatment at 90%RH. The degree of moving of each loop was reduced with increase in the number of cycles, Table 7.3.

The results above showed that the sorption induced dimensional changes were basically similar to those of cement paste: a more significant change in dimensions occurred in the low RH region of the isotherm. A decrease, instead of increase (as for that of mass) in slope occurred at higher RHs. These 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 indicated that volume change in CBPB was not solely due to movement of water in or out of the system.

It should be noted that the features for the thickness are the same as those for the length though with a significant difference in quantity (see Figure 7.9 and 7.10, and Table 7.2 and 7.3).

The history in the change of CBPB plotted as the mass change ($\Delta M / M$) versus length change ($\Delta L / L$) and the mass change versus thickness change ($\Delta T / T$) for ten cycles is shown in Figures 7.13 and 7.14. The loops for both $\Delta L / L$ to $\Delta M / M$ and

$\Delta T / T$ to $\Delta M / M$ are very close. The curves for desorption appear somewhat to be straight, and to be parallel between each loop. This indicates that the relationship between the length or thickness change and mass change is very similar under desorption and is independent of the immediate RH. However, unlike the other plots aforementioned, the width of the loop is getting wider with the number of cycles. The adsorption part of the loop was complicated by the discontinuity at a certain point when condensation of moisture onto the CBPB is dominant, producing a different relationship between mass and dimensional changes. The decrease in the slope of the length or thickness change versus mass change plot reduces with cycles. The location of the intersection between adsorption and desorption curves changed and was approaching the ultimate point as the number of cycles increased. This point could be considered as the critical point which most likely divided the history in the change of CBPB as 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).

7.8 Effect of Different Cyclic RH Regimes on the Behaviour of CBPB

7.8.1 Effect on Mass and Dimensional Changes

Results

The mean mass, length and thickness changes of CBPB on cycling between different ranges of RH are shown in Figures 7.15, 7.16 and 7.17 respectively.

The effect of the number of cycles on the mass and dimensional changes of CBPB under adsorption and desorption are summarized in Table 7.4. The deviation between cycle 35 - 90 %RH (regime I) and cycle 35 - 65 - 90 %RH (regime II) are also included in this Table.

Discussion

In Figures 7.15, 7.16 and 7.17, it is apparent that the differences in both mass and

dimensional changes occurred when CBPB was subjected to the cycling regime I (single step) compared to the regime II (multistep). 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 processes. However, higher levels of mass and dimensional changes occurred for the single step process.

It is evident, in these Figures, that desorption or adsorption curves for the mass and dimensions of CBPB on cycling under the regime II are enclosed within those curves derived from cycling under the regime I. The numerical comparisons are explicit in Table 7.4. During every adsorption or desorption phase (half cycle) (every row in Table 7.4) the maximum change values, whether mass, length or thickness, arising from regime II are lower than those from regime I. For example, over the first adsorption, the maximum mass, length and thickness changes resulting from regime II are 96 %, 90 % and 94 % of the maximum changes arising from regime I respectively, and 92 %, 91 % and 88 % over the third adsorption. The explanation for the pronounced effect of sorption history can be found in the effect of the gradient of moisture which resulted in a gradient of stress: 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 (Figure 7.15, 7.16 and 7.17). However it will be seen, in Figure 7.18 and 7.19, that the effect of the vapour gradient on the dimensional change is less or retarded compared to the effect on the mass change due to effects of other mechanisms.

Although the phenomenon has not been investigated extensively here, there is little reason to doubt that CBPBs all show essentially the behaviour described for in other materials (Rao, 1941; Urquhart, 1960). That is, at a particular temperature, the full curves define the limiting equilibrium values and thus may be viewed not as equilibrium loci but as borders that outline the hysteresis area. Hence, the full cycle isotherms 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. If the process of adsorption or desorption 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 piece 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.

Maximum change values of mass, length and thickness of CBPB under both cyclic regimes decrease in the successive sorption phase (comparison in each row in Table 7.4). As mentioned above, this is attributable to the consistent change in both wood chips and cement paste.

7.8.2 Effect on the Relationship between Dimensional and Mass Changes

Results

Figure 7.18 and 7.19 (markers) represent the plots of length change to the mass change, and thickness change to the mass change of CBPB.

The lines fitted to these experimental data are also reproduced to provide the hysteresis of CBPB under two different frames of RH. The R^2 values range from 0.99 to 1.00.

Discussion

Dimensional changes to mass change ($\Delta L / \Delta M$ or $\Delta T / \Delta M$) show that changes of both isotherms are similar, as discussed above. However, the rate and amount of $\Delta L / \Delta M$ or $\Delta T / \Delta M$ for the regime II are greater than those for the regime I. This dimensional changes per unit mass change is opposite to the mass or dimensional changes with time.

It is suggested that there exists a different reaction between CBPB and moisture under different sorption histories, both sorption sites and structure may change differently with the various approaches to reach the same RH. On adsorption, when samples were first diffused with lower RH, and then with high RH, moisture was firstly absorbed into smaller sizes of pores and then 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 interparticles closer, blocking some of spaces at the first stage and resisting the further adsorption in the smaller size of pores. Thus (relatively) the amount of moisture adsorbed in the smaller size of pores was less over the latter regime than over the former regime, and accordingly lower percentage dimensional changes per unit mass change were produced under the cycling regime I than under the cycling regime II. 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.

However, on desorption, the higher gradient of vapour pressure (deviation in RH) at the beginning of desorption may caused a rapid contraction of the interparticles, the paths of moisture transportation / evaporation may be partly blocked resisting the further movement of moisture and subsequently reducing the sorption in the smaller size of pores.

7.9 Interim Conclusions 4

1) CBPB underwent significant movement over the RH ranging from 35 % to 90 %. The behaviour was in better agreement with that of cement paste in that, initial exposure brought about pronounced irreversible changes both in mass and dimensions. The observed behaviour suggested that there existed further chemical and physical reactions inside CBPB.

2) Normalized with respect to the effects of RH and the structure of CBPB, the trend of length change was the same as that of thickness change. However, the change in the thickness of CBPB under cyclic RH was much higher than that in the length.

Double the rate of thickness change to length change appeared during 35 %RH and 65 %RH, and triple the rate during 65 %RH and 90 %RH, showing the contribution of both cement paste and wood chips.

3) The response of mass and dimensions to cyclic RH exposure was very different: most of the dimensional changes occurred in the first 2 or 3 days, while the mass change needed a much longer time to reach this change level.

4) There appeared to be close relationships between the levels of RH and mass or dimensional changes, showing that double the rates of length change occurred at lower RH (cycle 65 %RH and 35 %RH) while significant differences of mass change appeared between adsorption and desorption during the cycle 65 %RH - 90 %RH.

5) Considered with respect to the mass change of CBPB during one complete cycle, the desorption and adsorption curves under lower RH were similar to that of wood or other wood based materials, but the adsorption curve under higher RH was dominated by the condensation of moisture onto the CBPB.

6) Unlike the change in the length of CBPB under cyclic RH, the large carbonation shrinkage of cement paste in CBPB could not be reflected in change of thickness. A similar behaviour of thickness change covered the whole range of RHs (35 %RH - 90 %RH).

7) There was an accumulated increase in mass as the number of cycles increased: about 2.8 % irrecoverable increase was produced after 10 cycles compared to about 2.6 % for RH change from 35 - 90 %RH.

8) There was a substantial decrease in both length and thickness as the number of cycles increased: about 0.06 and 0.10 % for length and thickness.

9) The relationship between the dimensional change and mass change was in agreement with those under the single changing RH.

10) Both reversible and irreversible movement occurred in the CBPBs subjected to the cyclic RH, giving rise to hysteresis loops for both mass and dimensions. All hysteresis loops cannot close at the ultimate RH. Ad - and de - sorption curves for mass change intersected at between 65 %RH and 90 %RH, depending on the number of cycles. However, the ad - and de - sorption curves for dimensional change cannot intersect over the range of RH tested.

11) The width of hysteresis loops for mass, length and thickness, plotted against the RH, decreased as the number of cycles increased, indicating that a structure change in CBPB occurred during the RH cycle.

12) 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 as the number of cycles increased but also confirmed the structure change.

13) The desorption curves for the $\Delta L / \Delta M$ and $\Delta T / \Delta M$ for all cycles appeared straight and parallel between each cycle. However, the slope of adsorption curves changed between the successive cycles.

14) The hysteresis loop for mass change moved upward but the hysteresis loop for dimensional changes moved downward. The degree of movement between the successive cycles decreased with the number of cycles.

15) Like those under single changing RH, the overall dimensional changes were only dependent on the mass change but were independent of the immediate change in RH. The relationship between the dimensional and mass change from the experimental data was in agreement with those for both cement paste and wood chips (only if without condensation).

16) The sorption behaviour and dimensional movement of CBPB has been shown to be influenced not only by temperature and RH, but also by its immediate history.

The full or wider range adsorption and desorption isotherm simply defines a delimiting loop that encloses a hysteresis region, and any point within this region may be reached through a given intermediate curves by subjecting CBPB to an appropriate step.

17) 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.

18) The maximum change values within every phase of sorption, in both mass and dimensions, were higher for the cycling regime I than cycling regime II. However, the maximum change values within every phase of sorption were reducing with the number of cycles.

19) Different sorption histories resulted in different moisture reaction within the CBPB. The rates of dimensional changes to mass change of CBPB were greater under the cyclic regime II than under the regime I though the trends of the relationships were similar.

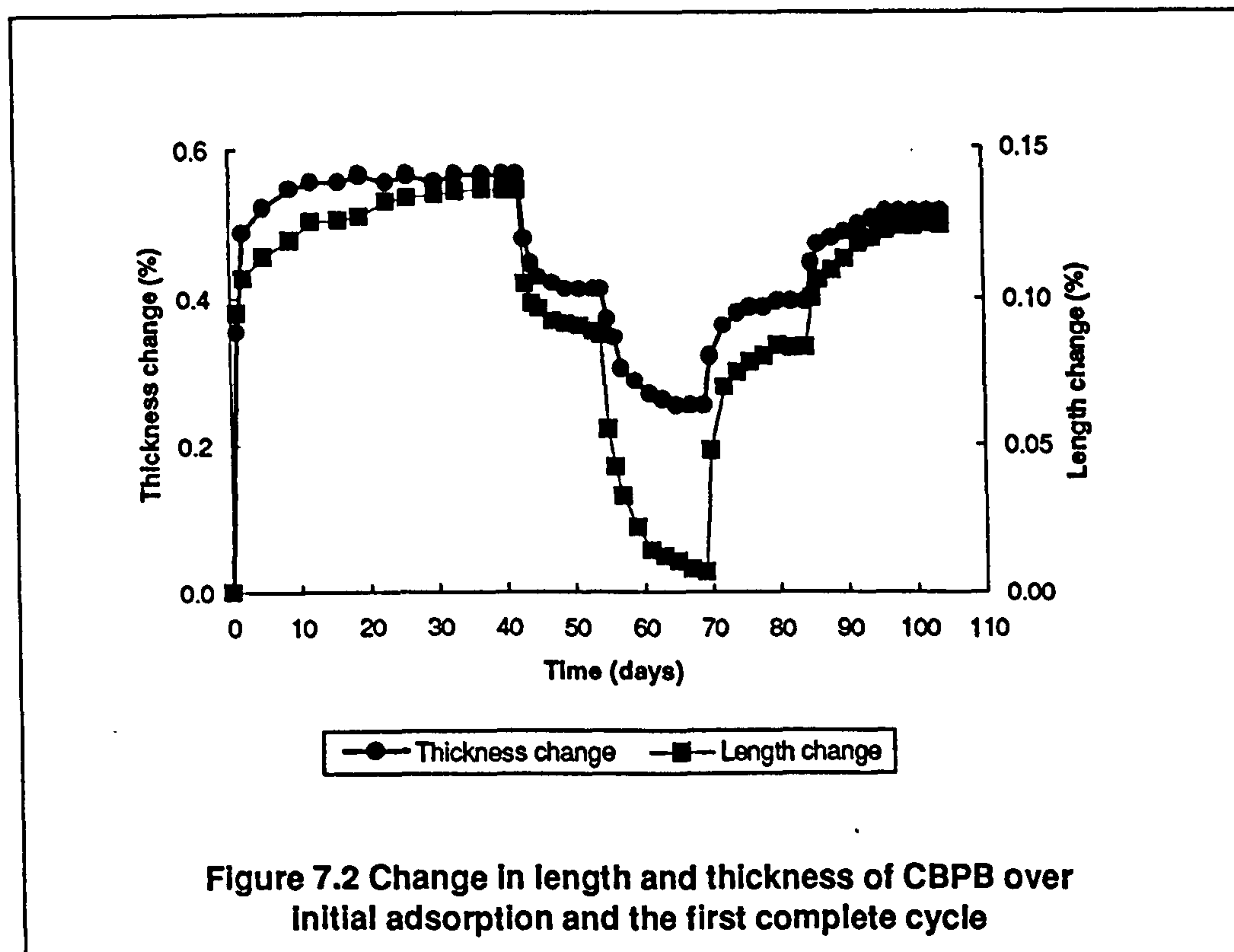
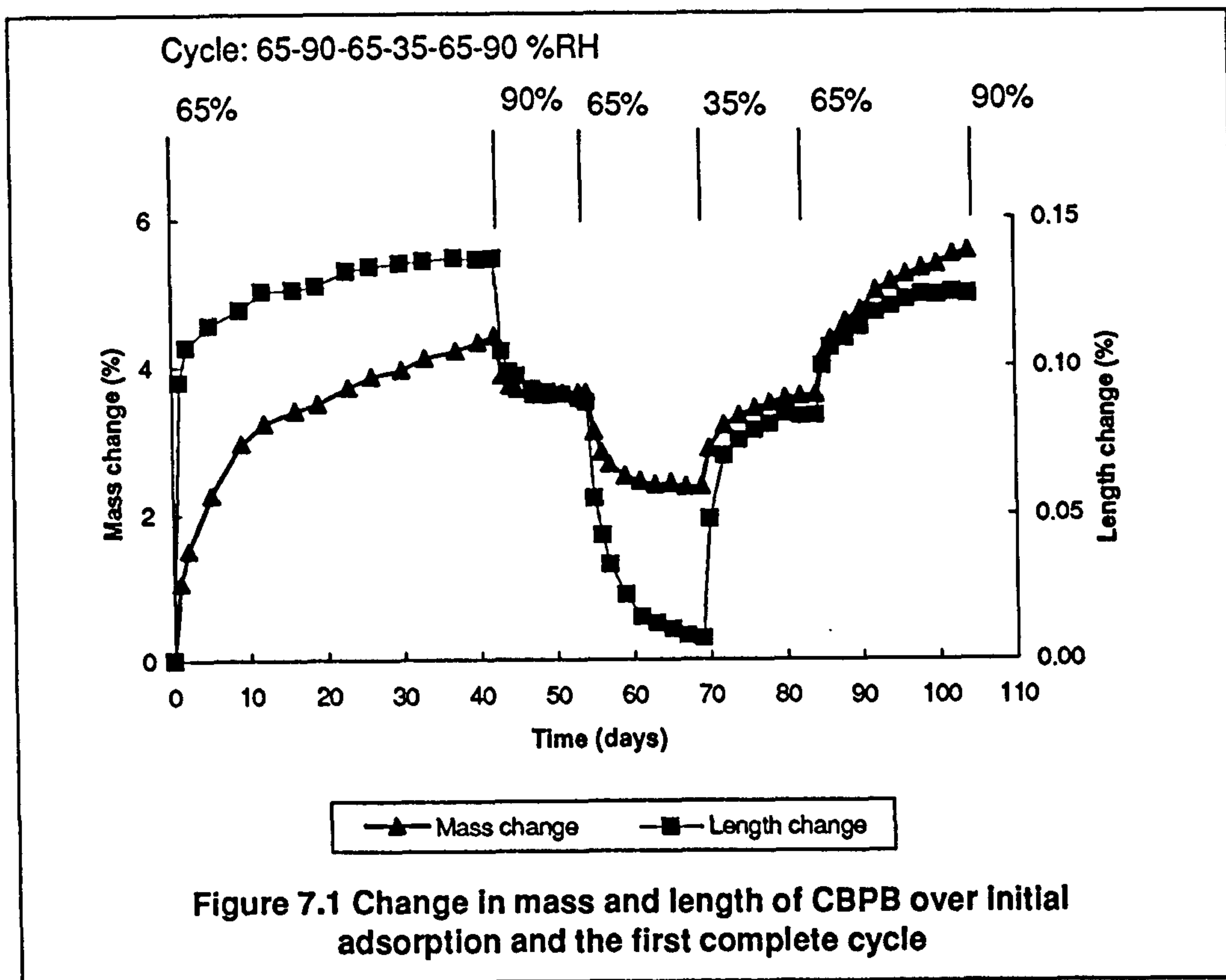


Table 7.1 Effect of RH change on mass and length of CBPB in the first complete cycle

Change in RH (%)	Change in mass (%)	Change in mass (%) Change in RH (%)	Change in length (%)	Change in length (%) Change in RH (%)	Change in thickness (%)	Change in thickness (%) Change in RH (%)
90-65	0.07	0.003	0.049	0.0018	0.152	0.0061
65-35	1.27	0.042	0.081	0.0027	0.160	0.0053
35-65	1.22	0.041	0.076	0.0025	0.143	0.0048
65-90	1.95	0.078	0.041	0.0016	0.118	0.0047

Table 7.2 Width of hysteresis loops at 65 %RH (%)

Cycle	Mass change	Length change	Thickness change
1st	-0.0385	-0.0043	-0.0169
2nd	-0.4934	-0.0180	-0.0169
3rd	-0.4159	-0.0129	-0.0137
4th	-0.4267	-0.0140	-0.0156
9th	-0.3913	-0.0121	-0.0084
10th	-0.3964	-0.0095	-0.0069

Table 7.3 Width of hysteresis loops at 90 %RH (%)

Mass change	Length change	Thickness change
1.1192	-0.0122	-0.0506
0.5331	-0.0083	-0.0453
0.2943	-0.0110	-0.0506
0.1544	-0.0068	-0.0253
0.0916	-0.0019	0.0000

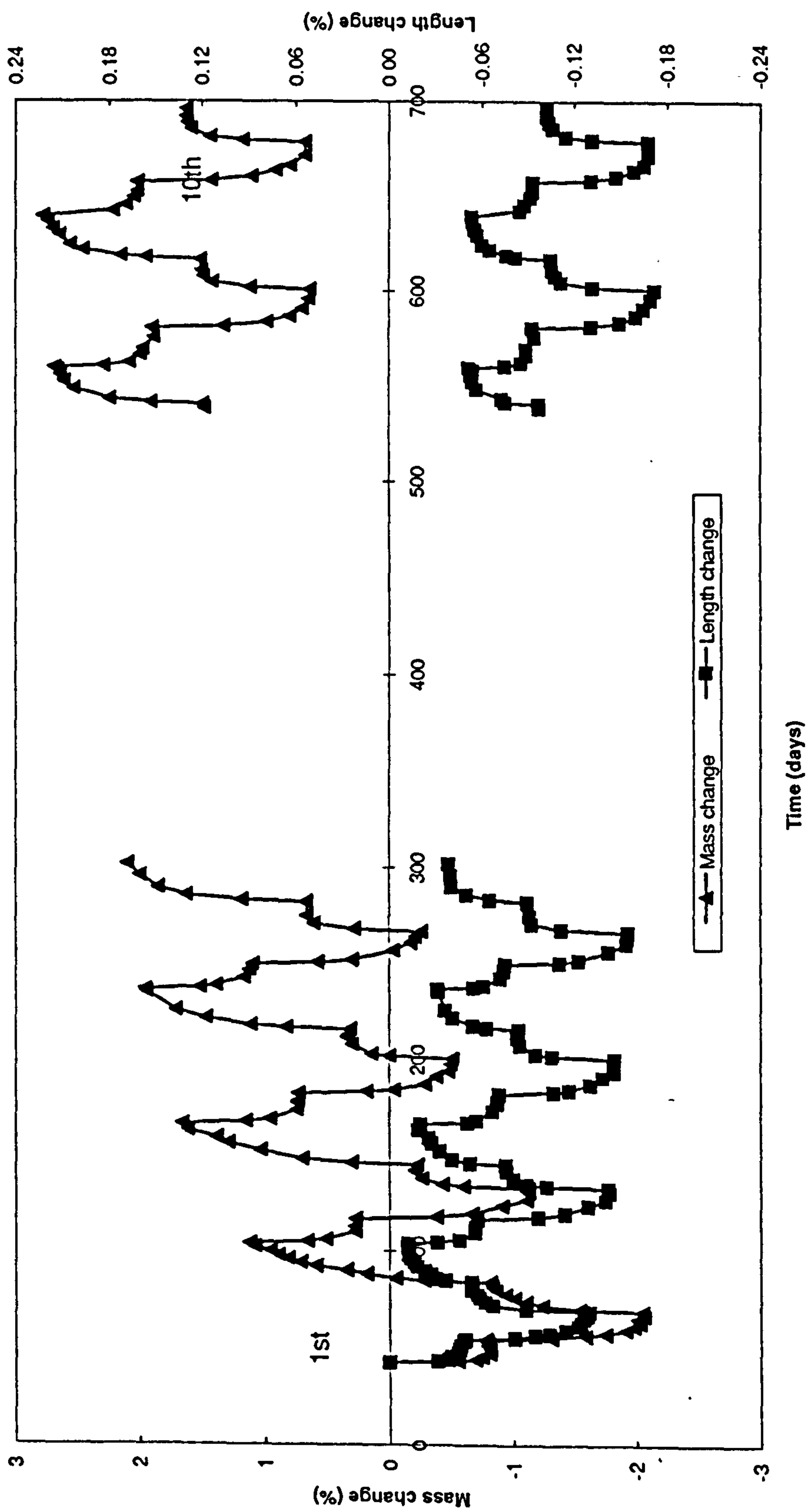


Figure 7.3 Change in mass and length of CBPB subjected to cyclic RH: 90%-65%-35%-65%-90%RH

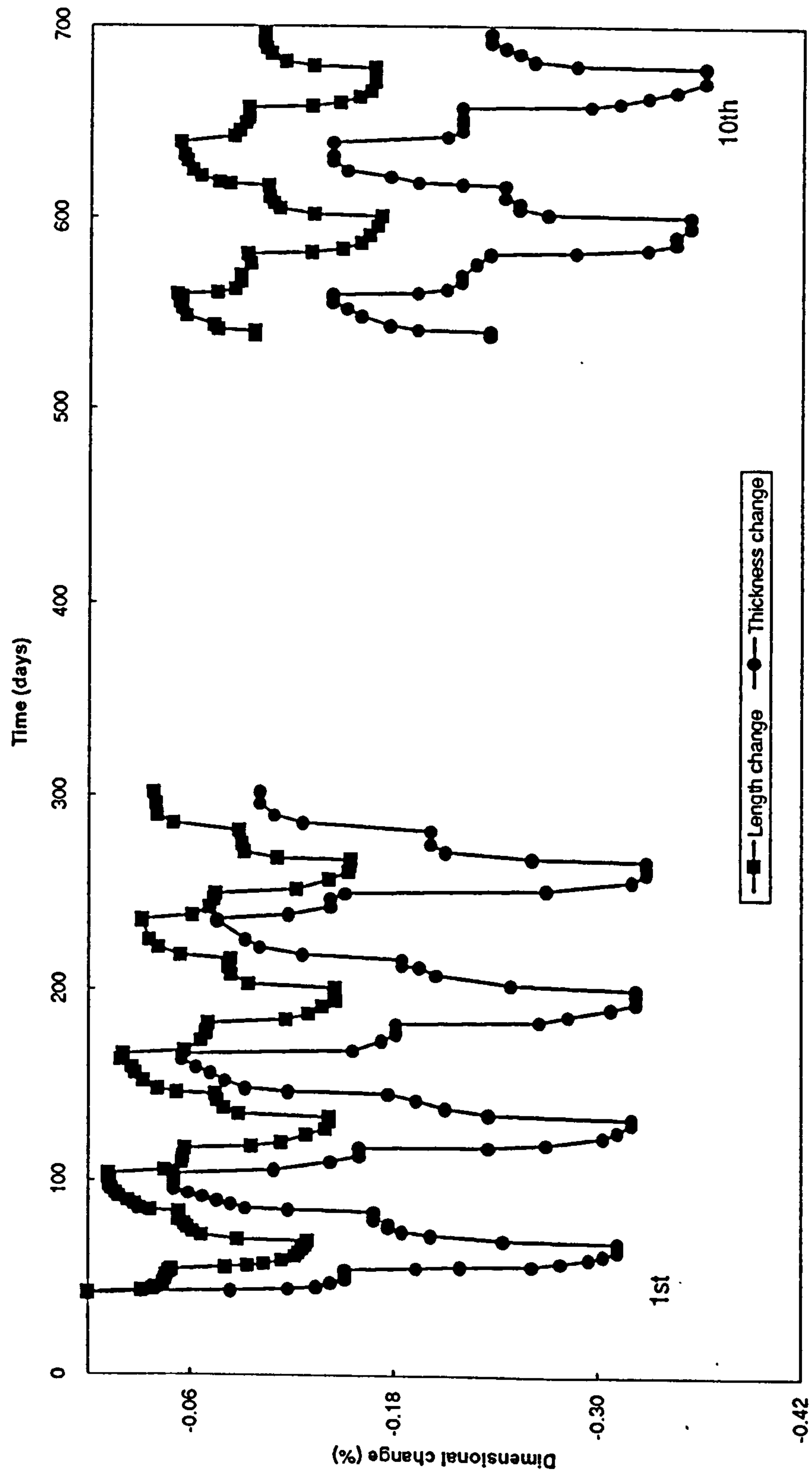
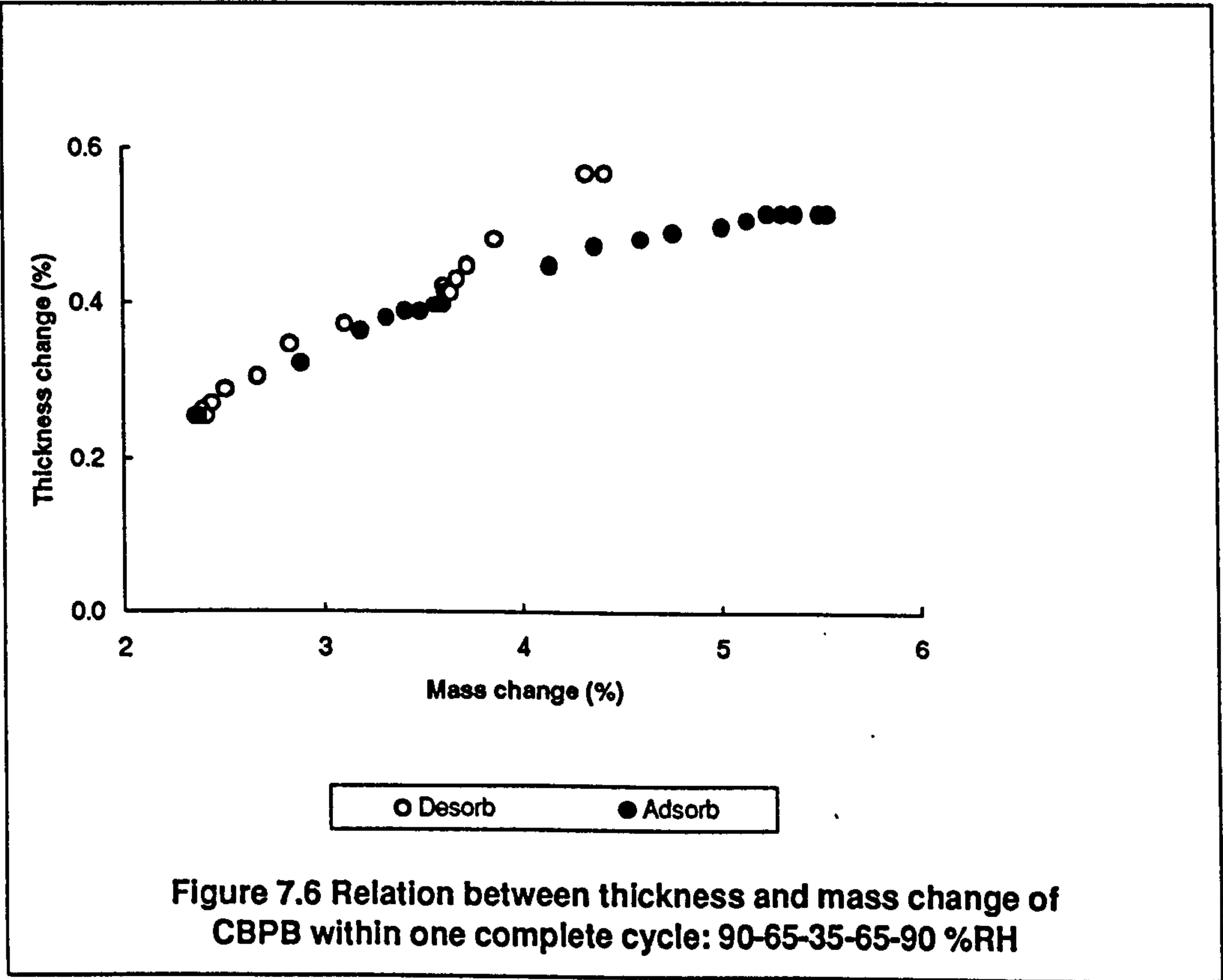
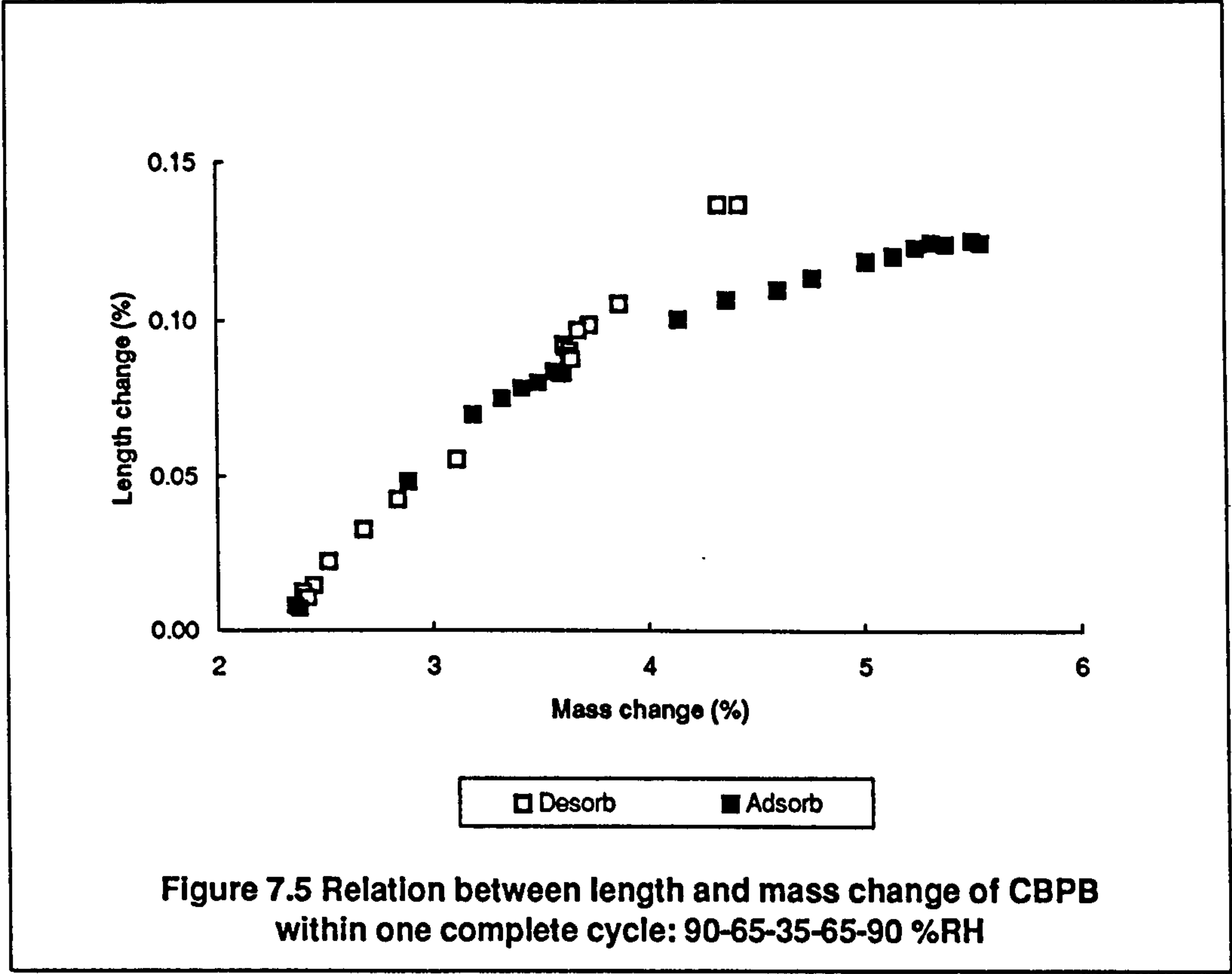


Figure 7.4 Change in length and thickness of CBPB subjected to cyclic RH: 90%-65%-35%-65%-90%RH



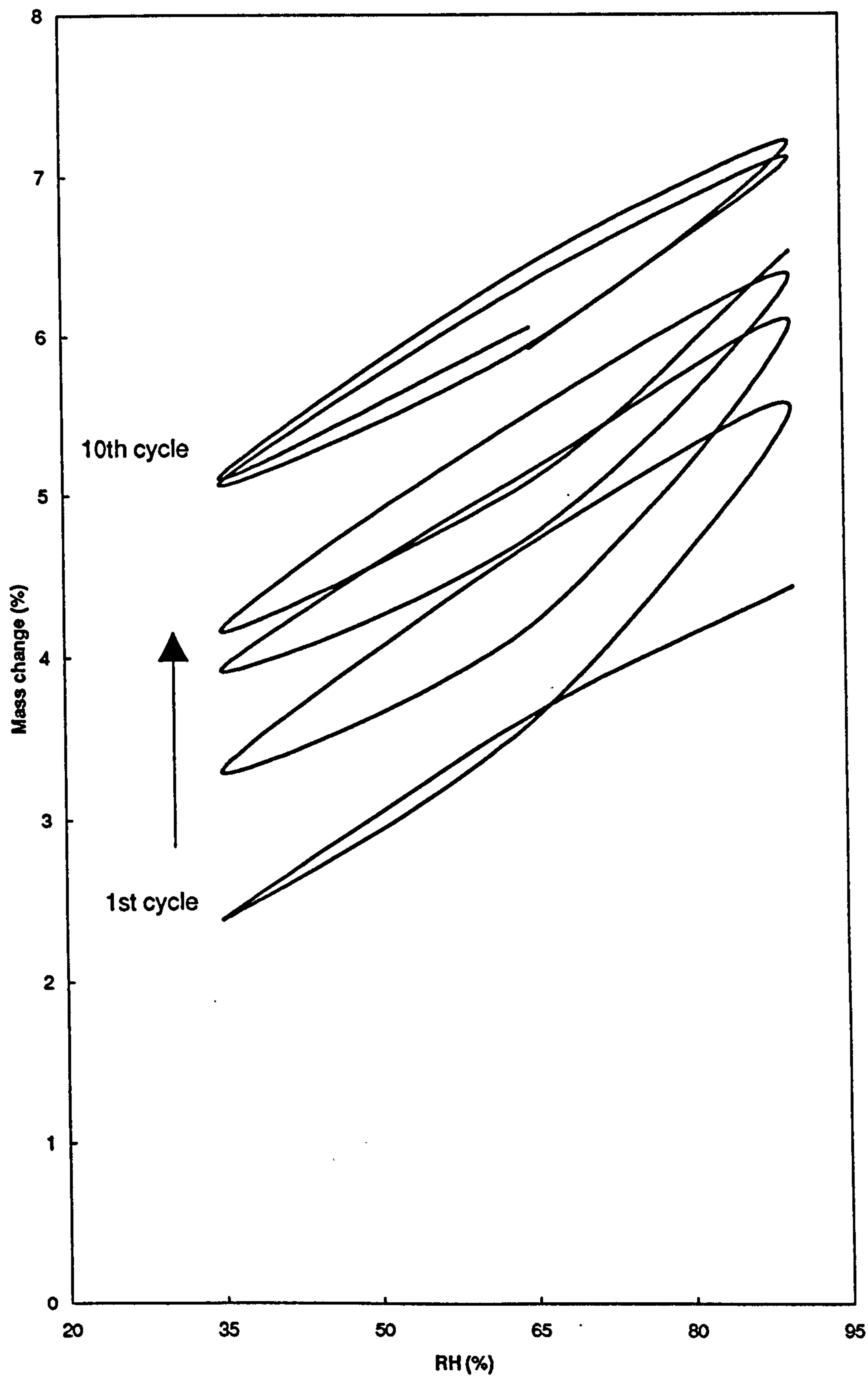
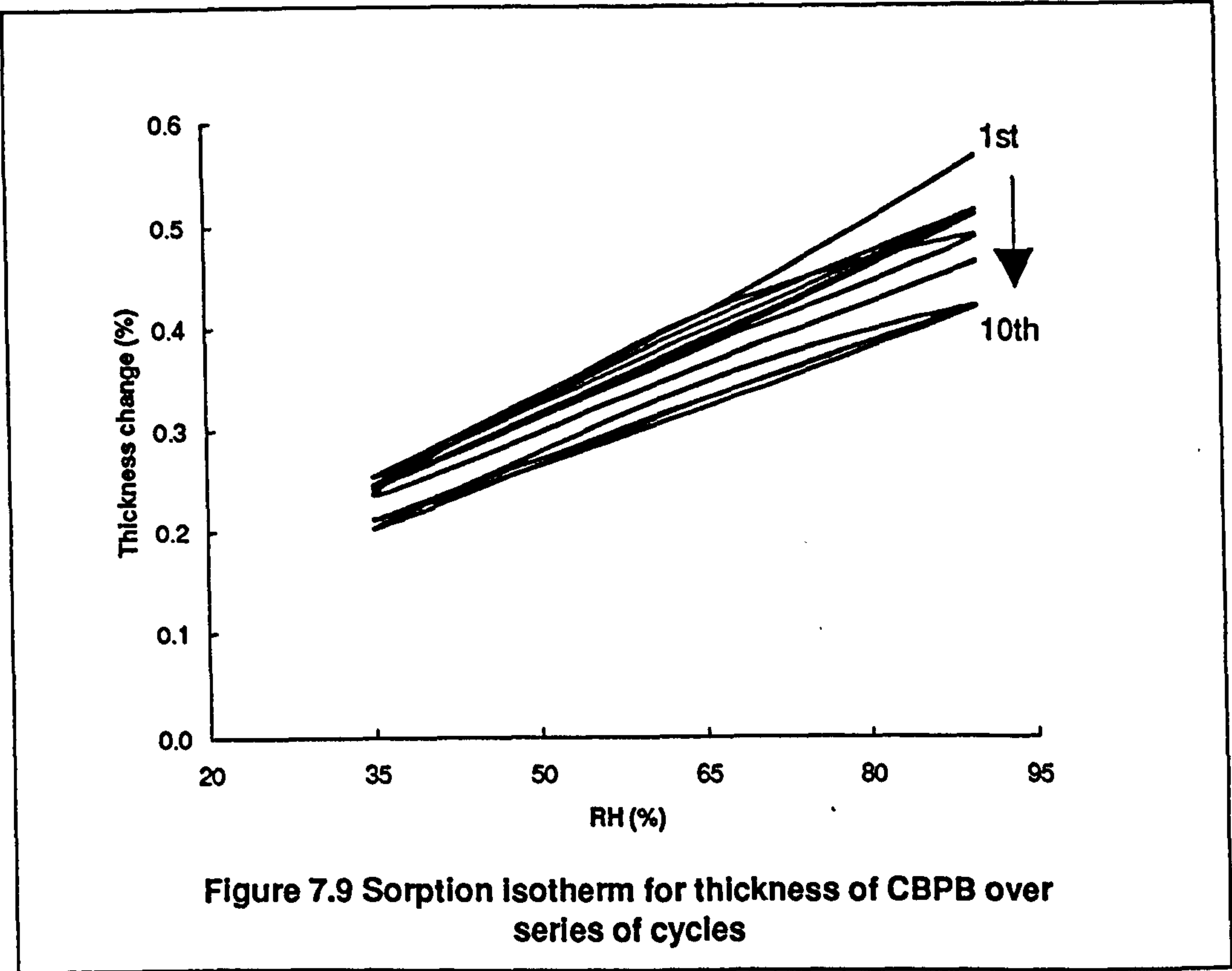
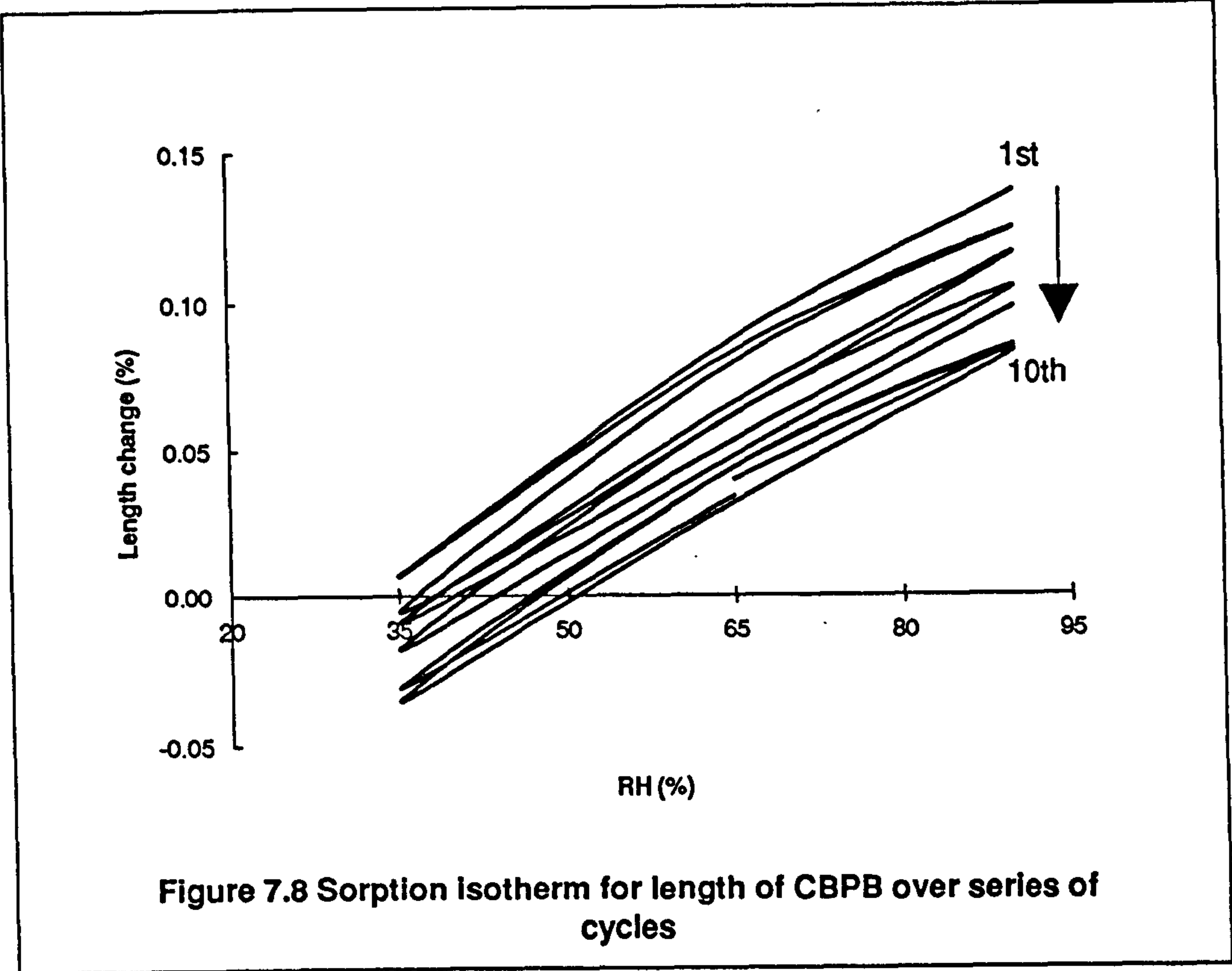


Figure 7.7 Sorption Isotherm for mass of CBPB over series of cycles



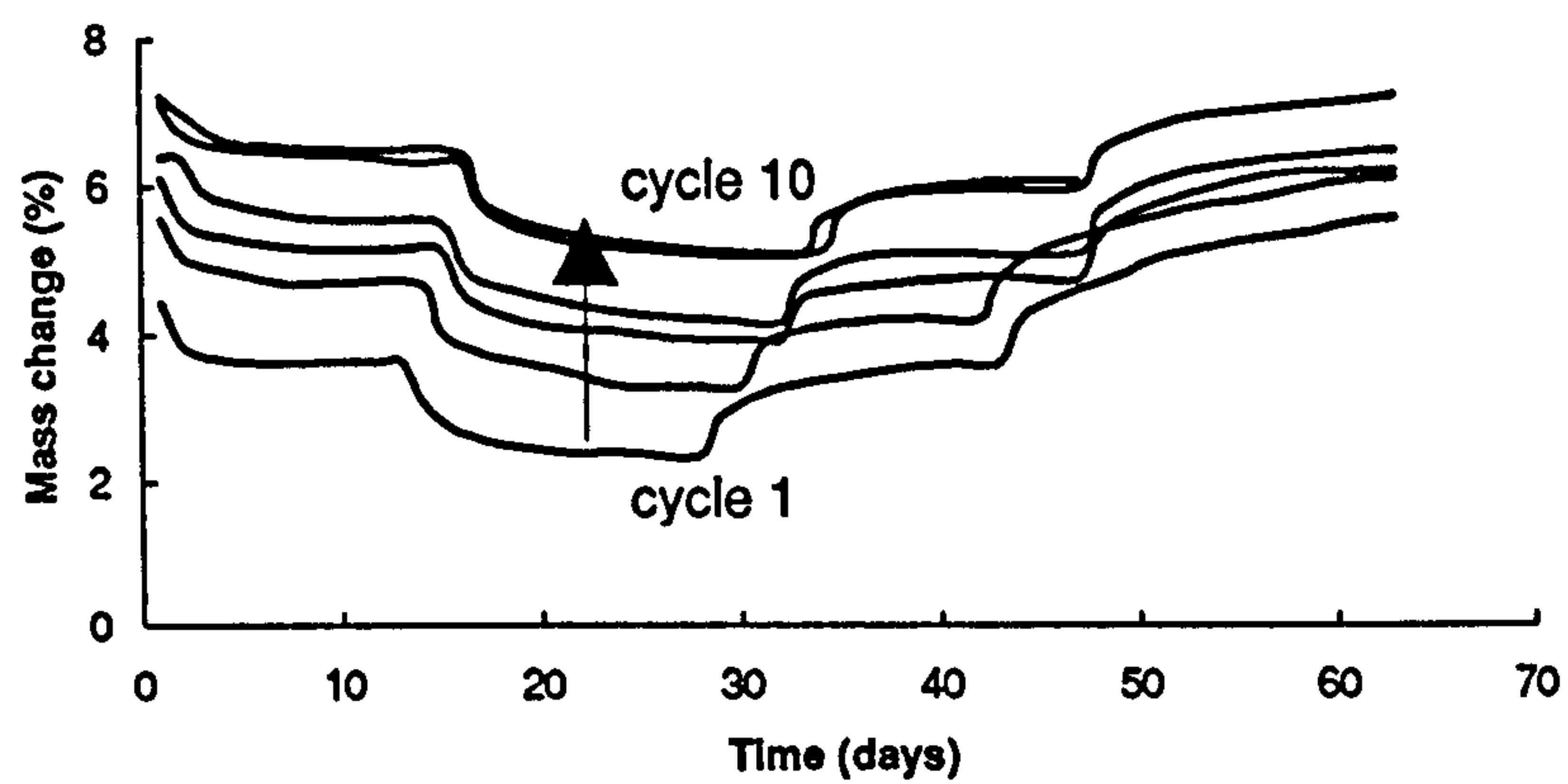


Figure 7.10 Mass change of CBPB between successive cycles: 90-65-35-65-90 %RH

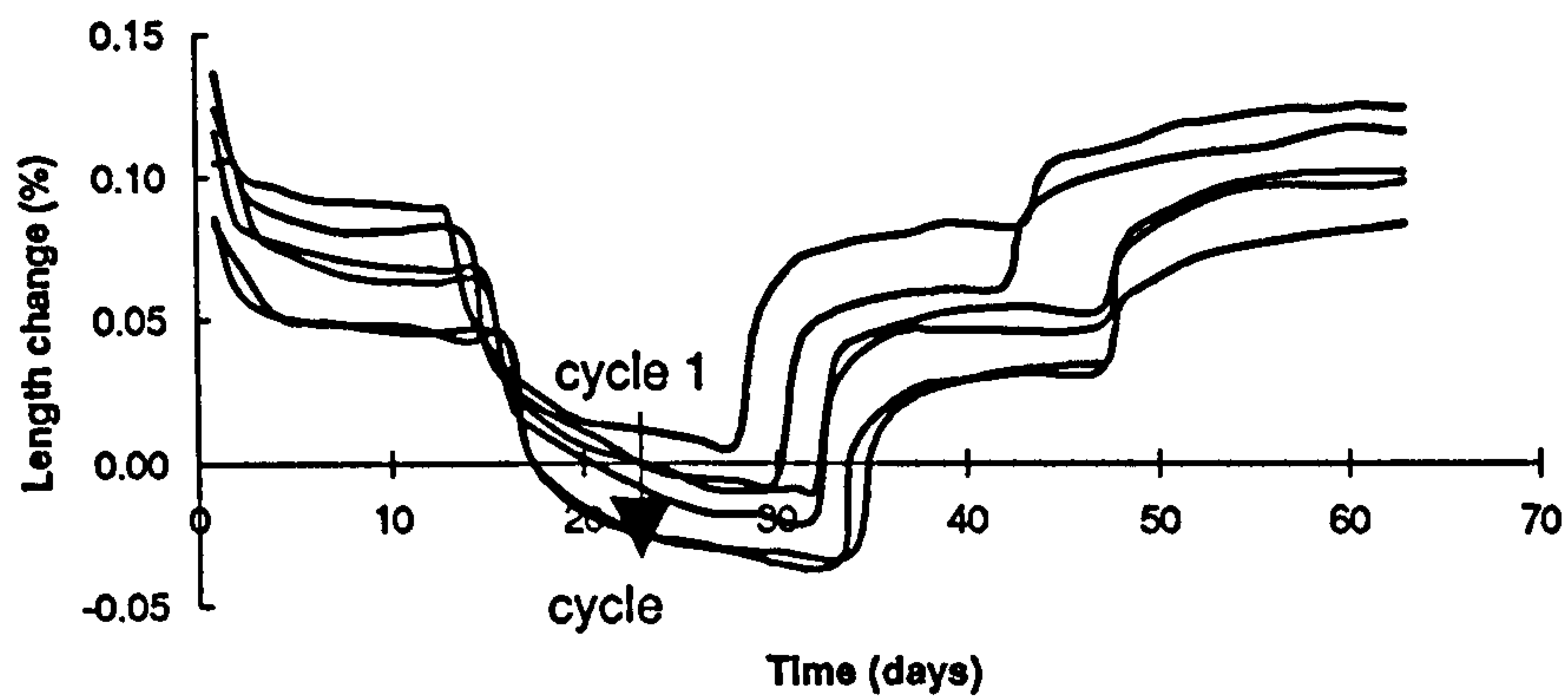


Figure 7.11 Length change of CBPB between successive cycles: 90-65-35-65-90 %RH

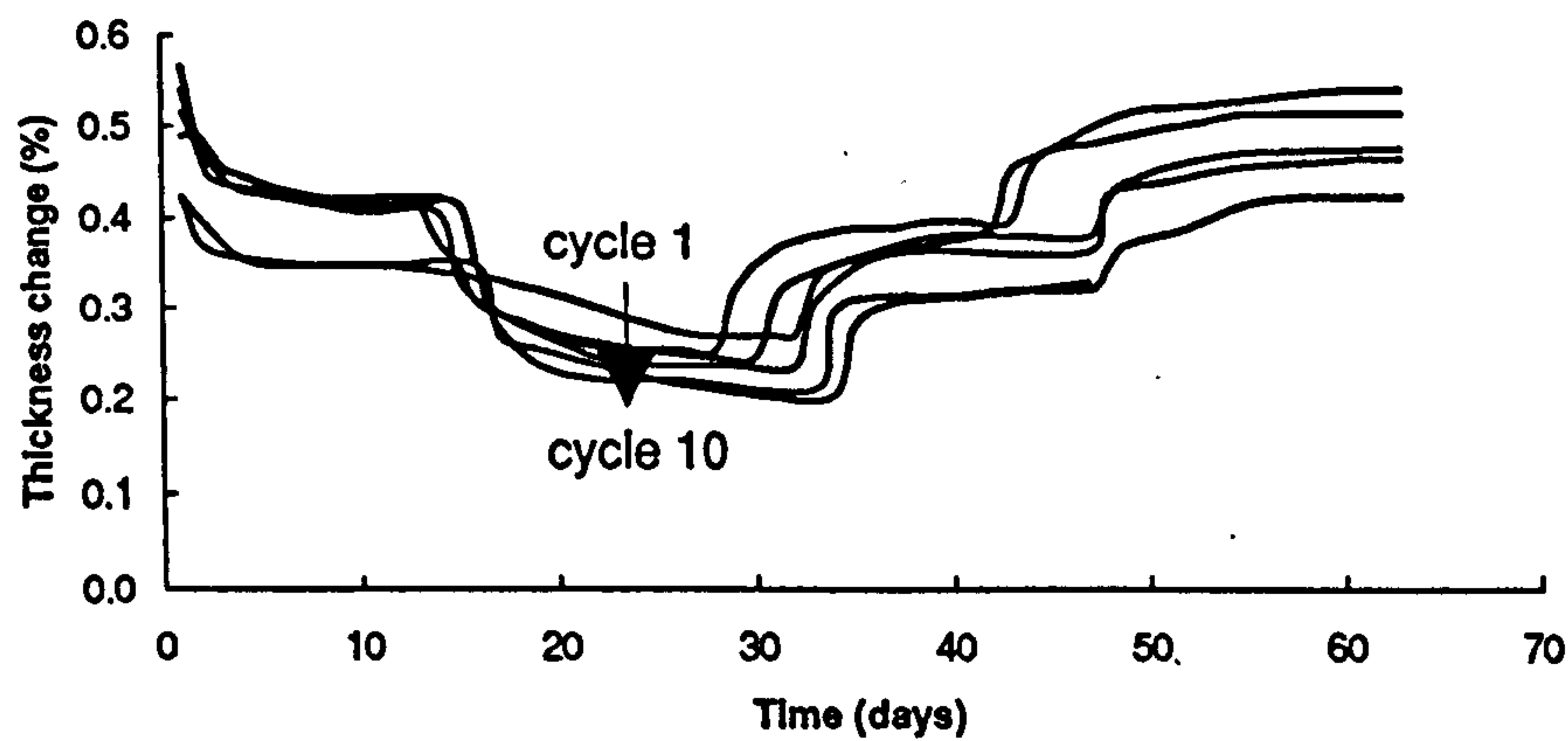


Figure 7.12 Thickness change of CBPB between successive cycles: 90-65-35-65-90 %RH

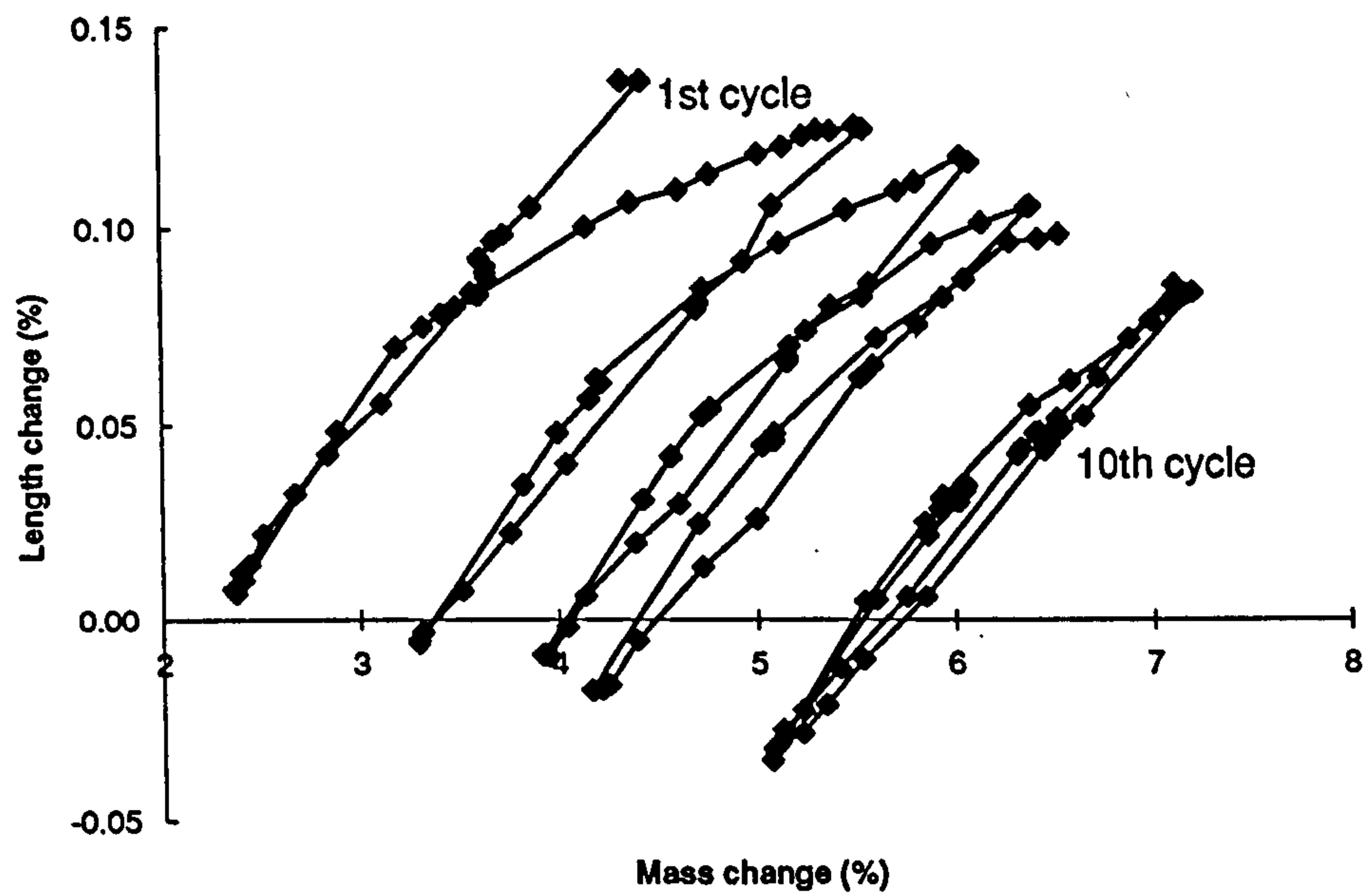


Figure 7.13 Length change vs mass change of CBPB over series of cycles

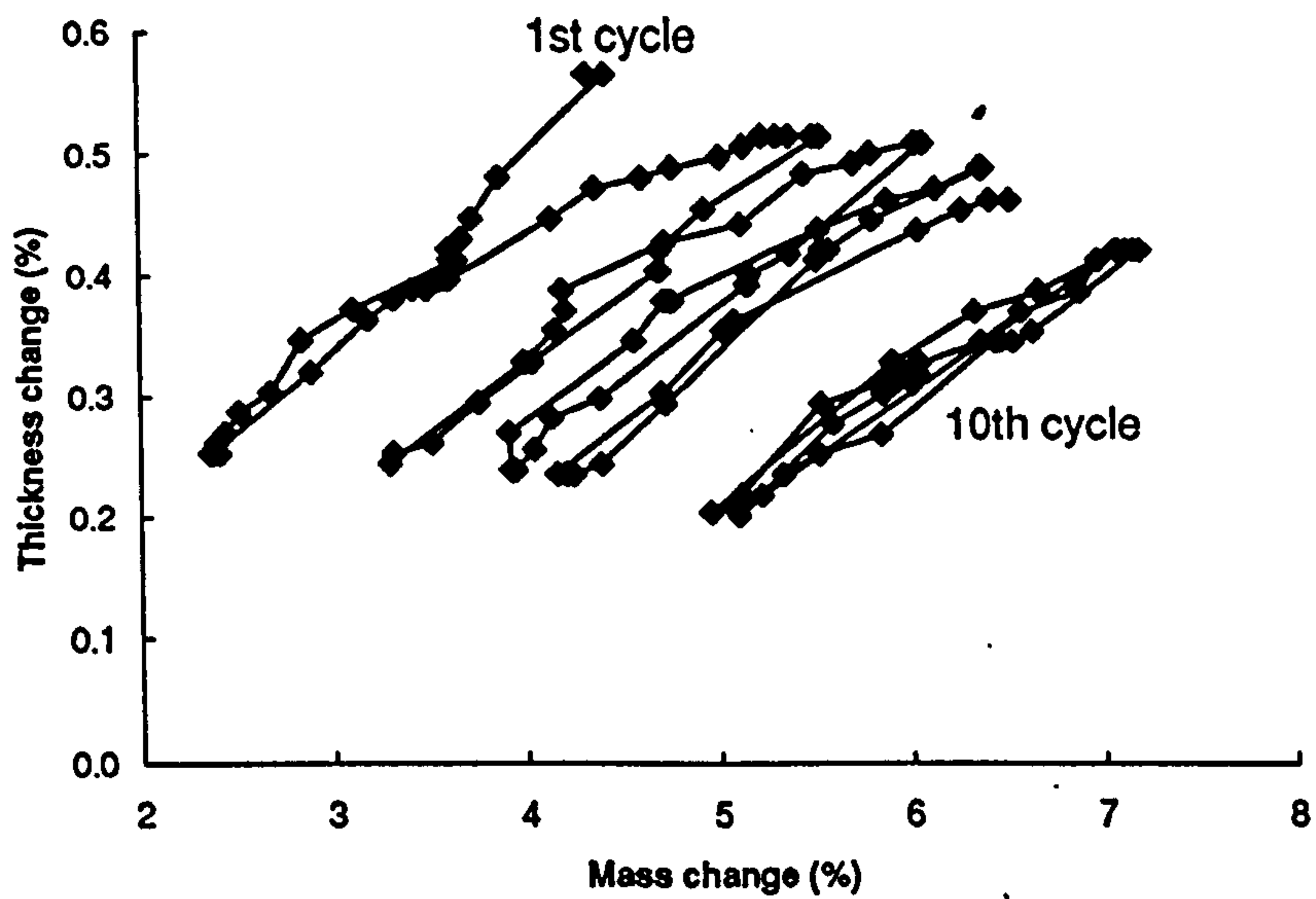
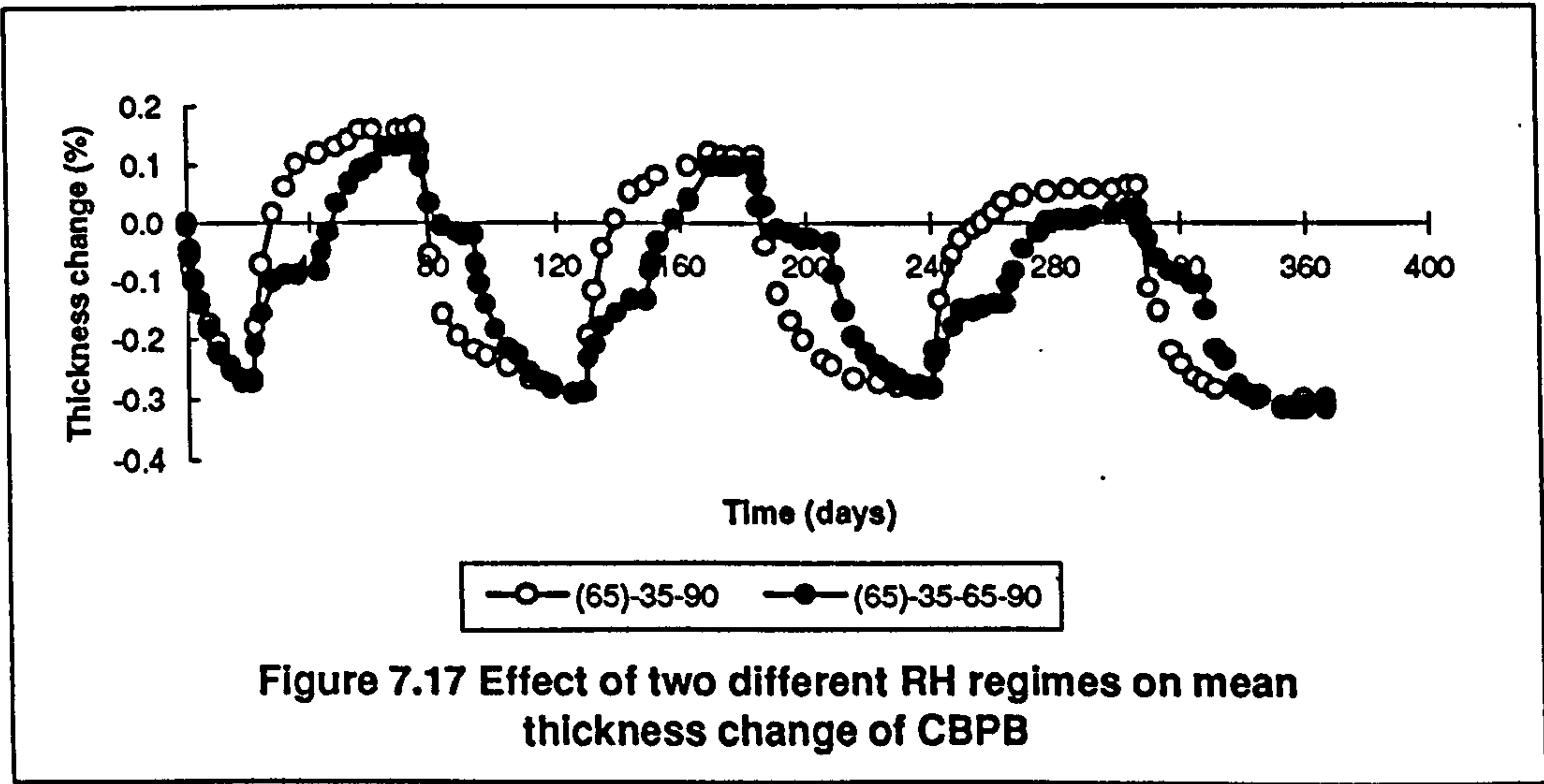
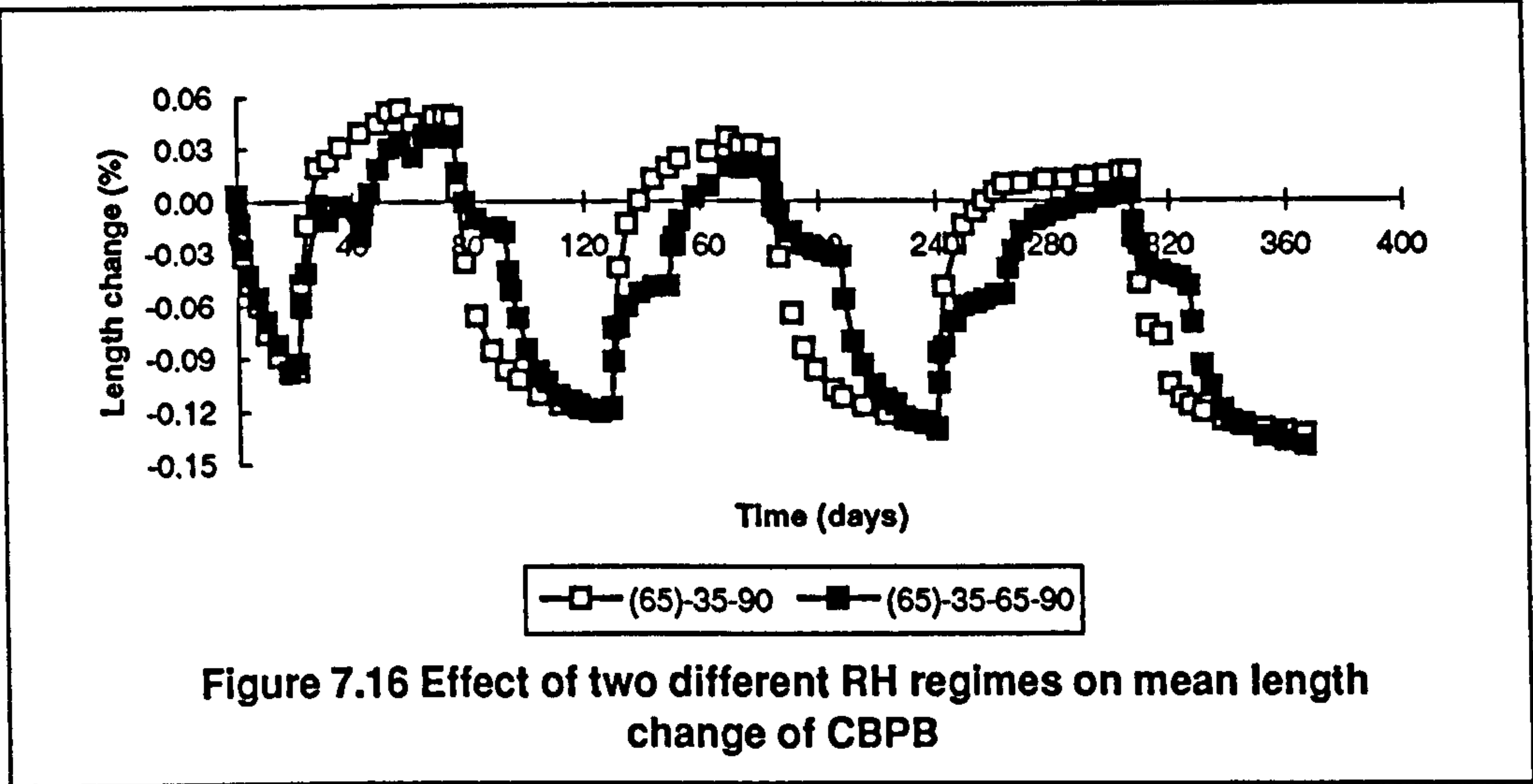
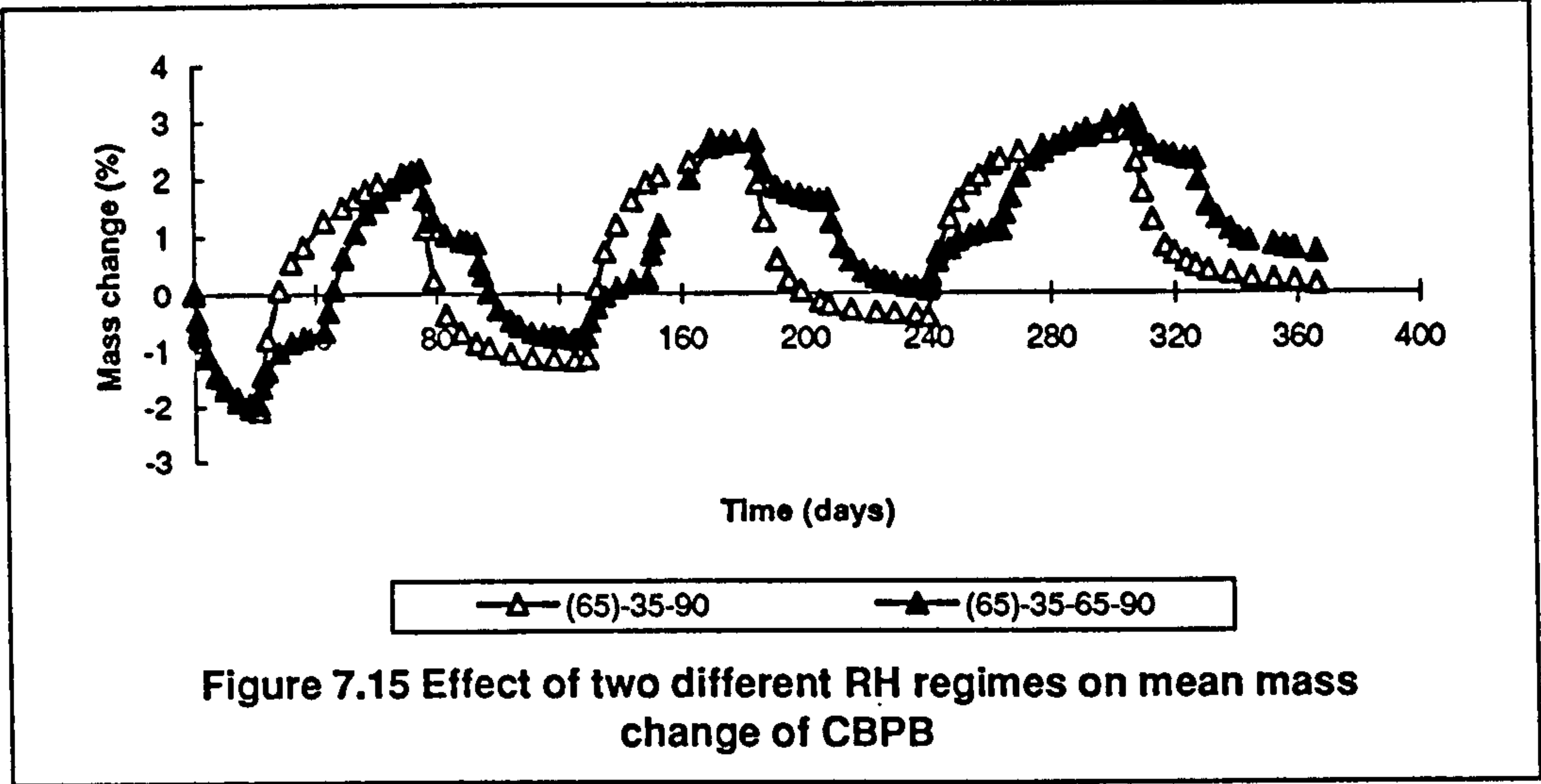


Figure 7.14 Thickness change vs mass change of CBPB over series of cycles



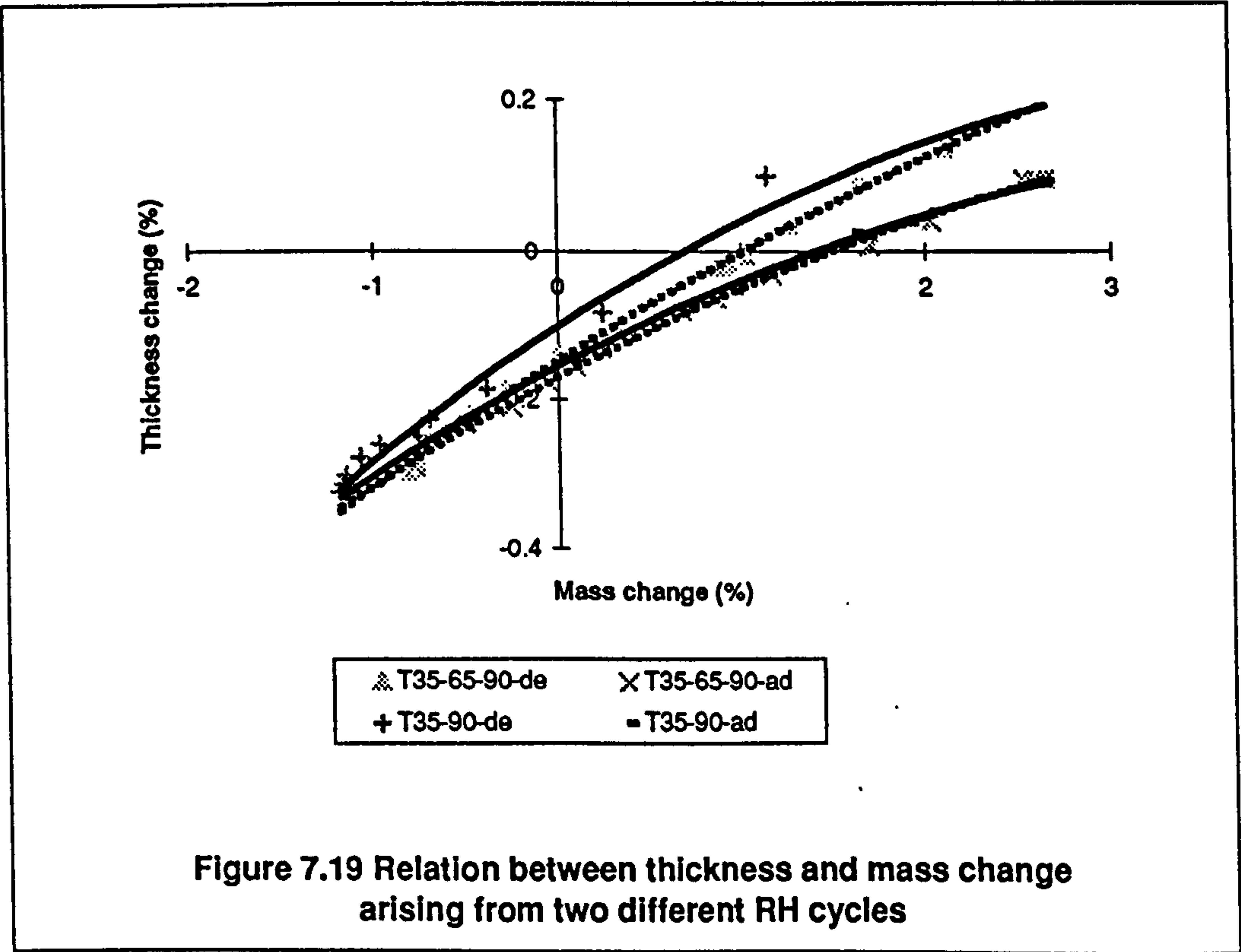
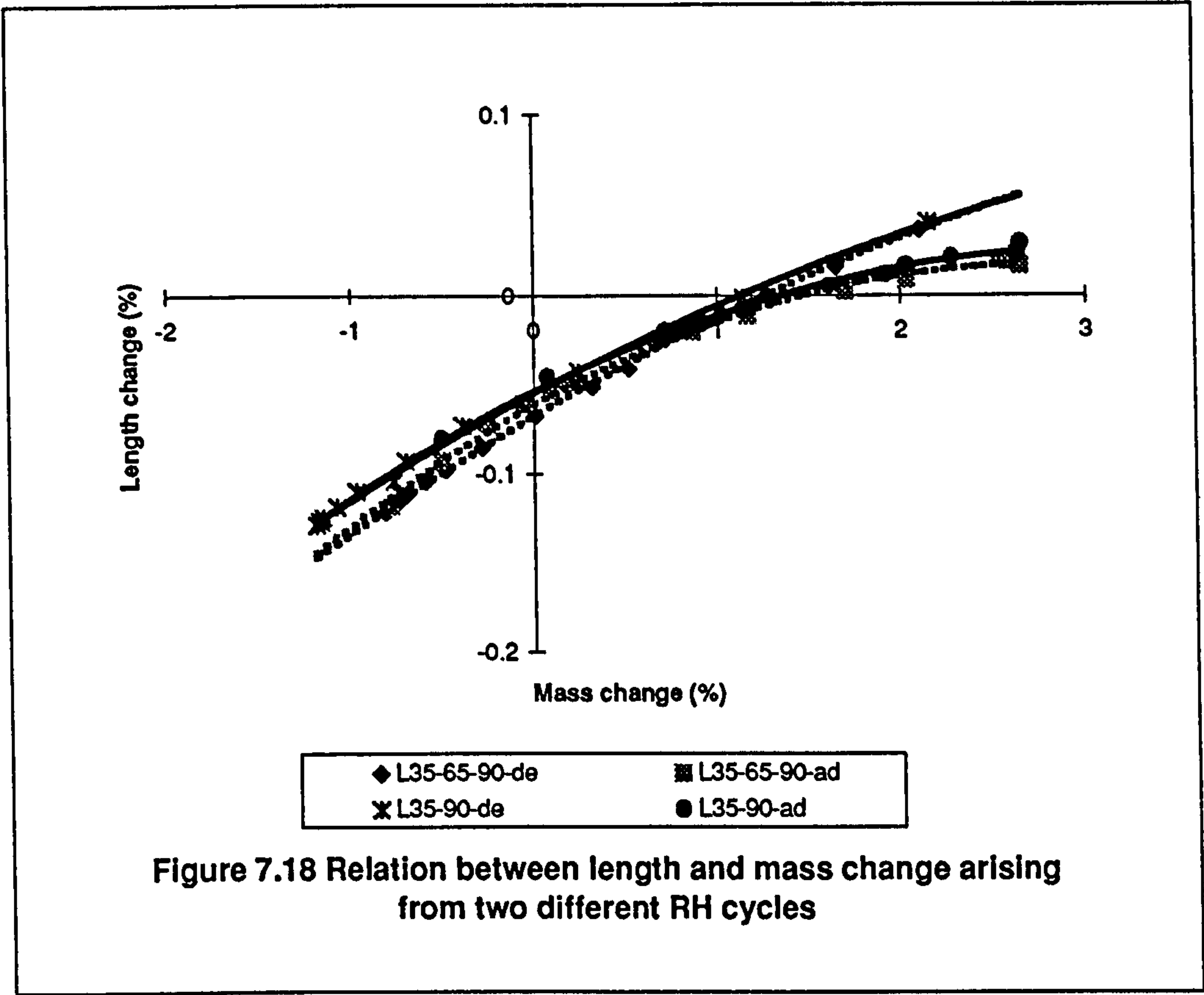


Table 7.4 Maximum changing values of mass, length and thickness of CBPB under various durations

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

* Regime I = 35 %RH - 90 %RH; regime II = 35 %RH - 65 %RH - 90 %RH;

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

Chapter 8

BEHAVIOUR OF CBPB CYCLING BETWEEN OVEN DRYING AND 20 °C / 65 %RH, AND BETWEEN WATER SOAKING AND 20 °C / 65 %RH

8.1 Introduction

In this chapter, the behaviour of CBPB cycling between water soaking and 65 %RH, and oven drying and 65 %RH, are discussed to supplement the information given in earlier chapters, aiming at examining the behaviour of CBPB over the whole range of moisture change (oven dry to water saturation).

8.2 Behaviour over a Cycle Embracing Water Soaking - 65 %RH - Oven Drying

Experimental results

Curves of the mass change versus time for CBPB cycling between soaking or oven drying and 65 %RH are presented in Figure 8.1. The corresponding deformation is given in Figures 8.2 and 8.3. The deformation versus mass change (approximately equal to the water change) for both cycles is shown in Figure 8.4 and 8.5.

Discussion

Figures 8.1, 8.2 and 8.3, show that when CBPBs were out of water and exposed to 65 %RH, the mass and dimensional changes are rapid at the early stage of exposure and slow down with time. Oven drying accelerates this processes considerably. Re - exposure to 65 %RH results in rapid increases in both mass and

dimension initially, but then slowing down rapidly to an almost constant level which is much lower than the values on the previous exposure to the same RH (65 %RH). It is apparent that, at the beginning of exposure to 65 %RH, free water was released, this water being water in the cell lumens of wood chips or some large cavities in cement paste and interfacial area. This results in a considerable mass decrease but only slight decreases in dimensions (see Figure 8.4). The process of movement of free water out of CBPB may carry on for a certain period depending on the thickness and density of the CBPB, receding further from the surface into the centre of the CBPB. However, at the beginning of the exposure the absorbed / bound water near the surface of the CBPB starts evaporating and brings about a substantial dimensional decrease. Such a slight change due to the movement of free water in the deeper of CBPB could not be reflected in the total change values measured. Therefore the duration of movement of free water was shown to be a very short period.

Drying absorbed / bound water from wood and from cement paste (gel water) should result in commensurate dimensional changes. This relationship is confirmed in Figures 8.4 and 8.5, in which linear relationships were produced in the second stage of exposure, on moving samples from water to 65 %RH, and in the first stage of the exposure on transferring samples from 65 %RH to oven drying. The slight increase in the slope of lines for the relationship between mass and dimensional change of CBPB at the later stage of exposure to 65 %RH indicates a slight increase in the mass of CBPB after long - term exposure. This is attributable to carbonation.

In Figure 8.5, It appears that during the second stage of oven drying (DE), withdrawal of adsorbed water in CBPB results in a high shrinkage rate. This phenomenon, in theory, is not however attributable to the shrinkage of wood chips, but to the mechanism of the deformation of cement paste, where the movement of water is thought to result in spontaneous closing of gaps, reducing intra - crystal layer spacing.

In the reverse process, dry CBPB expands with increasing RH. In Figure 8.5, it can be seen that the mass increase at the beginning of the exposure to 65 %RH did not bring about a commensurate increase in dimensions, suggesting that there may exist another process which was thought to be due to the temperature change since the boards were removed from 100 °C to 20 °C, causing a shrinkage in dimensions

of CBPB. After a slow increase, the relationship between mass and dimensional change became linear. Again, the decrease in the slope of the lines at later stages of exposure is attributable to carbonation after long - term exposure to a 65 %RH (normal) air environment.

A linear relationship was also found in the early stage of water soaking. At this time the water probably was firstly absorbed by the wood cell wall and the gel pores of cement paste. Above FSP of the wood chips moisture increase will not bring about dimensional change. Hence at this time the location of water in cement paste is mostly in the capillary pores which in turn result in less deformation compared to the removal of gel pore water. Therefore, the slope of lines significantly decrease at the later stages of soaking. The duration of the first stage strongly depends on the structure of the interface between wood chip and cement paste. It can be seen that in Figure 12.2, the path of transverse flow may be blocked by the cement paste.

The significant features of behaviour of CBPB are clearly seen from the description of deformation versus mass change: the deformation over the whole range of moisture loss comprises five distinct stages (Figures 8.4 and 8.5):

- O - A Beginning of the drying period at 65 %RH, Low shrinkage rate associated with high water loss.
- A - B Steady shrinkage rate, deformation is linear with water loss, which should continue up to the end of the 65 %RH exposure, provided that the environment contains no carbon dioxide.
- B - C Steady shrinkage rate but with higher slopes due to the contribution of steady carbonation in cement paste of CBPB.
- C' - D Linearity between deformation and mass regain extends on further drying from 65 %RH to the first stage of oven drying.
- D - E Final stage of oven drying. High shrinkage rate with almost linear relationship between mass and dimensional changes but with relatively small amounts of water loss causing a considerable increase in the slopes of the lines.

The deformation of CBPB due to moisture regain also comprises five distinct stages but with irreversibility.

Regions F - G, G - H and H' - I correspond to regions C - D, B - C and A - B in drying respectively, but with different degrees of irreversibility. Region E - F is

the first stage of the adsorption with very low swelling rate. This plateau indicates that there may exist two processes counterbalancing each other. Region I - J is the final stage of swelling under liquid water: a considerable increase in mass of CBPB only brings about a slight increase in dimensions.

8.3 The Different Effect of Water Soaking and Oven Drying during Successive Cycles

Discussion

There are three significant differences in the behaviour of CBPBs between cycling of water soak - 65 %RH and 65 %RH - oven dry (Figures 8.1, 8.2 and 8.3). Firstly, with respect to the difference in changes between mass and dimensions, mass change of CBPB under water soaking was greater than that under oven drying, while dimensional changes under water soaking were less than those under oven drying. Features of both cement paste and wood chips are reflected in the two different cycles. Under soaking, the free water was absorbed by both cement paste and wood chips, resulting in mass increase. However, a change of this type of water brought about much less change in dimensions, and probably can't make any change in the wood chips when the moisture content in the wood is over FSP. Under oven drying, adsorbed / bound water was involved, and relatively small changes in moisture had a great influence on dimensional change.

Secondly, it is very interesting to note that the difference in changes between length and thickness not only lay within single treatment but also between two treatments. It can be seen that the change in the length of CBPB was only about 0.2 times the change in the thickness under water soaking, while it was about 0.7 times under oven drying. This phenomenon can only be interpreted after a consideration of the structure of CBPB and the characteristics of both cement paste and wood chips. The anisotropic characteristic of wood contributed to the difference in change between length and thickness due to a high percentage of wood chips across the thickness of the CBPB and flat distribution of wood chip in the CBPB. The change in different type of water in cement paste brought about a significant difference in

length change between oven drying and water soaking exposure.

The third difference is in the accumulated change over successive cycles. It appears that there was a reduction in amplitude in both mass and dimensional change as the number of cycles increased. However, under the cycle of oven drying and 65 %RH, the values of mass increased and the values of dimensions decreased consistently in successive cycles; under the cycle of water immersion and 65 %RH, the values of both mass and dimensions decreased after water immersion treatment with cycles, while after 65 %RH exposure mass slightly increased but decreases in dimensions were not clearly observable with cycles. Both phenomena indicated that there was a process of stabilization of the CBPB, and the contrasting change between mass and dimensional changes over the cycle between 65 %RH and oven drying is attributable to the certain carbonation of cement paste in the CBPBs.

8.4 Comparison of Behaviour of CBPB Exposed to Liquid and Vapour Water

Experimental results

Figures 8.6, 8.7 and 8.8 illustrate the comparisons of mass and dimensional changes versus time arising from cycling CBPB between water soaking and 65 %RH and those arising from cycling between 35 %RH and 90 %RH.

Discussion

In Figures 8.6 - 8.8 illustrates the different behaviour of CBPB under vapour and liquid exposure, though the final conditions were not exactly the same. The difference reflected the capability of sorption of CBPB under these conditions and the effects of carbon dioxide in the vapour air environments.

One of these differences is the rate of change (see Figures 8.6, 8.8 and 8.8). It is very significant that the rate of mass change under liquid water soaking was considerable higher than that under water vapour, while the rate of dimensional change was similar under both exposures. The phenomenon clearly illustrated the

filling of free water into the cavities in CBPB.

The second of these differences is the trend of the change under successive cycles. The maximum values of mass increase under liquid water soaking consistently decreased with the number of cycles, while under 90 %rh water vapour it consistently increased with the number of cycles. The trend of dimensional changes was the same for both treatments. The difference was obviously related to the carbonation and stabilization of CBPB. It is suggested that the process of carbonation in CBPB could be avoided by soaking materials in liquid.

The third of these differences is the irreversibility. It is apparent that the changes in both mass and dimensions were irreversible, with mass being higher and length being lower than its original values. The degree of irreversibility in the mass of CBPB after two treatments was exactly the same. An exception is that the values after every water soaking was decreasing with cycles.

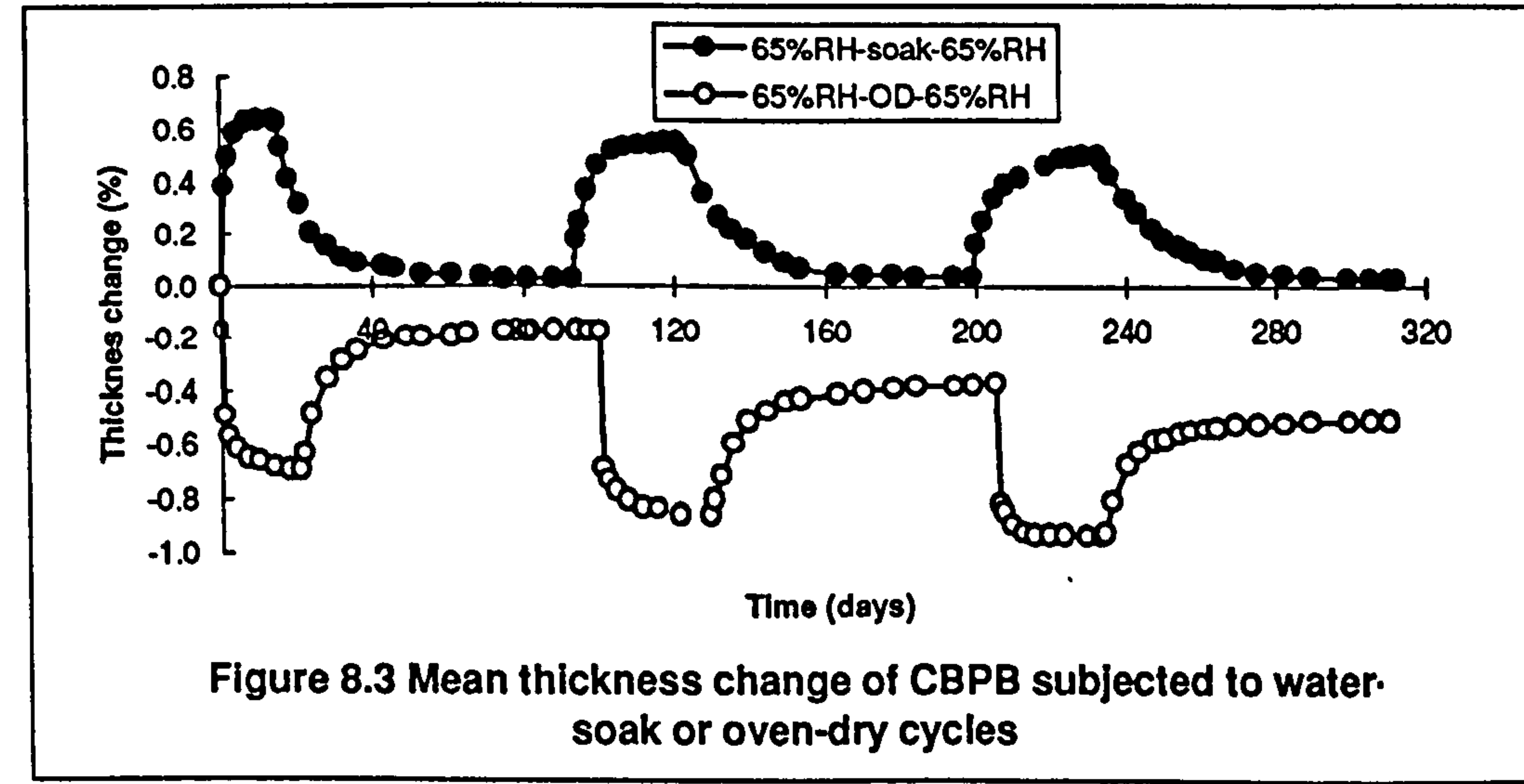
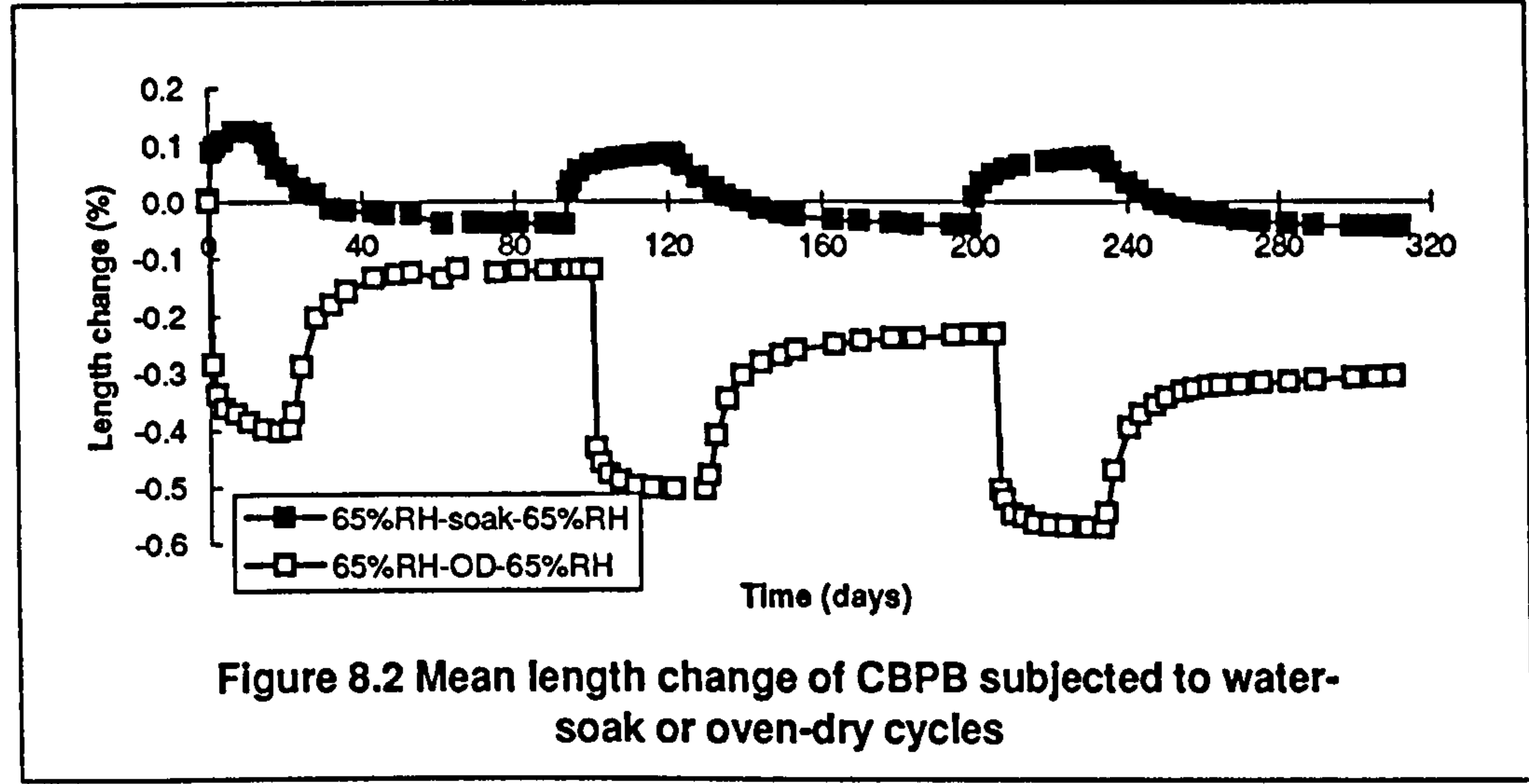
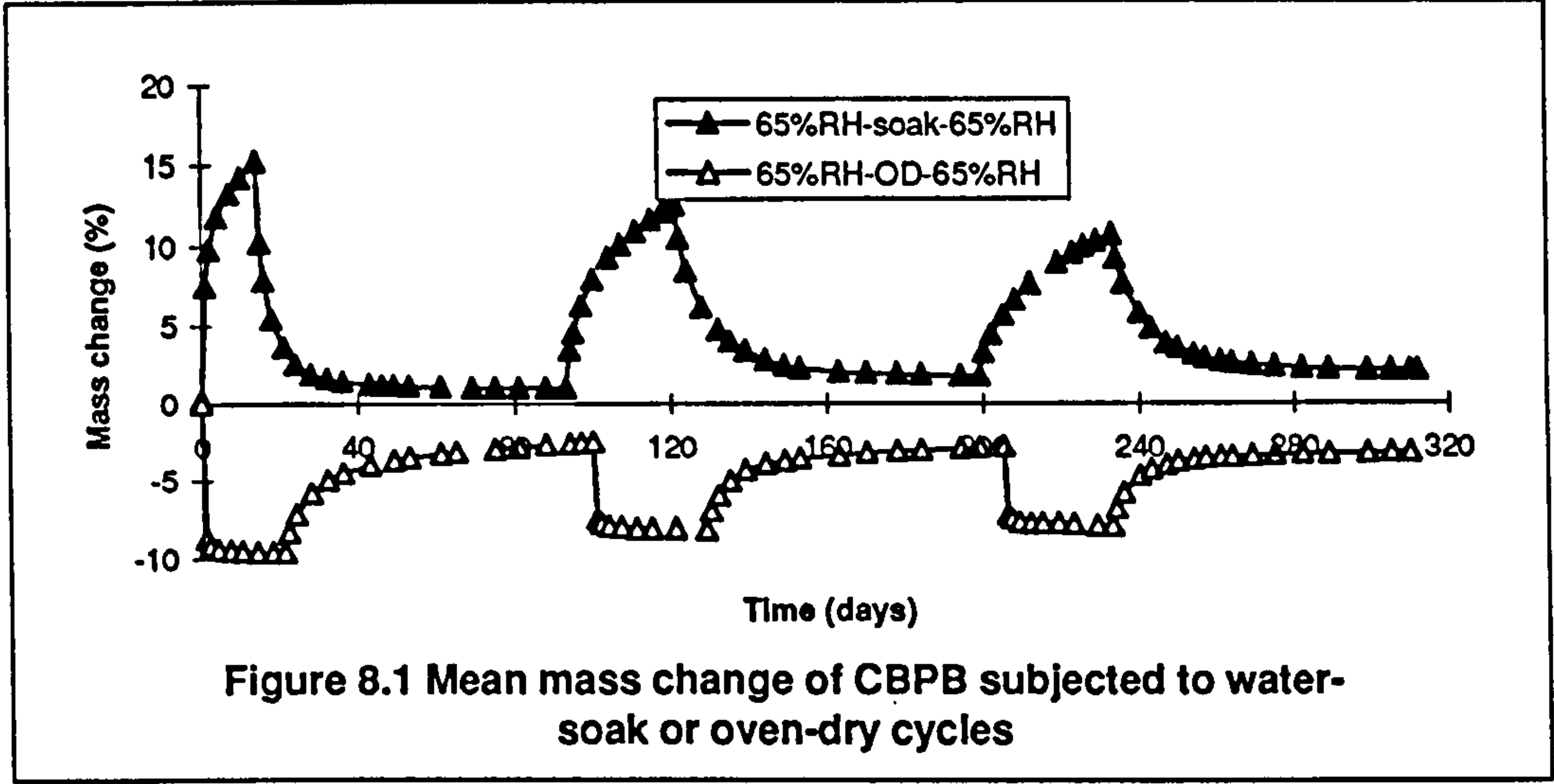
The fourth of these differences is the difference in the change between the length and thickness. Length change was higher but thickness was lower under water vapour than under liquid water soaking, showing the effect of the distribution of cement paste or wood chips across the thickness and length.

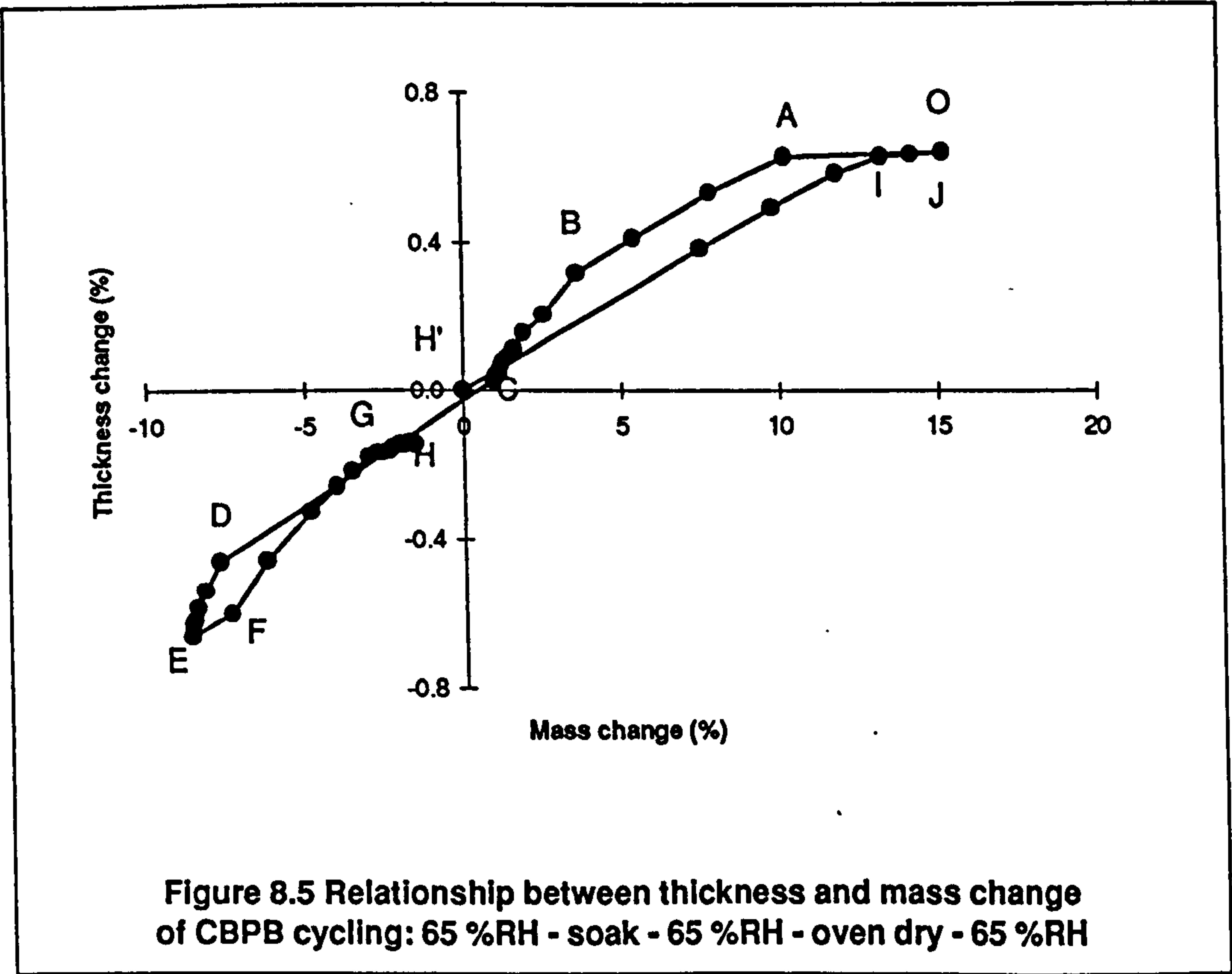
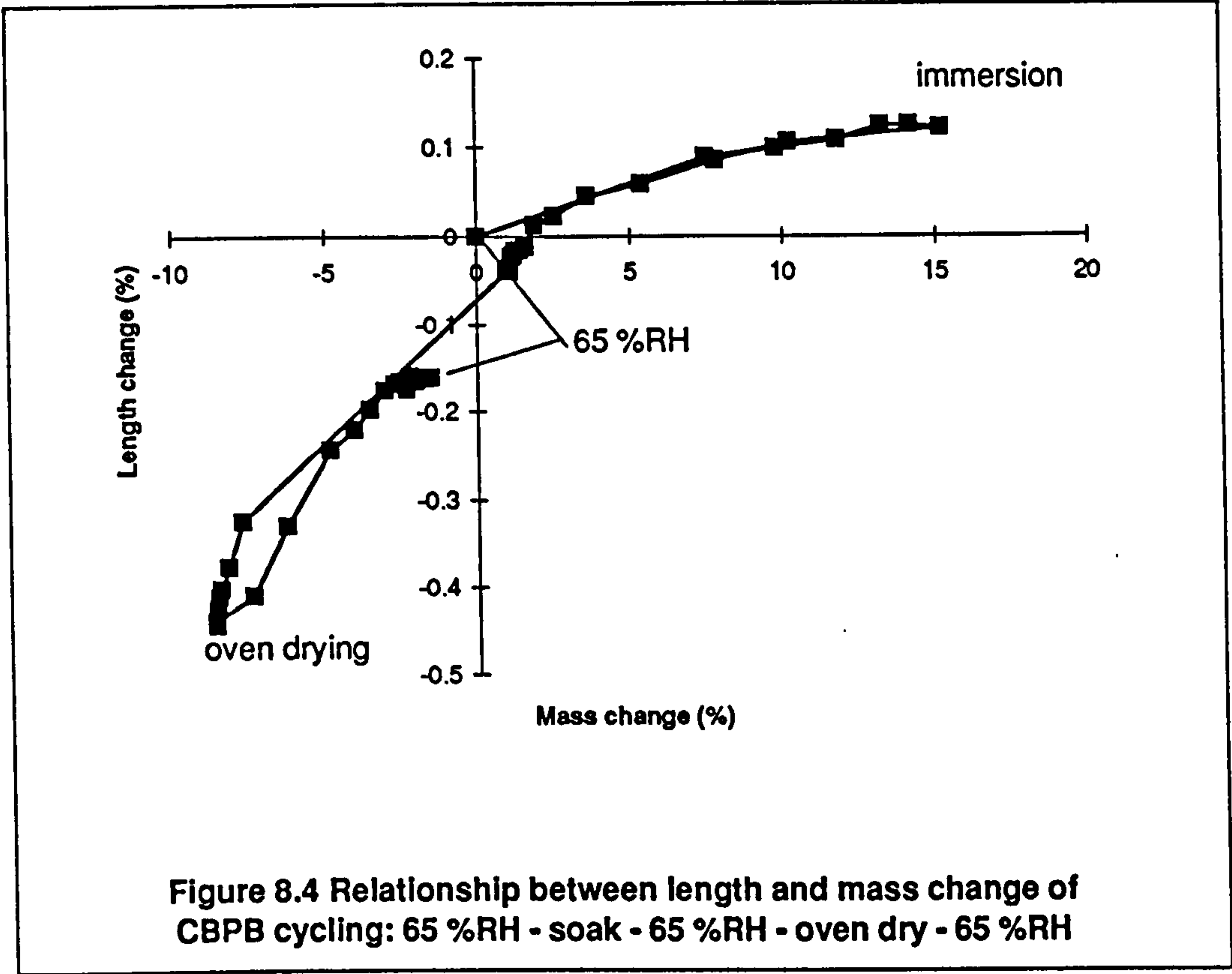
8.5 Interim Conclusions 5

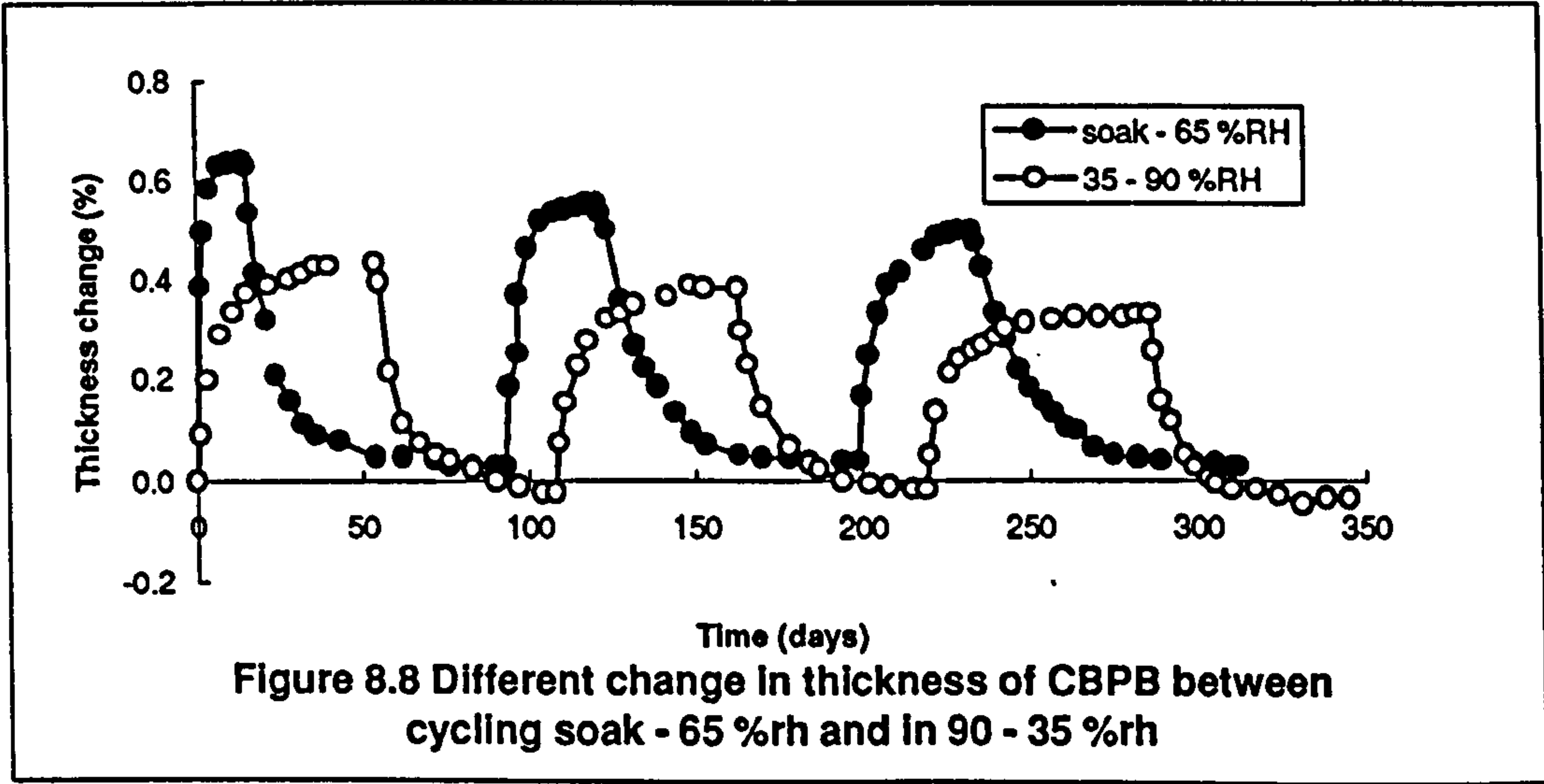
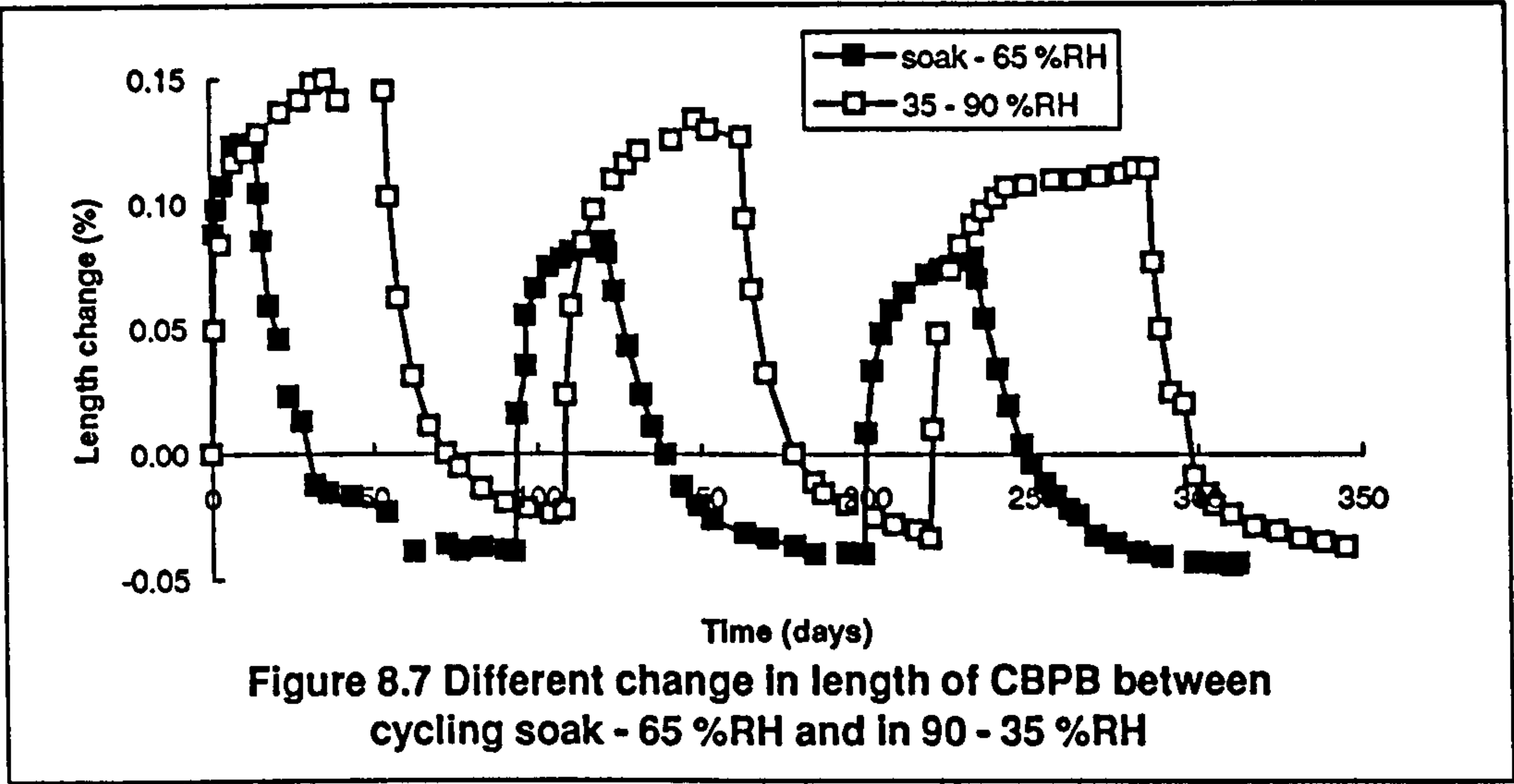
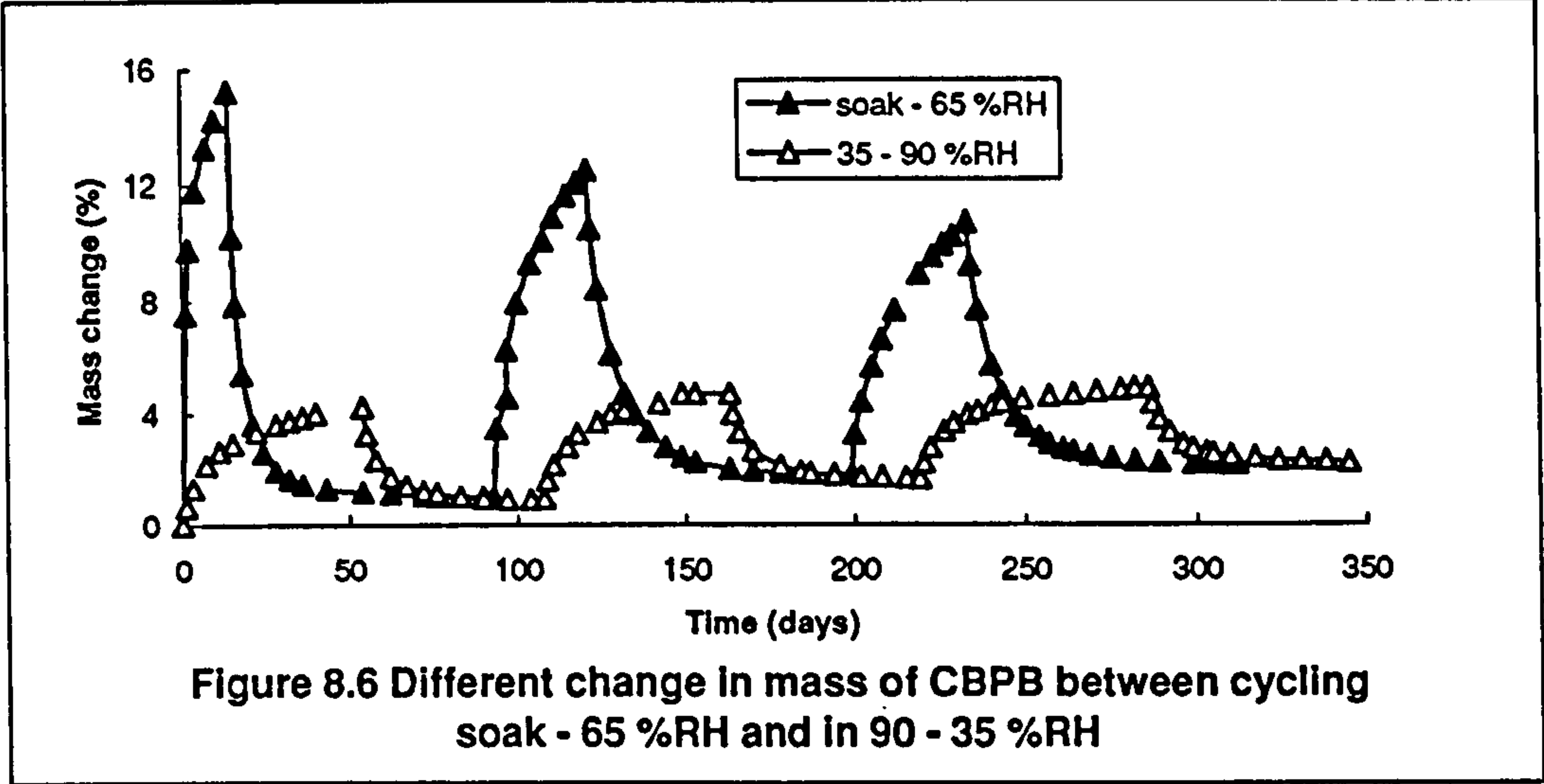
- 1) The deformation of CBPB over drying or wetting comprised at least five distinct stages, showing an association with the movement of different types of water, the features of both cement paste and wood chips, and with the exposure environments.
- 2) The plateau E - F at the beginning of wetting is evidence of two opposite processes counterbalancing each other.
- 3) Three significant differences occurred in the behaviour of CBPB between water soaking and oven drying treatments, including different mass and dimensional changes, different length and thickness changes, and different changes over successive cycles.

4) The behaviour of CBPB under liquid and vapour water exposure was considerably different. Four differences including the rate of change between mass and dimensions, the trend of change under successive cycles, the degree of irreversibility and the difference in change between thickness and length were noted.

5) Carbonation of CBPB occurred during exposure in the air environment, but was not observable in the water soaking. The carbonation of CBPB removed from water to air was not obvious at the beginning of exposure.







Chapter 9

THE BEHAVIOUR OF WOOD CHIPS IN RESPONSE TO THE ENVIRONMENT

9.1 Introduction

As stated before for CBPB, the total mass or dimensional changes were considered to be the combination of those of wood chips and cement paste. It was considered necessary to run similar experiments for these two components in order to determine their relative contributions to the composite.

In this chapter chips dissected from CBPB ("dissected chips") were subjected to corresponding conditions as those for the CBPB, that is, to single changes of RH and to cycling of RH.

The behaviour of chips has been evaluated, including the mass and dimensional changes with exposure time. Dimensional changes as a function of the mass change were also studied and compared to those arising from CBPB materials. The hysteresis loop was again produced. Part of chapter 9 evaluates whether there is a correlation between the parameters of the production of CBPB and the performance of wood chips at various stages of the production process.

9.2 Behaviour of Chips on both Adsorption (35 - 90 %RH) and Desorption (90 - 35 %RH)

Results

The mass change of chips dissected from CBPB is displayed graphically in Figure 9.1, which includes chips under both adsorption (moving chips from 35 %RH to 90 %RH) and desorption (moving from 90 %RH to 35 %RH). For ease of evaluation, the curves arising from raw wood chips and CBPB materials are given on the same graph.

The corresponding curves showing the length and width (thickness) changes of the chips dissected from the CBPB are provided in Figure 9.2 and 9.3.

Discussion

It appears that the change in mass of the chips dissected from CBPB was much lower than that of the raw wood chips, but higher than that of the CBPB. The change in the mass of the "dissected" chips due to moisture change was only slightly different between adsorption and desorption. The trends of the changes under adsorption and desorption followed those of the CBPB although the values of the changes were considerably different. For all materials, the changes occurring in the early stages of exposure were very significant, but after a certain period the rate of the mass change markedly reduced. However, under adsorption further exposure of the dissected chips resulted in a consistent increase in mass.

In contrast, instead of a marginal increase (as in the case of CBPB), prolonged exposure had no influence on the mass of the dissected chips under desorption. After 26 hours the changes in mass of the dissected chips under adsorption and desorption were 4.94 % and 5.41 % respectively, and after 173 hours 6.07 % and 5.86 %, while after 580 hours of exposure the values were 6.89 % for mass increase under adsorption but only 5.85 % (decrease) under desorption. This suggests that the liquid phase of the cement had (during manufacture) somewhat penetrated into the cell lumen (especially fractured cell lumen), fractured cell walls or other checks and cavities, if not into the cell wall, resulting in the bulking in the chips. This confirms the results presented by other authors (Ahn and Moslemi, 1980; Steward, 1986).

The inclusion of cement paste in wood chips played an important role in determining mass increase under adsorption (as discussed in the previous chapters). It increases the basic value of dissected chips due to the much higher density of cement paste. Hence, the mini pores in the cement paste are able to hold large quantity of water. It is apparent that the consistent increase in mass of dissected chips under adsorption at 90 %RH is attributable to moisture condensation on the cement paste in the chips by virtue of the absence of carbonation of CBPB over the short term period of exposure. This can be confirmed by the plots arising from the

dissected chips under desorption, in which, unlike the long term exposure of CBPB, the mass of dissected chips reached a constant value.

It is highly likely that the CBPB should be considered as a two - phase material. The strain and sorption may be quantified in terms of the moduli and volume concentration of the two components. This will be discussed in part 3.

It seems that there is somewhat of an exception for the change in dimensions of the dissected chips when compared with those from raw wood chips and CBPB (Figures 9.2 and 9.3). However, some subtle facts and relationships emerge by a scrutiny of the graphs, in conjunction with a consideration of the structure of CBPB and the degradation of wood chips under the alkali environment.

Firstly the dimensional change of dissected chips (under both adsorption and desorption) was higher than those of raw wood chips. This result was thought to be due to increased accessibility of moisture as a result of the increased hygroscopicity of the cell wall at presence of calcium hydroxide, particularly in the lower ordered regions within the cell wall, i.e. in areas of high hemicellulose and lignin content. This suggestion is in agreement with results found by Kollmann and Côté (1968); Steward (1988); etc. (section 2.4.4.1), who found that calcium hydroxide had a significant effect on the swelling properties of wood, inducing decreased rather than increased dimensional stability.

Another explanation for the higher dimensional changes in the dissected chips than in the raw wood chips was considered to be stress relief of individual wood chips contorted during fabrication, pressing and curing. In particular for CBPB products, a long period is required to cure the cement paste, inducing dimensional shrinkage of panels. Because the stiffness of cement paste is higher than that of wood chips, this extended curing could result in stress on the wood chips.

Secondly there were considerable differences in the changes in length and in thickness of dissected chips compared to CBPB. Over the time period investigated (about 360 hours), the change in length of the dissected chips (under both adsorption and desorption) was about 2.5 times higher than that of the CBPB. However, the width (thickness) change of the chips dissected from CBPB was about 15 times higher than that of CBPB.

This difference was explained by a combination of the structure of CBPB and

the nature of wood. The curves arising from both types of chips (Figure 9.2 and 9.3) illustrate the remaining of anisotropic characteristic of wood chips. However, the length change of CBPB was not only contributed to by the longitudinal change of the chips but also by the transverse change of the chips. On the other hand, the thickness change of CBPB was attributed not only to the transverse change but also to the longitudinal change of the chips. Consequently the rate of change in length of CBPB increases while the rate of change in thickness decreases as comparing to the rate of the change of the dissected chips.

Thirdly changes of the dissected chips, both in length and thickness, were much greater than those of CBPB. This was thought to be due to the bulking of the cell wall. The result also confirms the results reviewed (section 2.4.4). It is again illustrated that the behaviour of CBPB reflects the response of the chips and of the cement paste due to the effect of moisture.

Fourthly the lower change in the mass of the chips dissected from the CBPB compared with raw wood chips contrasted with the higher change in dimensions of the chips dissected compared with raw wood chips during exposure. This observation again reflects that during fabrication, the chips were penetrated with cement paste and most of the peripheral fractured cell lumens were filled with hydrated cement paste (as revealed by scanning electric microscopy by other authors: Ahn and Moslemi 1980; Steward 1986). That part of the cement paste absorbed by chips contributed to a reduced change of total mass change at unit mass, and the degradation of alkali solution may induce a decrease in the dimensional stability of dissected chips.

Fifthly the consistent increase in the mass of dissected chips under adsorption at 90 %RH did not occur in the dimensional change under the same exposure. The explanation of this lies in the effect of moisture condensation on the embedded cement paste.

9.3 Behaviour of Dissected Chips under Cyclic RH Conditions

Results

Like those subjected to a single change of RH, the mass change of dissected chips under cycling RH is presented in Figure 9.4. The length and thickness changes are plotted in Figure 9.5 and 9.6. The values of the changes are based on the maximum values of the dissected chips under 90 %RH. The behaviour of raw wood chips is also provided for comparison (dotted lines).

Discussion

Overall the same ranking order of mass, length and thickness changes occurred for dissected chips and raw wood chips under cyclic RH as under a single change in RH. At various stages during cycling the RH the change in the mass of dissected chips was about half that of the raw wood chips.

However, for the chips removed from the CBPB (but not the raw chips) mass increased with increasing number of cycles regardless of their small size (Figure 9.4), as with CBPB (Figure 7.3). This implies that a portion of the hydrated cement paste is lodged within the chips, and that the chips inside CBPB may undergo structural change with cyclic RH change. Over 3 cycles the increase in the mass of dissected chips (at 65 %RH) was about 1.3 % for desorption and 1.2 % for adsorption.

Change in dimensions of the chips dissected from CBPB under cycling RH (Figures 9.5 and 9.6) showed that, as for a single moisture change, the difference in change between the wood chips and the chips dissected from the CBPB is more significant in length than in width (thickness) though with a similar trend. The change in dimensions of the raw wood chips was less than those of chips removed from the CBPB board. Overall the change in the length of dissected chips was about 2 - 3 times that of raw wood chips, while the change in the width (thickness) of dissected chips was about 1.5 - 2 times that of raw wood chips.

With increasing number of cycles, only a slight decrease in the width (or thickness) of chips was observed at the end of 3 cycles (Figure 9.6). This may reflect a lack of sensitivity in the measuring equipment. The reason for the slight increase in length (Figure 9.5) over 3 cycles is unknown, though the hypothesis can be presented that the loosening of the structure due to cement penetration prevented recovery of the wood chips to its original dimensions during the cyclic RH exposure.

It was also observed that there was a different response of the dissected chips to different parts of the range in RH. High RH (90 %RH) brought about a continual increase in the mass of the dissected chips. The change in the mass of dissected chips in moving from 90 %RH to 65 %RH was less than that on moving from 65 %RH to 35 %RH. The rate in the change in transferring dissected chips from 35 %RH to 65 %RH is lower than that from 65 %RH to 90 %RH. A similar relationship was found in dimensional changes over the range of RH exposed. During one complete cycle: 90 % - 65 % - 35 % - 65 % - 90 %RH, the ratio of mass change was 1.0 : 1.2 : 0.9 : 1.6 for dissected chips, and the ratio of width (or thickness) and length change of dissected chips was 1.0 : 0.8 : 0.5 : 1.2 and 1.0 : 0.7 : 0.7 : 1.3 respectively. A complete examination of all these different responses of chips to cyclic RH indicates the nature of their contribution to the behaviour of CBPB. Since about 65 % of the volume of CBPB is comprised of wood, this high volume may have contributed to different dimensional changes of CBPB between lower and higher RH regions.

It is clear that the difference in the changes of length and thickness (width) of the dissected chips under both a single and cycle of RH was mainly characterized by the nature of wood (anisotropy) although the total change of the dissected chips could be supplemented by the cement paste embedded in it [observable in the thickness change at later stages of both ad- and de-sorption exposure (Figures 9.7 and 9.8)]. Under both cyclic and single changes of RH, the maximum change of the width (thickness) is about 10 times that of the length change per unit mass change over both adsorption and desorption.

9.4 Relationship between Dimensional and Mass Change of Dissected Chips

Results

Figures 9.7 and 9.8 show the results arising from the exposure of dissected chips under a single change of RH (including adsorption and desorption), while Figures 9.9 and 9.10 show the results from the exposure of the dissected chips to cycling RH (for the first complete cycle). The Figures all illustrate the relationship between length

and mass change, and between thickness and mass change.

Discussion

It seems a linear relationship covered almost the whole range of adsorption and desorption, whether under a single or cyclic RH change. However, there was an indication that after a period of exposure, the mass increase did not result in a corresponding thickness change of the dissected chips under a single change of RH (Figure 9.8).

9.5 Sorption and Dimensional Change Isotherms (Hysteresis Loops) of Dissected Chips

Results

The difference in the rate of change in mass between adsorption and desorption for dissected chips (between 35 %RH and 90 %RH) gives rise to the existence of hysteresis loops. Figure 9.11 shows a set of hysteresis loops of dissected chips as a function of RH (solid line); for comparison, the hysteresis loops of raw wood chips derived from the same experimental condition are included in the same graph (dotted line).

The corresponding hysteresis loops for dimensional changes, including change in the length and the thickness, are presented in Figures 9.12 and 9.13. The loops across the centre of the loops in Figure 9.12 were those of the length change of dissected chips.

Discussion

In Figure 9.11, it is apparent that the hysteresis loops of the dissected chips are not of the types for raw wood chips, but are more similar to those of CBPB (Figure 7.7). The similarities include:

- 1) In each hysteresis loop, a gradual mass loss appeared on desorption, whilst the

mass change on adsorption was more dependent of the level of the RH. The regain in mass under lower RH was slower than under higher RH. Hence, compared to the rate of mass decrease on desorption, the rate of regain in mass in moving dissected chips from 35 %RH to 65 %RH was lower, whilst that from 65 %RH to 90 %RH was higher than those representing the mass loss when the corresponding range of RH was reversed.

2) There exists an intersection between the adsorption and desorption curves. The location lies between 65 %RH and 90 %RH, depending on the cycles. In other words, the loops do not close at the ultimate RH cycled, but the intersection divides the loops into two parts, one closed and another open.

3) The isotherm curves within one complete cycle seem to follow the rule of the moisture reaction only for desorption and adsorption at lower RHs. The isotherm curve for adsorption at higher RH was influenced by moisture condensation.

4) The area of the closed part of hysteresis loop increases with the number of cycles. In other words the intersection is approaching the extreme end of the RH cycle if dissected chips are continuously cycled.

5) The vertical movement of the hysteresis loop of the dissected chips was very clear. This suggests that the mass of the dissected chips increased consistently with successive cycles. At 90 %RH, the increase in the mass of the dissected chips was 1.01 % and 2.44 % for the first three cycles and first six cycles respectively.

This similarity between CBPB and dissected chips confirms the penetration of the cement paste into the wood chips. It strongly indicates that the embedded cement paste plays an important role in the mass change when dissected chips are exposed to moisture change.

Comparison of the slope of the hysteresis loops arising from dissected chips with those derived from raw wood chips shows a great reduction in the significance of the change in mass of dissected chips. Alkali effects on the wood result in a higher swelling and mass decrease which are the reverse to the phenomenon above, such that the bulking of the cement paste could be the only explanation. The effect of bulking of cement paste is reflected in three ways: one is the restraint on the chip when it swells (normally much higher than cement paste); another is the higher density of cement paste increasing the basic value; and the third is the reduced

moisture adsorption in unit cement paste than in unit wood chip over the range of RHs investigated (see chapter 4 for moisture content) (this is valid in the case without moisture condensation). This also makes it possible to explain the different relationship between the loops of dissected chips and that of raw wood chips at low and high RHs (Figure 9.11), that is, the loops of the dissected chips at 35 %RH is much higher than those of raw wood chips, but at 90 %rh is similar during the first several cycles.

It should be noted that the moving up of the loops of dissected chips with the cycles may not only be caused by carbonation of cement paste embedded within the chips, but also be attributable to the further penetration of cement paste, inducing expansion in the wood chips which may not be recovered on drying.

In addition to the specific changes in the mass, the features pointed out in Figures 9.11 can be seen in the hysteresis loops arising from the thickness (width) changes of dissected chips, Figure 9.12. The hysteresis loops of dissected chips are moving downward as the number of cycles increases. The adsorption curves are not able to reach the desorption curves within one complete cycle, forming a open loop as that arising from CBPB. Hence, compared to those arising from raw wood chips (which form a closed loop), the maximum width of the hysteresis loops derived from dissected chips is narrower.

It can be seen that there is an exception for the length change, in Figure 9.13. This was explained in previous sections.

The hysteresis loops arising from mass change, thickness change and length change are different compared to the corresponding loops of raw wood chips. The loops for the mass change of dissected chips in the first three cycles are higher than those of raw wood chips only for a low range of RH, and all other loops for mass change are significantly higher than those of raw wood chips. The loops for the thickness (width) change of dissected chips are slightly higher when RH approaching to 90 % but lower when approaching 35%RH compared to those arising from the raw wood chips. The loops for the length change of dissected chips are higher than those of raw wood chips over whole range of RH investigated.

9.6 Behaviour of Wood Chips Removed at Different Stages in Board Manufacture under Cyclic RH

Five types of the chips from different stages of the production process were subjected to cyclic RH after two months storage at 20 °C / 65 %RH. The mass and dimension changes were examined.

The behaviour of these chips under a first adsorption at 90 %RH is presented in Figure 9.14, and Figures 9.15 A and 9.15 B. The change in mass of the five types of chips during three cycles is provided in Figures 9.16 A and 9.16 B. The corresponding changes in the width / thickness and length are shown in Figures 9.17 A, 9.17 B, 9.18 A and 9.18 B.

9.6.1 The Effect of the First Adsorption at 90 %Rh

It appears that there is a very different response to moisture for the five types of chips. In Figure 9.14, the rate and amount of adsorption of the chips coated (after mixing) but un - pressed was considerably lower compared to the other types of chips; while the rate and amount of adsorption for raw wood chips and chips collected from the edges of the board after pressing and heating (first oven "boosting") was greatest. Increase in the mass of chips dissected from boards lay between them. Chips dissected both from boards prior to final conditioning and from the final product showed very similar changes in the mass.

For both raw wood chips and chips collected from the edges of boards after the first oven boosting, considerable adsorption occurs during the first 24 hours, and after about 40 hour exposure constant values were obtained for the mass change of raw wood chips. However, the increase in the mass of the chips collected from the edges of boards was consistent over the whole period tested. Other chips, furnished (after mixing) or isolated from the board, show a gradual change in mass over whole range of RHs, though with a greater rate of change in the first stages than that at later stages (with the exception of furnished chips, which only had a slightly increase during the later stage of exposure).

The observations above not only confirm the penetration of the cement paste into

the wood (the diffusion of calcium hydroxide from the cement paste liquid phase), which cause a delayed increase compared to the change in the raw wood chips, but also confirm the effect of temperature on the degree of degradation of wood (section 2.4.2). Besides this, the additional explanation for the two extreme phenomena for chips collected from the edges of board and furnished chips (after mixing) is that after mixing, the surface of the wood chips were thoroughly covered with the cement paste and soaked with the liquid. Storage under 20 °C / 65 %RH resulted in a natural curing of the cement paste in the chips. In terms of shrinkage during curing, the higher the temperature, the higher is the size of the pores in heated, curing paste. The furnished chips not only are more integrated but also restrained by the enveloping stiff cement paste. When exposed to moisture it not only presented less space for the moisture, but also swelled less due to restraint. This brought about a reduced mass increase.

The extremely high moisture adsorption of the chips collected from the edges of CBPB was probably due to both the amount of cement paste contained and the penetration of cement paste. Compared to the chips coated but without any further processing, the penetration of the cement paste into these chips is very unlikely to be deeper due to the intensive curing during heating; compared to the chips isolated from the CBPB, the penetration of the cement paste into these chips is less due to the pressure which did not affect the chips located on the edges but did affect the chips inside the board. Less penetration of the cement paste makes this type of chip more representative of the nature of raw wood chips, resulting in a significant change of mass at first exposure, while the content of the cement paste made this type of chip change consistently in mass over the whole period of exposure.

A similar relationship can be seen for dimensional change with two exceptions (Figures 9.15 A and 9.15 B): one of these is that dimensional change of raw wood chips were lower than those of chips collected from the edges of boards or of chips isolated from the CBPB. This exception has been discussed in a previous section. The second exception is the dimensional increases in the furnished chips were less than those of the raw wood chips. This confirms that the furnished chips are more integrated and that cement covering the outside of the chips may restrain the swelling.

It should be noted that the slight deviation between relationships of dimensional change and relationships of mass change amongst the various chips may be attributable to the sensitivity of the measuring equipment. However, deviation in the stress or contortion among the different types of chips could be one of factors.

9.6.2 The Response to Cyclic RH

Generally speaking, the ranking order for the behaviour under cyclic RH between five types of chips is the same as those under first adsorption, with an exception for the chips collected from the edges of board. There exists unique characteristics for all types of furnished chips: all furnished chips exhibited a consistent increase in mass change with number of cycles but not for the raw wood chips. The explanation of this has been provided in a previous section. For the change in the mass within each cycle, both mass decrease under desorption and mass increase in moving the chips from 35 %RH to 65 %RH were very similar between the chips collected from the edges of the board and the furnished chips (after mixing). However, even after 3 cycles, the increase in the mass of the chips collected from the edges of the board was still very significant on transferring samples from 65 %RH to 90 %RH. The consistent increase of this type of chips between successive cycles is also most significant. These results indicate two characteristics of the chips collected from the edges of board: one is a dominant role of the high percentage of the cement paste contained in this type of chips and another is the loose structure of this type of chip.

For the dimensional change of the different types of chips under cyclic RH, relatively the change of the chips coated (but un - pressed) was extremely low, as were the chips collected from the edges of board. However, the chips dissected from the final product showed a great change in dimensions. This phenomenon may confirm one of the assumptions, i.e. the higher dimensional change of chips dissected from the CBPB compared to that of raw wood chips is due to the stress relief of the individual chips distorted during manufacture. It is also attributable to the combined effects of temperature and alkali environment.

Considered with respect to the pressure and temperature during manufacture of CBPB, it is apparent that in terms of the importance of the penetration of the cement

paste, both the duration after mixing and the pressure during pressing have a favourable influence on the stability of coated chips. Temperature normally has an adverse effect on the chips, however it could bring about a favourable effect on the flow of the cement paste liquid and shorten the curing period, consequentially changing the structure of the cement paste in the CBPB. The increase in the size of the pores on heating cement paste could result in less moisture adsorption under a normal service environment, but not under high RH, and this may have been misunderstood at the current time. The results on the components above confirmed the difference in response to RH change when assessed in terms of mass and dimensions. This manifested itself not only in terms of changing values with increasing number of cycles, but also in the fact the relative values for raw chips and various types of furnished chips differ when expressed in terms of mass and dimensions.

9.7 Interim Conclusions 6

- 1) The change in the mass of the chips dissected from CBPB, due to the moisture change under a single change of RH, lay between those of the raw wood chips and CBPB. i.e. the change in the mass of raw wood chips > dissected chips > the CBPB.
- 2) The nature of change on moving chip samples from 35 %RH to 90 %RH was close to that of CBPB, confirming that the cement liquid had penetrated into the cell lumen, fractured cell walls and other checks or cavities. Inclusion of cement paste in wood chips brought about a dominant effect on the increase of the mass of dissected chips at the late stage of exposure at 90 %RH due to the effect of moisture condensation.
- 3) Unlike for CBPB, under desorption a prolonged exposure had no influence on the mass change of chips dissected from final product, due to the lack of (or only very slight) carbonation of the cement paste embedded in the chips.
- 4) The dimensional changes arising from the dissected chips were higher than those

arising from raw wood chips, suggesting that there was an increase in accessibility of moisture as a result of the increased hygroscopicity of the cell wall at presence of calcium hydroxide, and / or there was stress relief of the individual wood chips which had contorted during fabrication, pressing and curing.

5) Over the time period investigated, the change in length of the dissected chips was about 2.5 times higher than that of the CBPB, but about 15 times higher for the width (thickness).

6) Overall the same ranking order of mass, length and thickness changes occurred between dissected chips and raw wood chips under cyclic RH as under a single change of RH. At various stages of RH, the change in the mass of dissected chips was about half that of raw wood chips, while the change in the length was about 2 - 3 times higher and the change in the thickness (width) was about 1.5 - 2 times higher than those of raw wood chips.

7) As the number of cycles increased, the mass of dissected chips increased consistently, implying the inclusion of cement paste into dissected chips which exhibited the nature of cement paste.

8) Only a slight decrease in width (thickness) of the dissected chips was observed with increasing number of cycles. However, the length slightly increased, which was hypothesised to be due to the loosening of the structure of dissected chips.

9) There existed a different response of dissected chips to different parts of the range of RHs and to different histories of sorption.

10) The hysteresis loops of the dissected chips were not of the types of raw wood chips (which remain the nature of wood), but were more similar to those of CBPB. The nature of hysteresis loops for mass change was:

a) In each hysteresis loop, a gradual mass decrease appeared under desorption, while the mass change under adsorption was more dependent of the level of the RH.

Hence, the rate of regain in mass in moving dissected chips from 35 %RH to 65 %RH was lower, and that from 65 %RH to 90 %RH was higher than the rate of mass loss in the corresponding RH reduction.

b) There existed an intersection between the adsorption and desorption curves. The location lay between 65 %RH and 90 %RH depending on the cycles. The intersection divided the loops into two parts, one closed and another open.

c) The area of the closed part of hysteresis loop increased with the number of cycles.

d) The vertical movement of the hysteresis loops of dissected chips was very clear, suggesting the mass of dissected chips increased consistently with successive cycles due not only to carbonation but also further penetration.

11) Comparing the slopes of the hysteresis loops for dissected chips and raw wood chips, there was a great reduction in the significance of the mass change of dissected chips, reflecting the effects of bulking of the cement paste, including restraint on the chip, the higher density contribution to the basic value and less moisture adsorption per unit of cement paste than per unit of wood chip.

12) The hysteresis loops arising from the dimensional changes were moving downward as the number of cycles increased. The adsorption curves were not able to reach the desorption curves within one complete cycle, the open loops occurred like those arising from CBPB.

13) Compared to those arising from the raw wood chips (which form a closed loop), the loops arising from dissected chips were located differently, depending on the mass, length or thickness, and on the range of RH.

14) The maximum width of the hysteresis loops derived from dissected chips was narrower than that of the loops derived from the raw wood chips.

15) The relationship between the dimensional change to the mass change for dissected chips also followed the trend of that of CBPB, showing the inherent nature

of the wood chips and the cement paste. This also confirmed the penetration of the cement paste.

16) Chips from the various stages of the production process showed very different responses to RH. Generally the chips coated without any further treatment were the most resistant in terms of both mass and dimensions. Raw wood had the greatest change in the mass while chips dissected from final product had the greatest change in dimensions.

17) The chips collected from the edges of boards were very sensitive to the high RH (90 %RH), showing substantial increases in mass due to the percentage of cement paste. However, the change under desorption and adsorption over lower RH behaved similar to those of chips after mixing.

18) All types of furnished chips showed a consistent increase in mass with number of cycles. A slight decrease occurred in the thickness (width) change with cycles.

19) Considering the effect of the parameters of the production, the results confirmed that the duration after mixing and pressure during pressing had a favourable influence on the behaviour of the chips due to increased penetration of the cement paste; conversely temperature had an adverse effect.

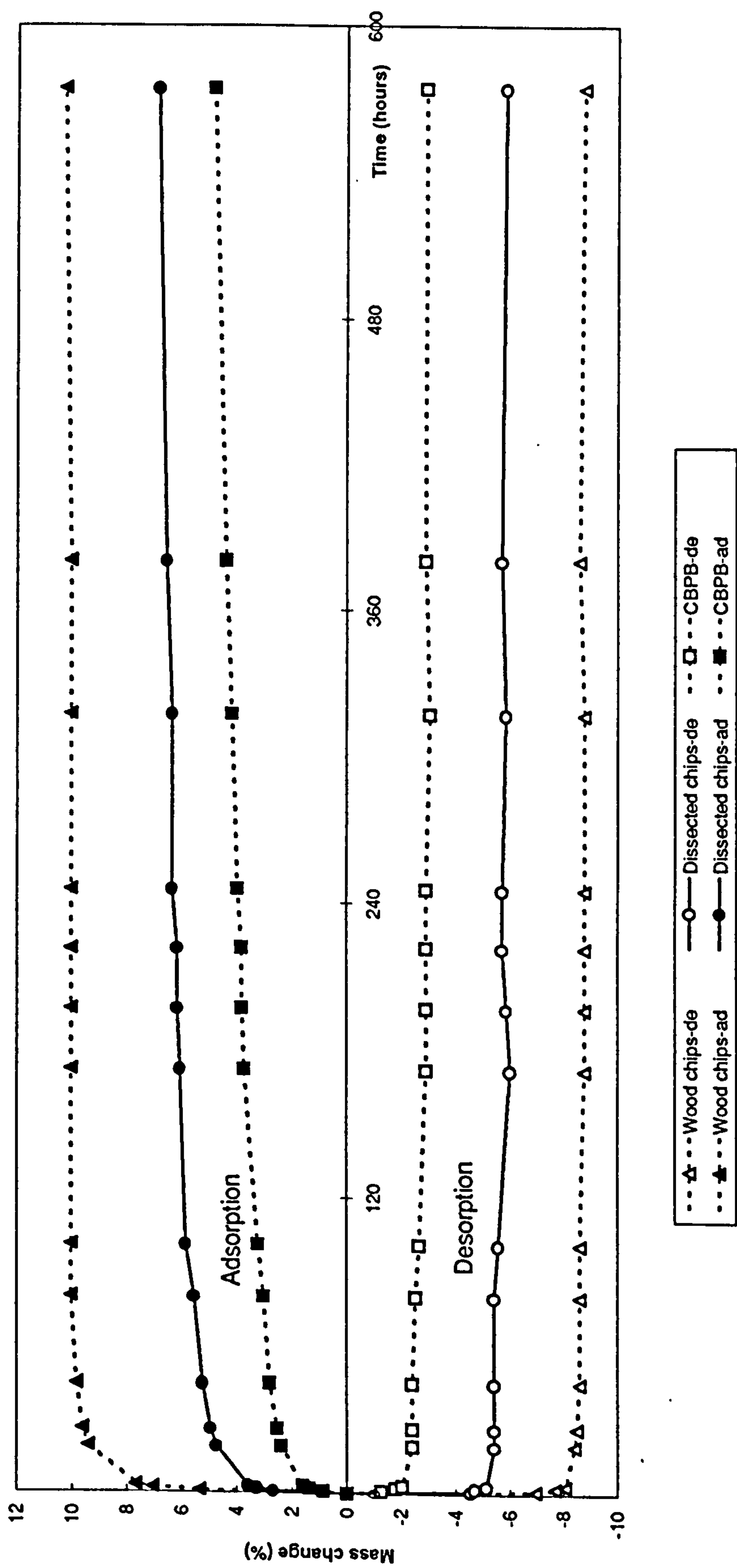
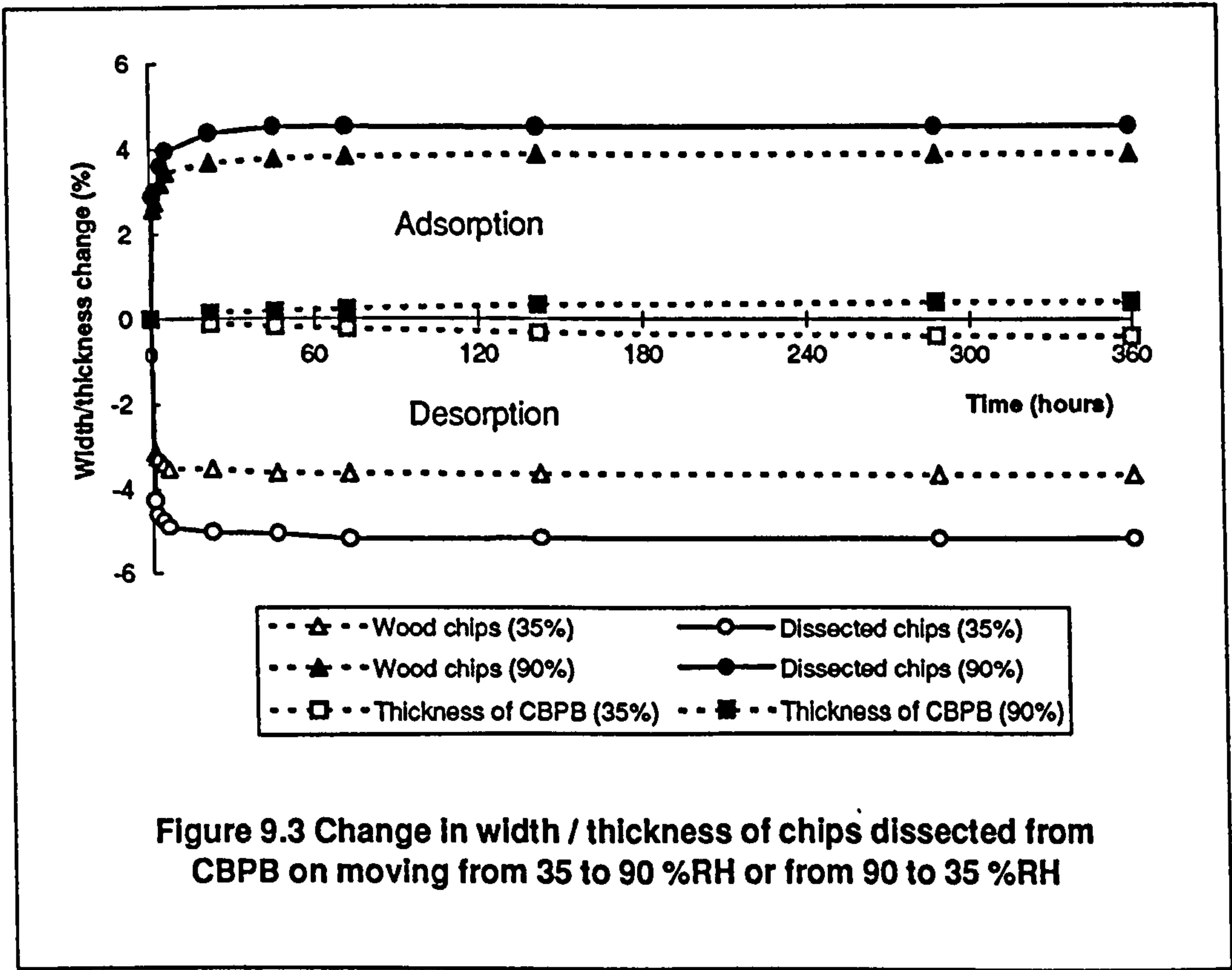
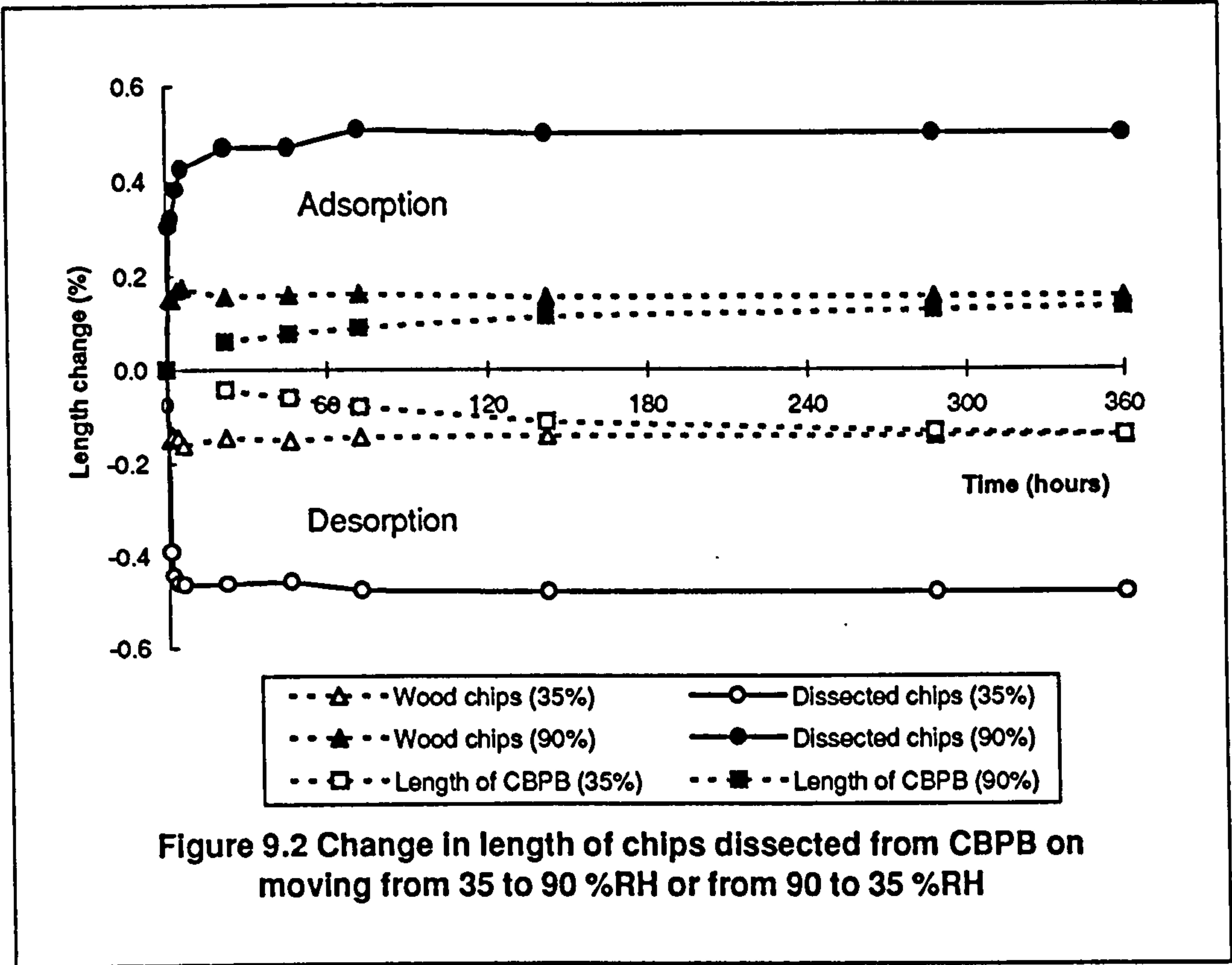
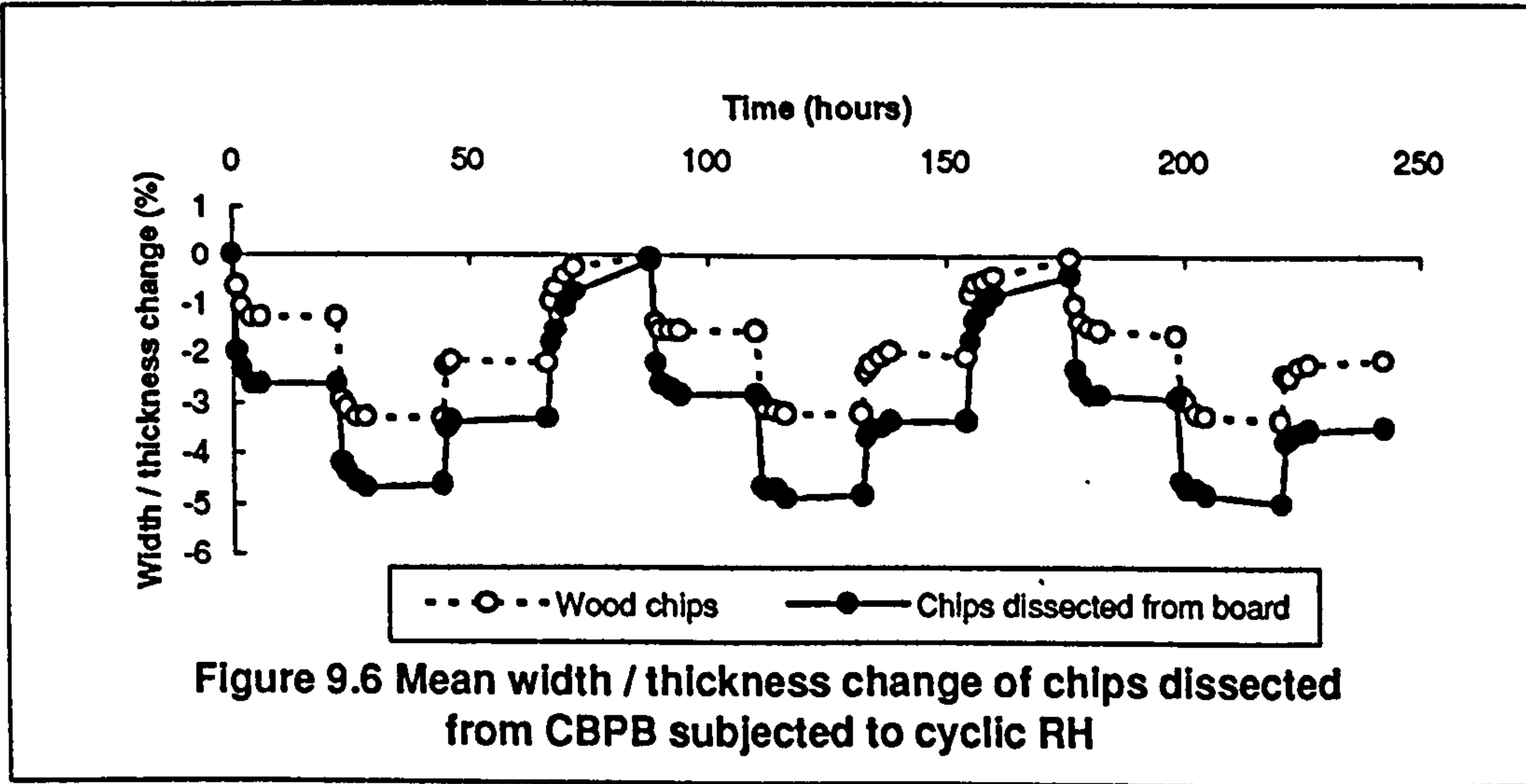
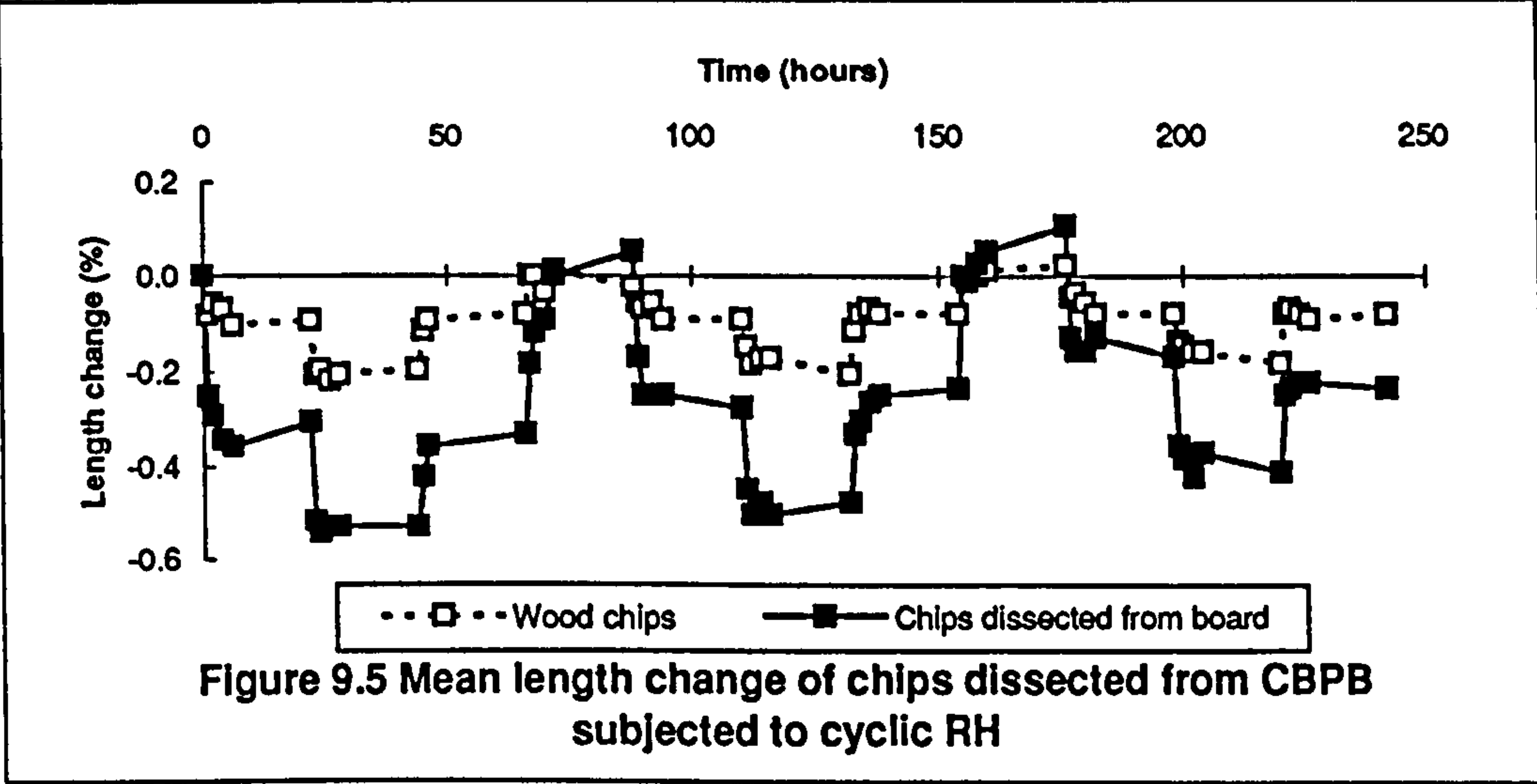
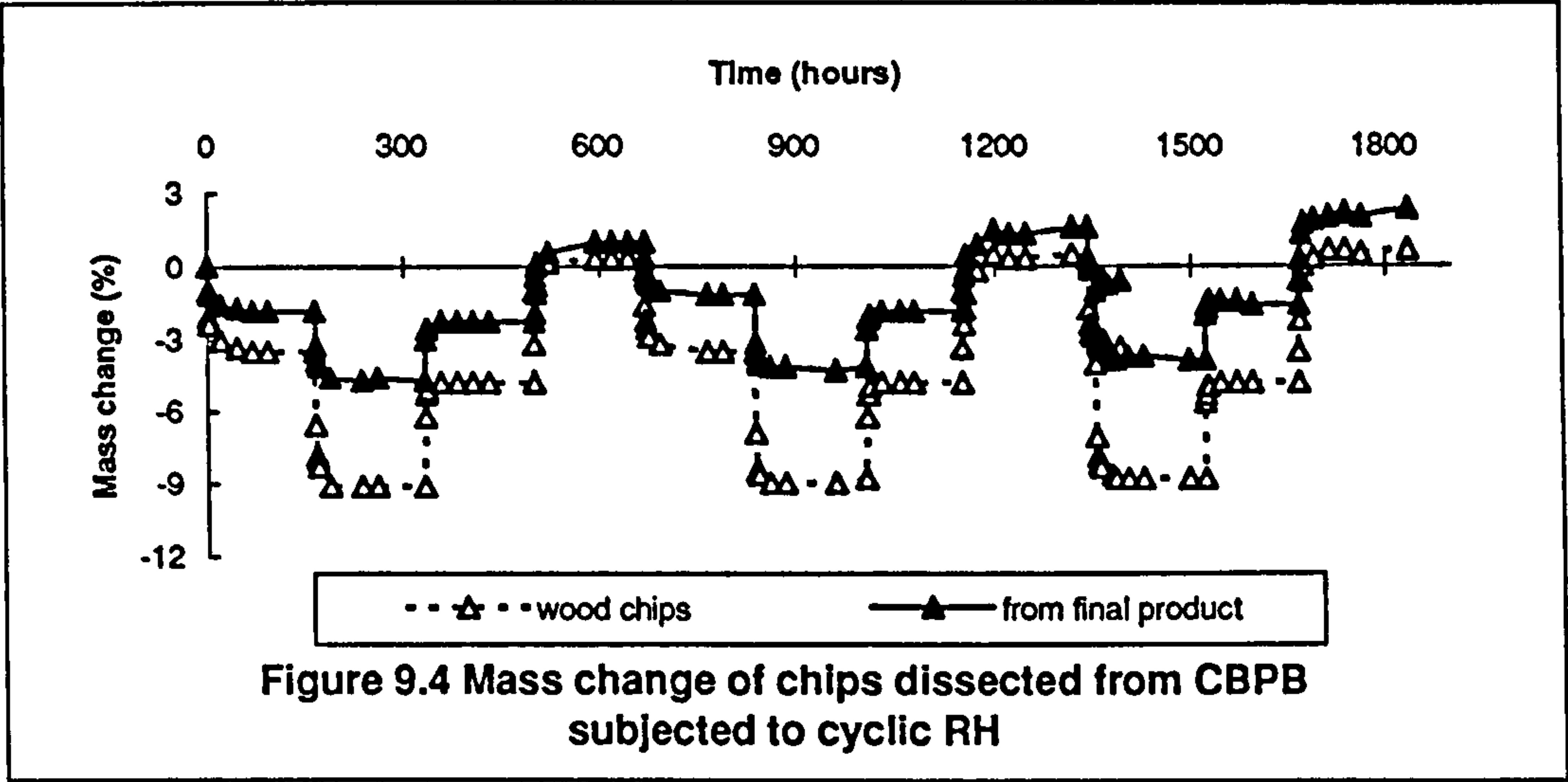
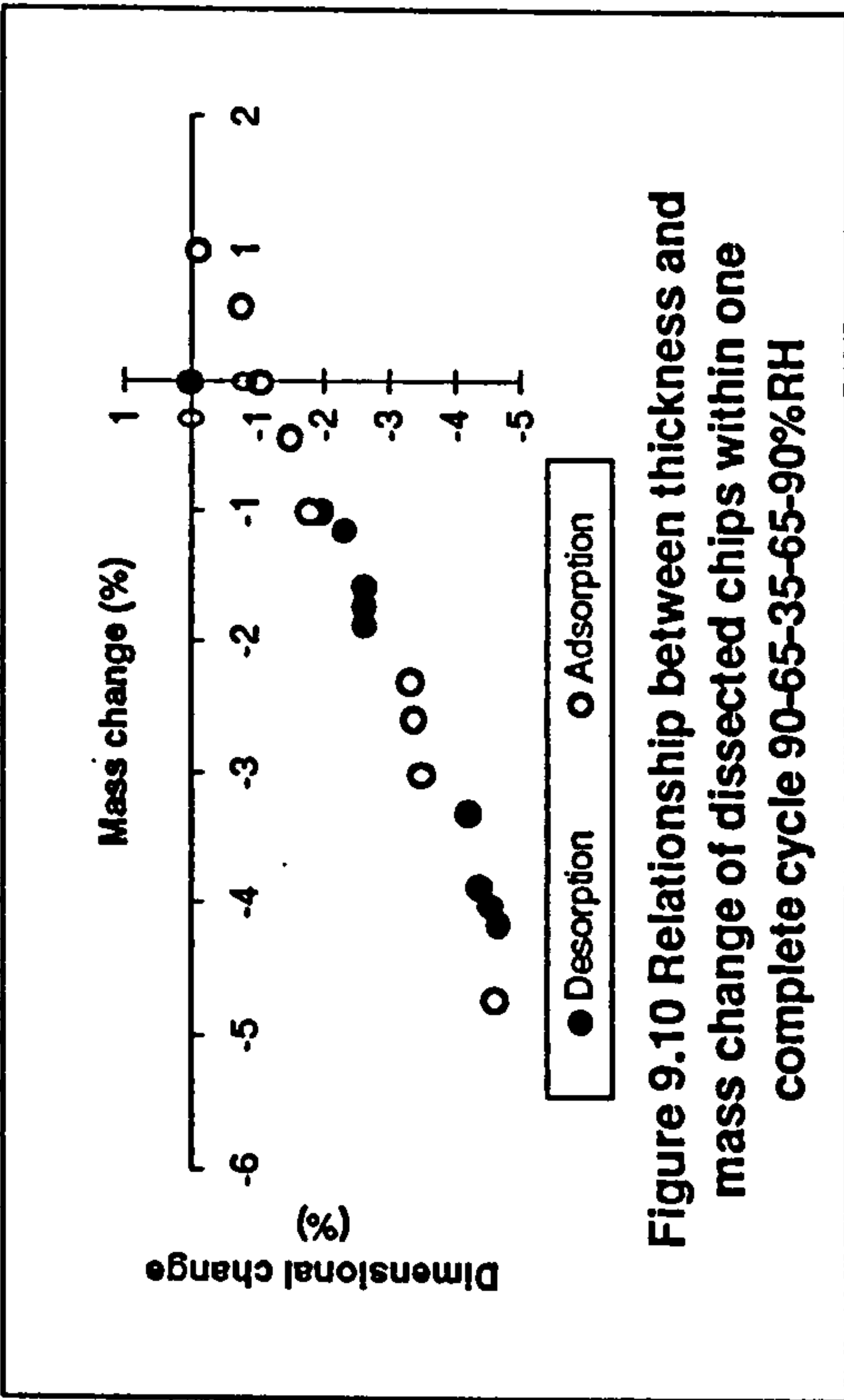
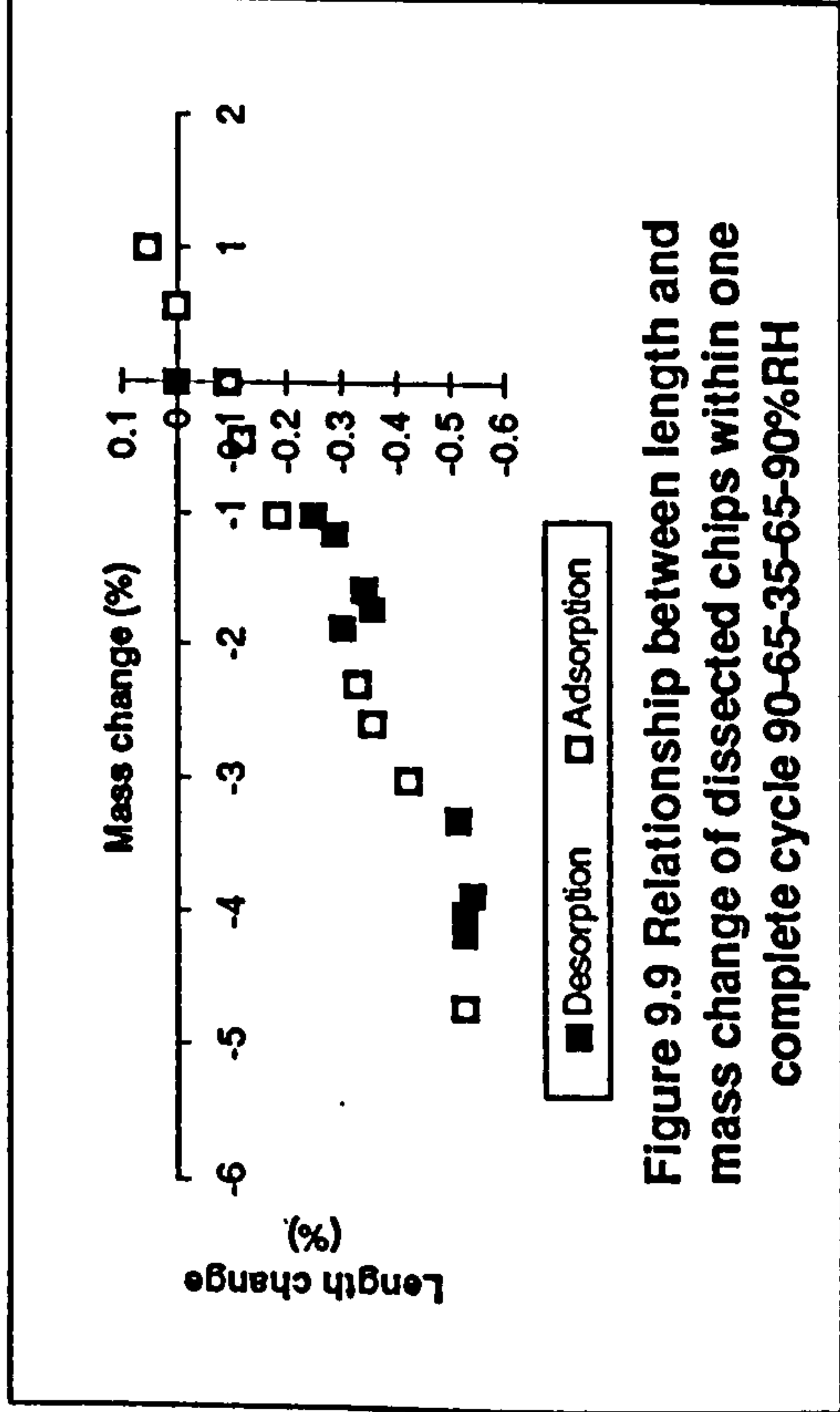
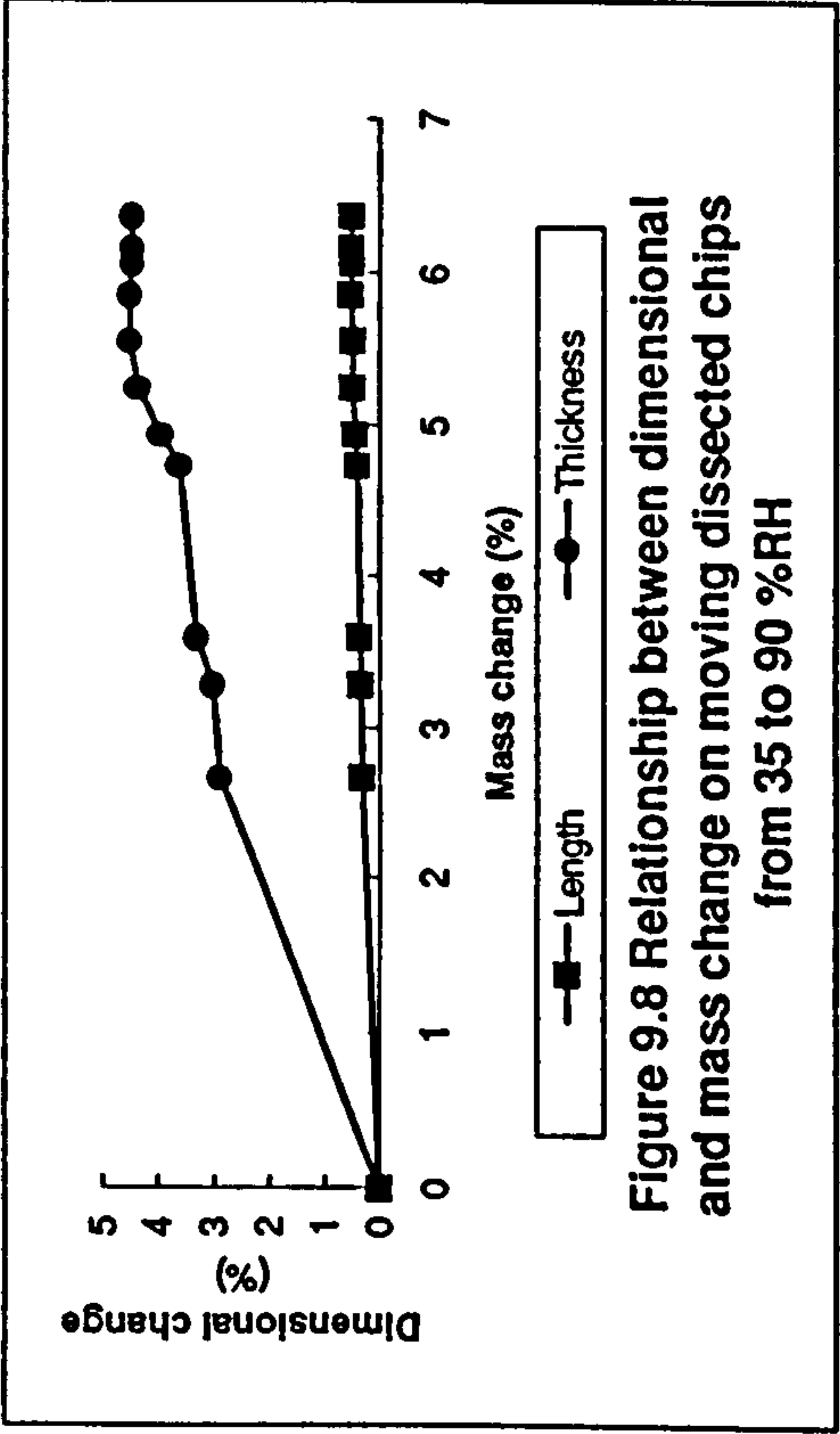
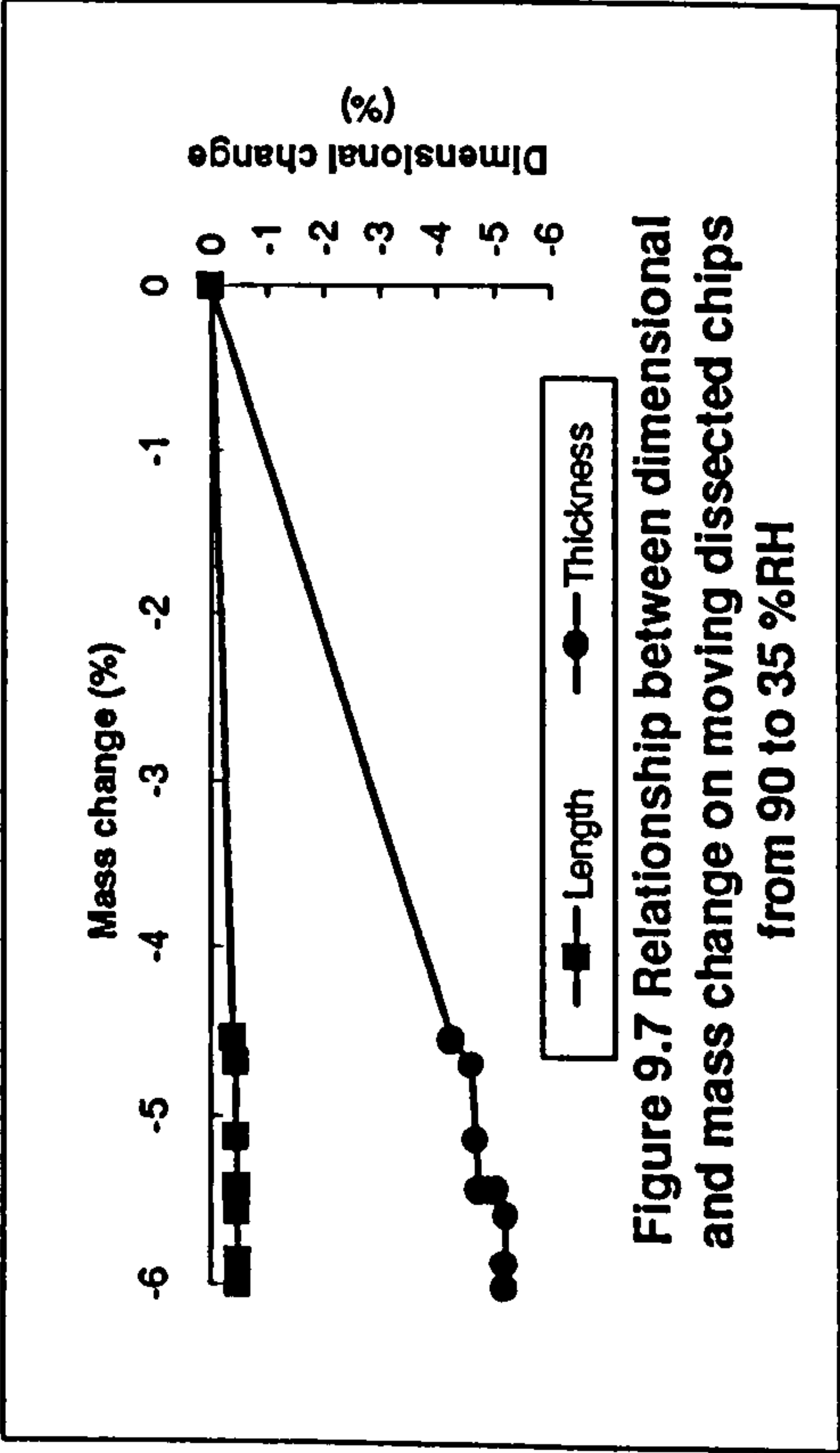


Figure 9.1 Mass change of chips dissected from CBPB on moving from 35 to 90 %RH and from 90 to 35 %RH







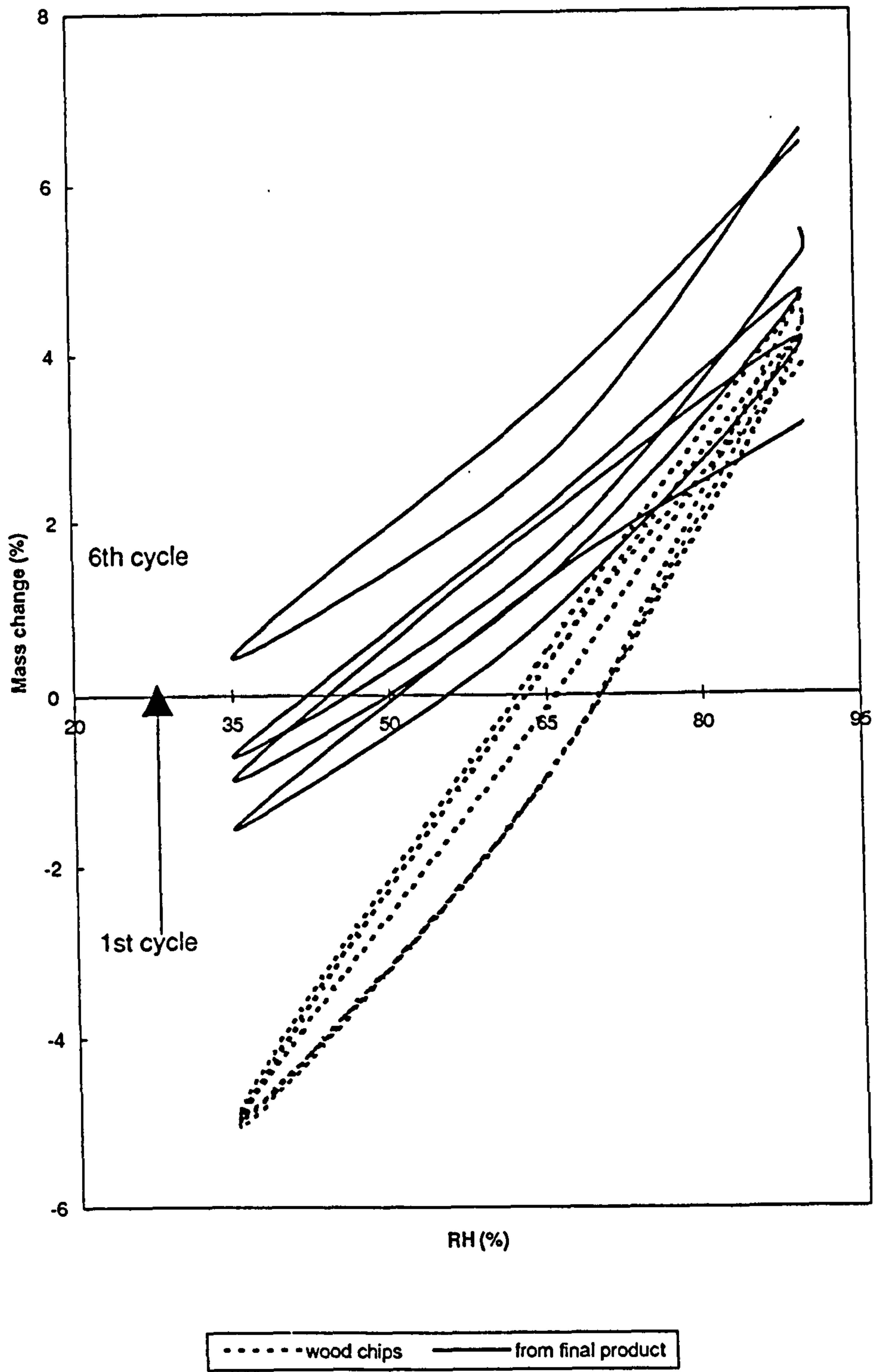
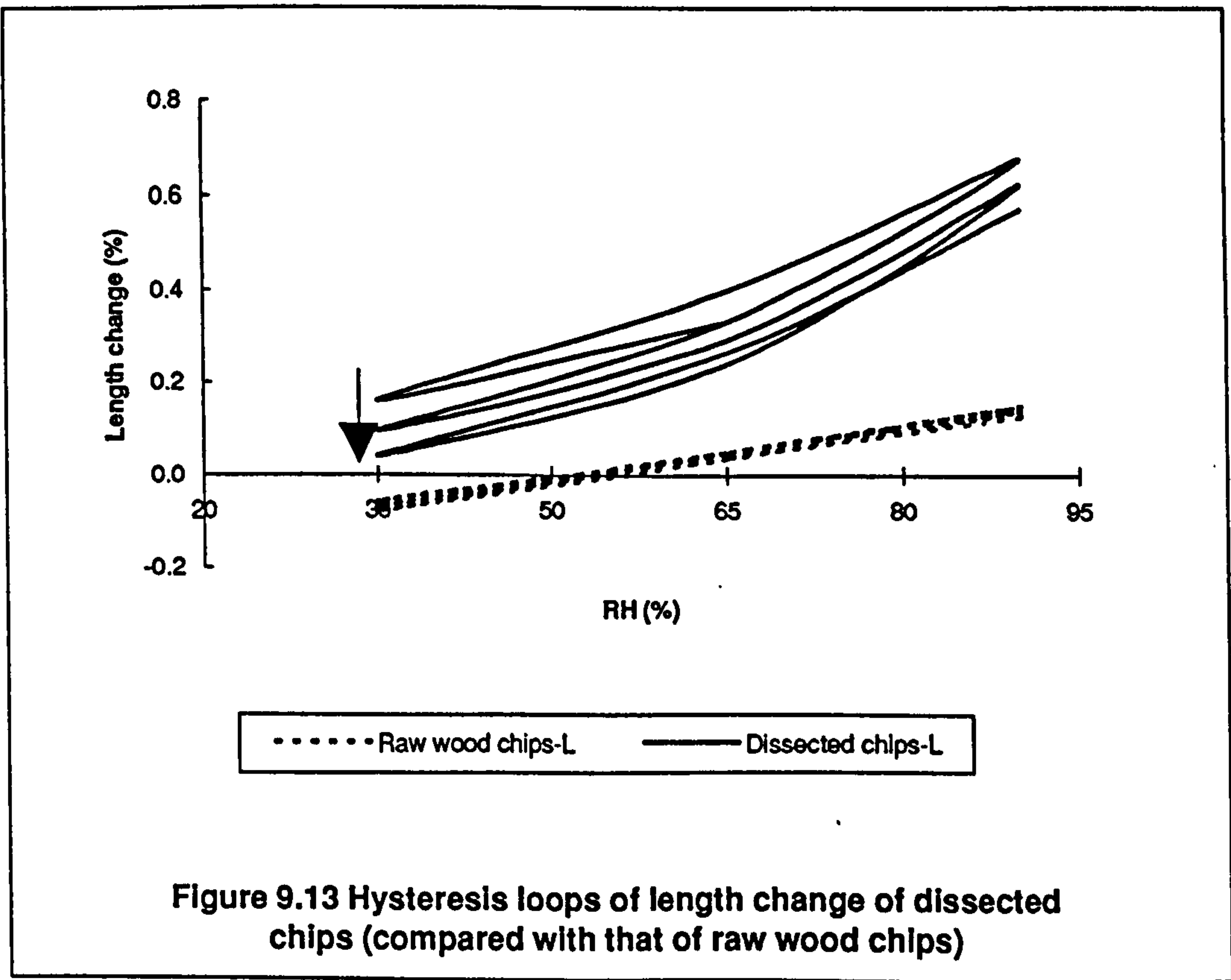
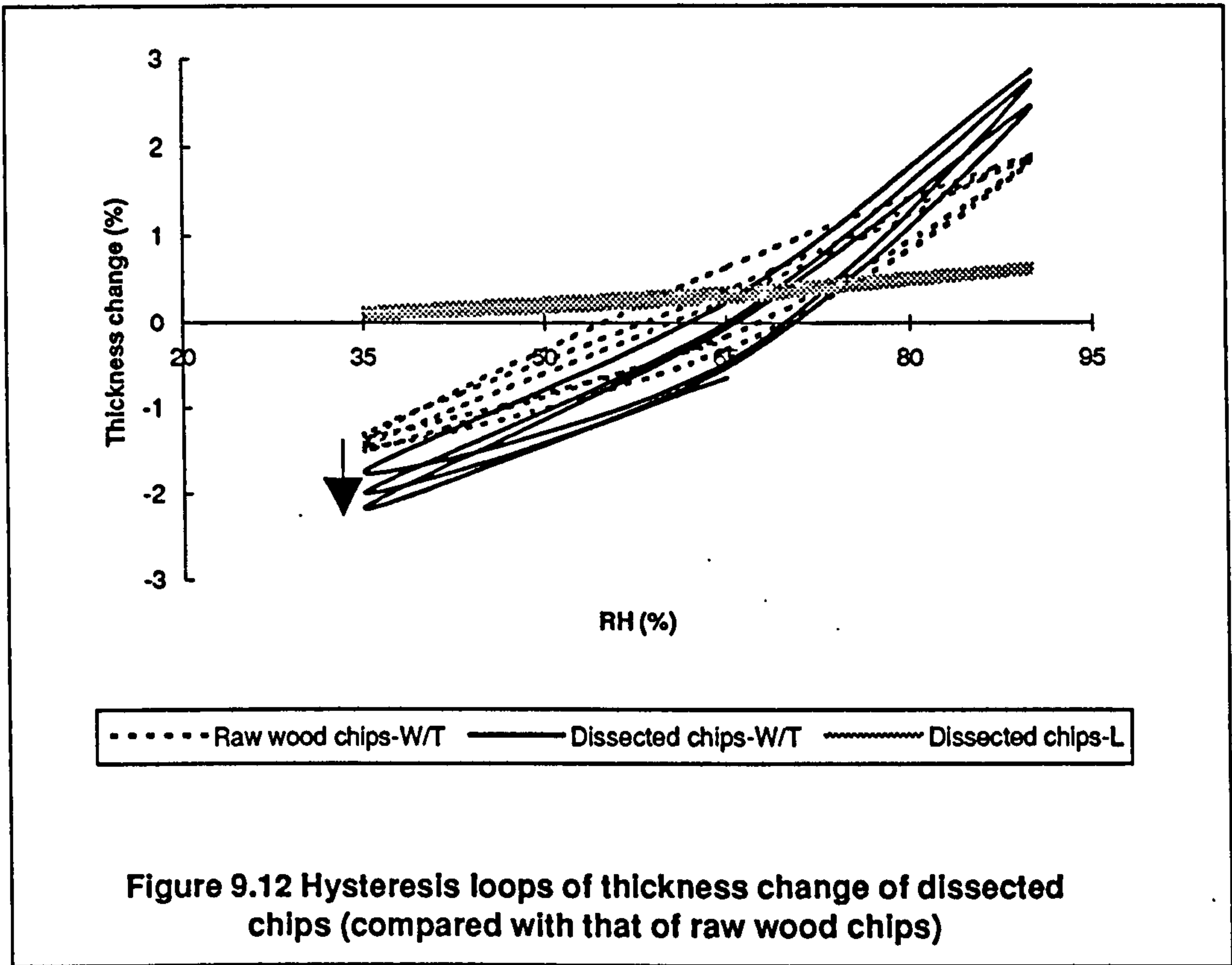
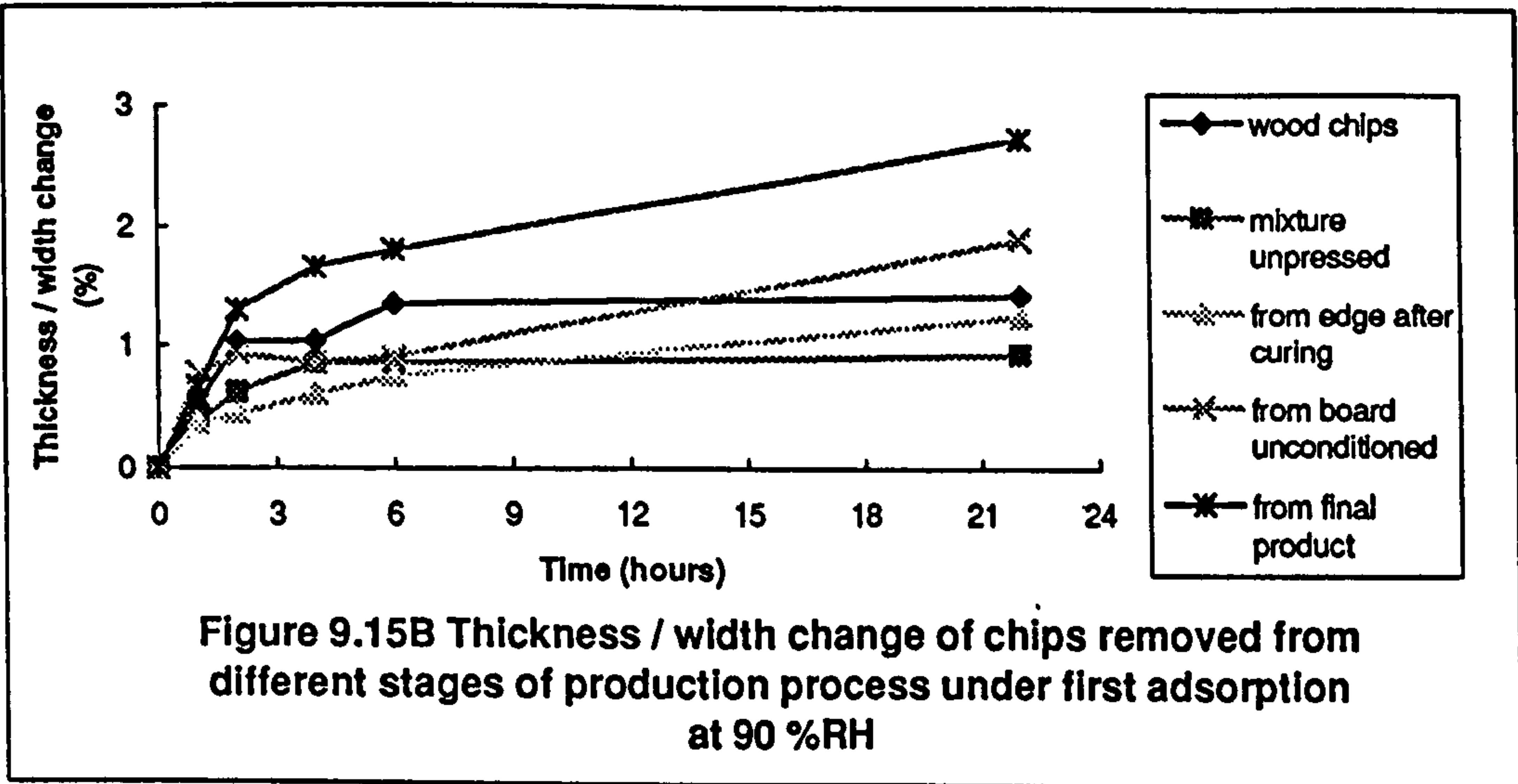
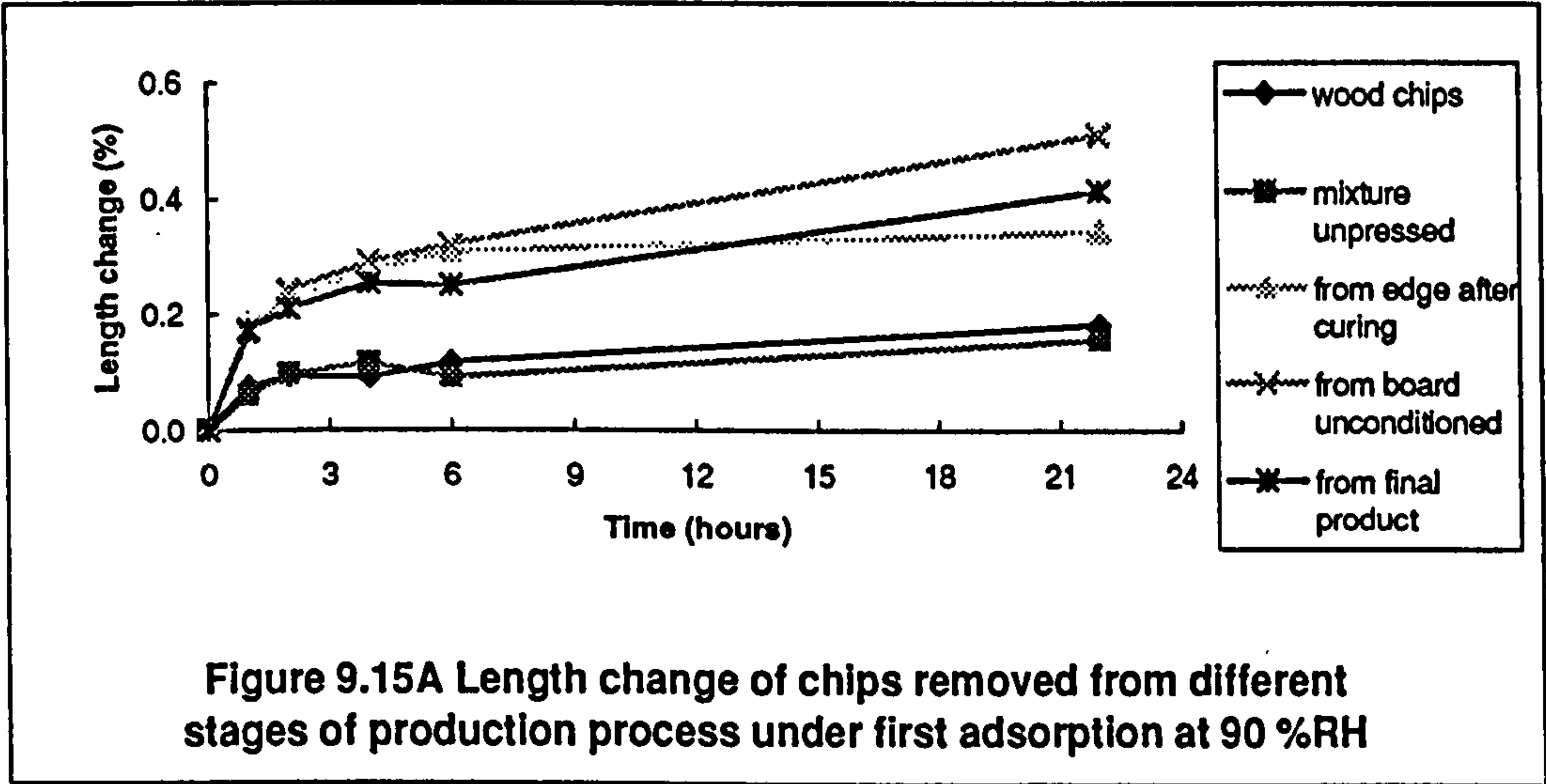
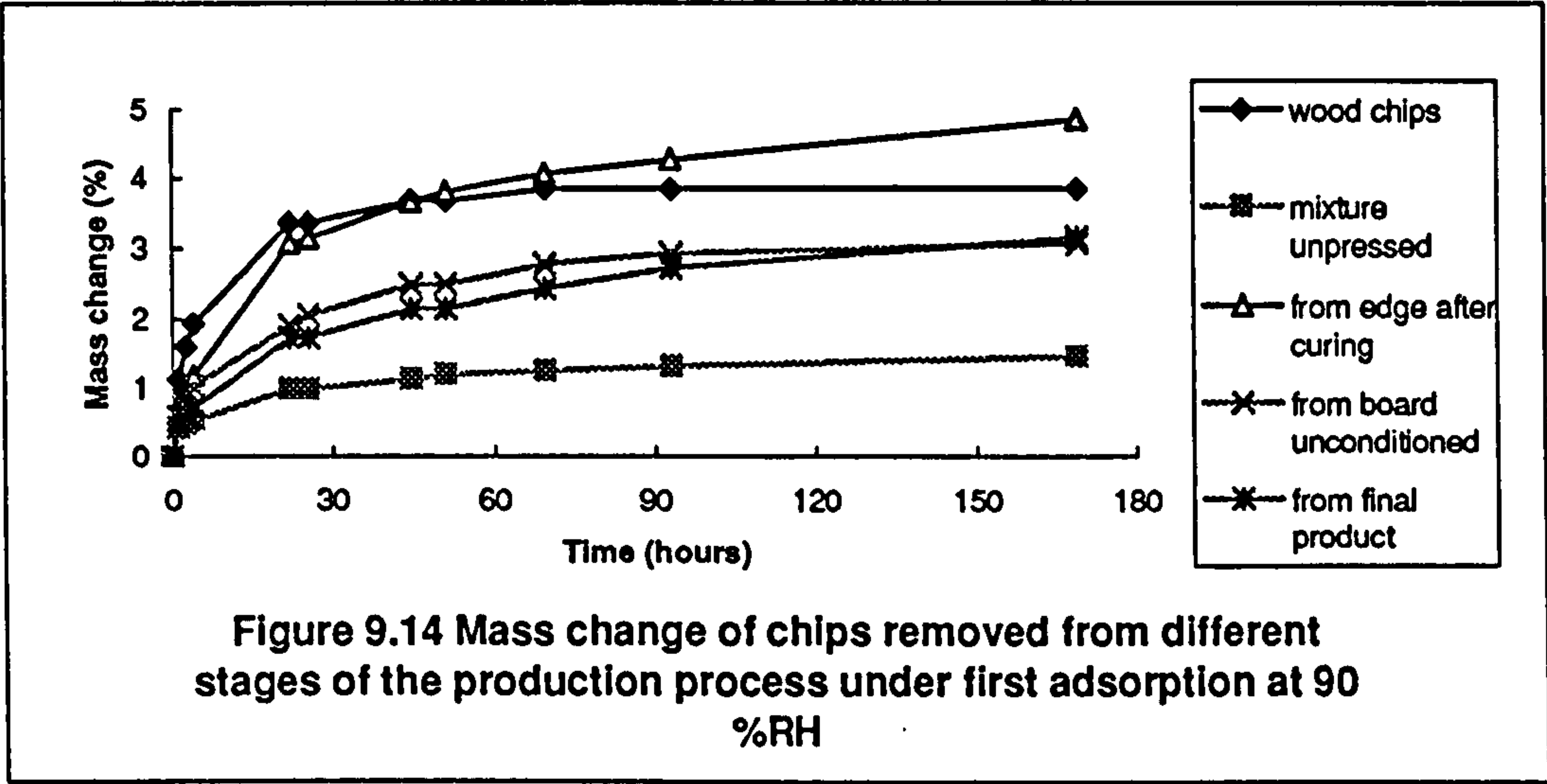


Figure 9.11 Hysteresis loops of mass change of dissected chips (compared with that of raw wood chips)





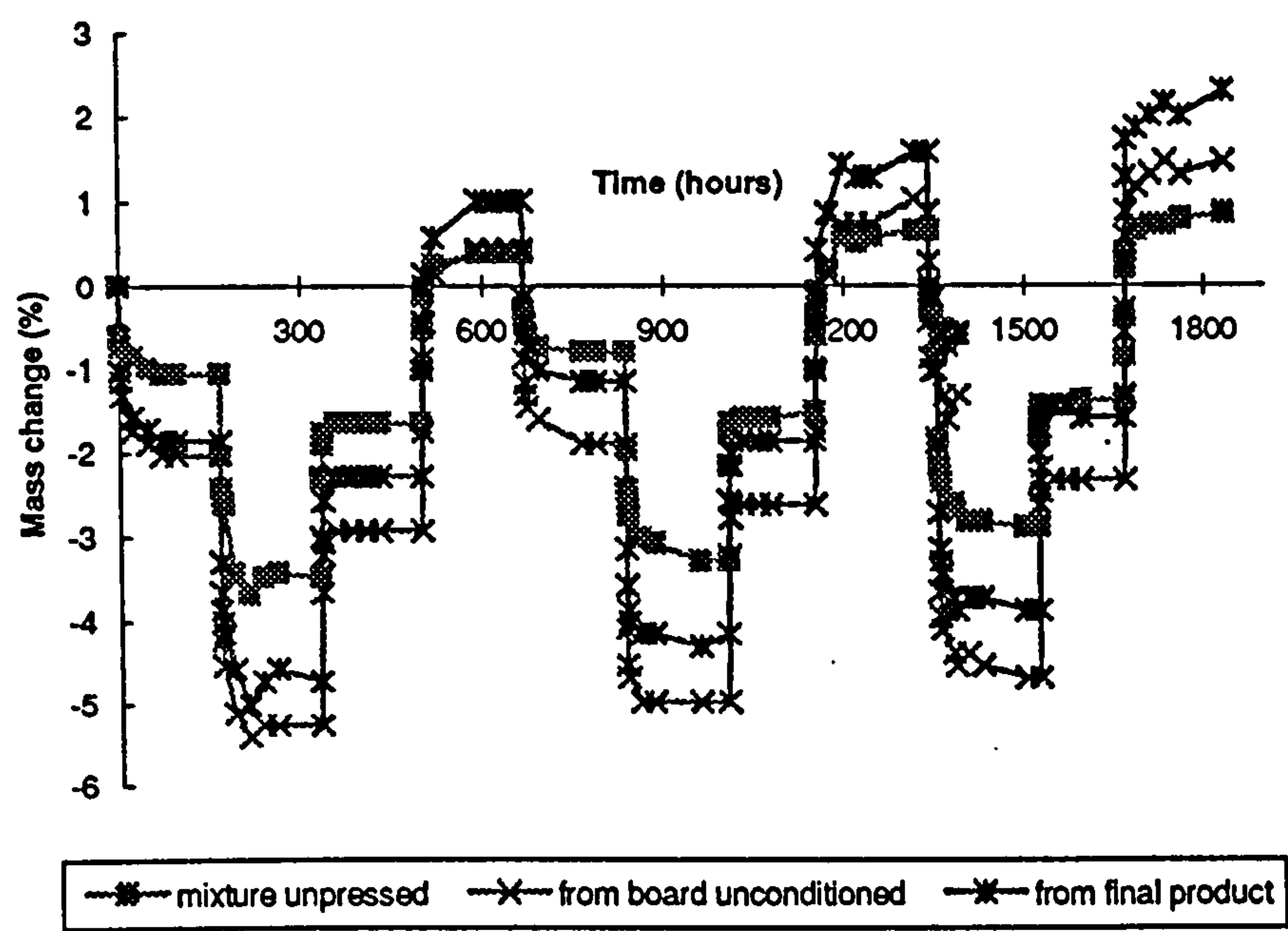


Figure 9.16A The behaviour of chips removed from different stages of the production process under cyclic RH

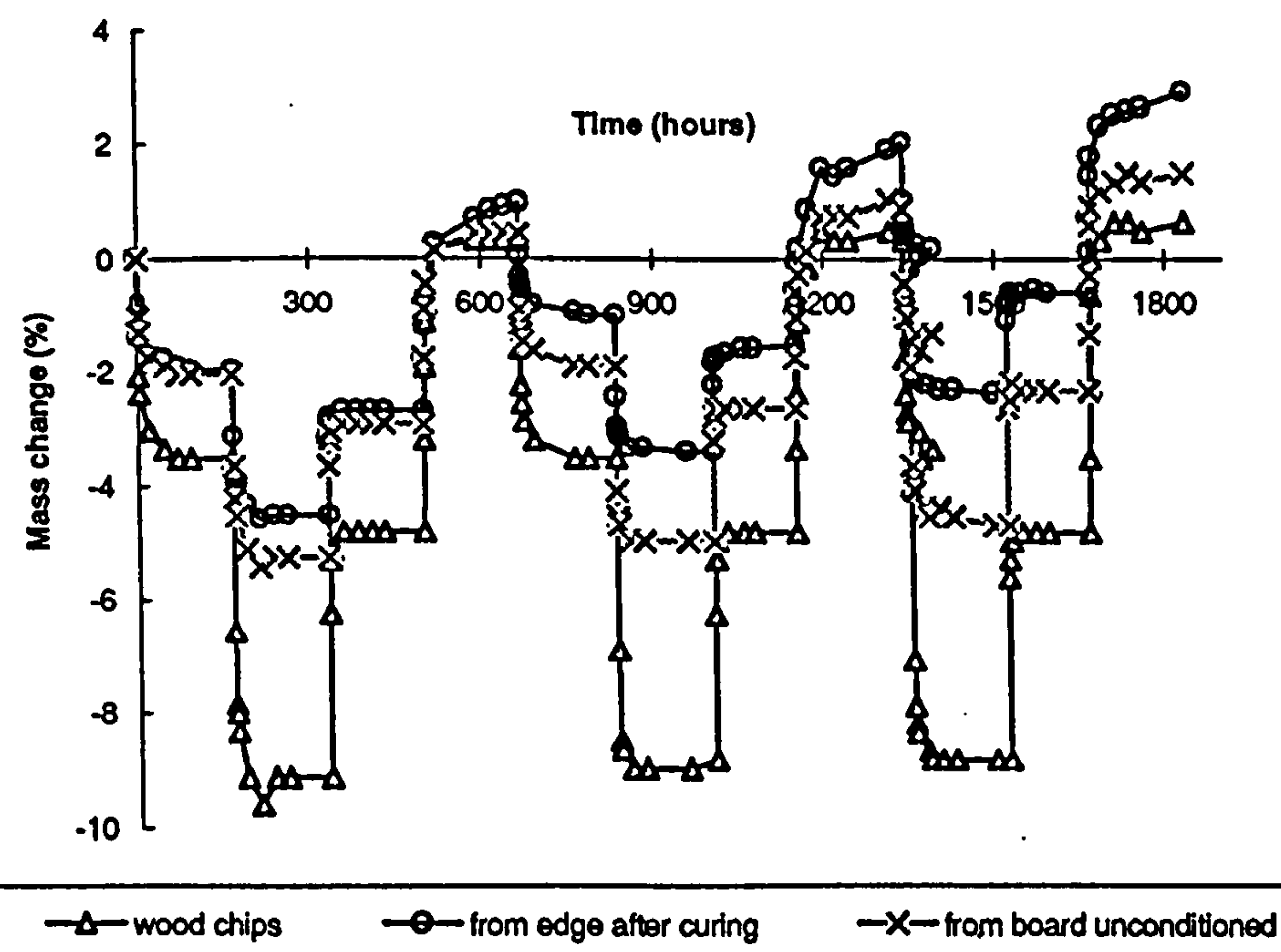


Figure 9.16B The difference in the behaviour of chips inside and outside of the mat under cyclic RH

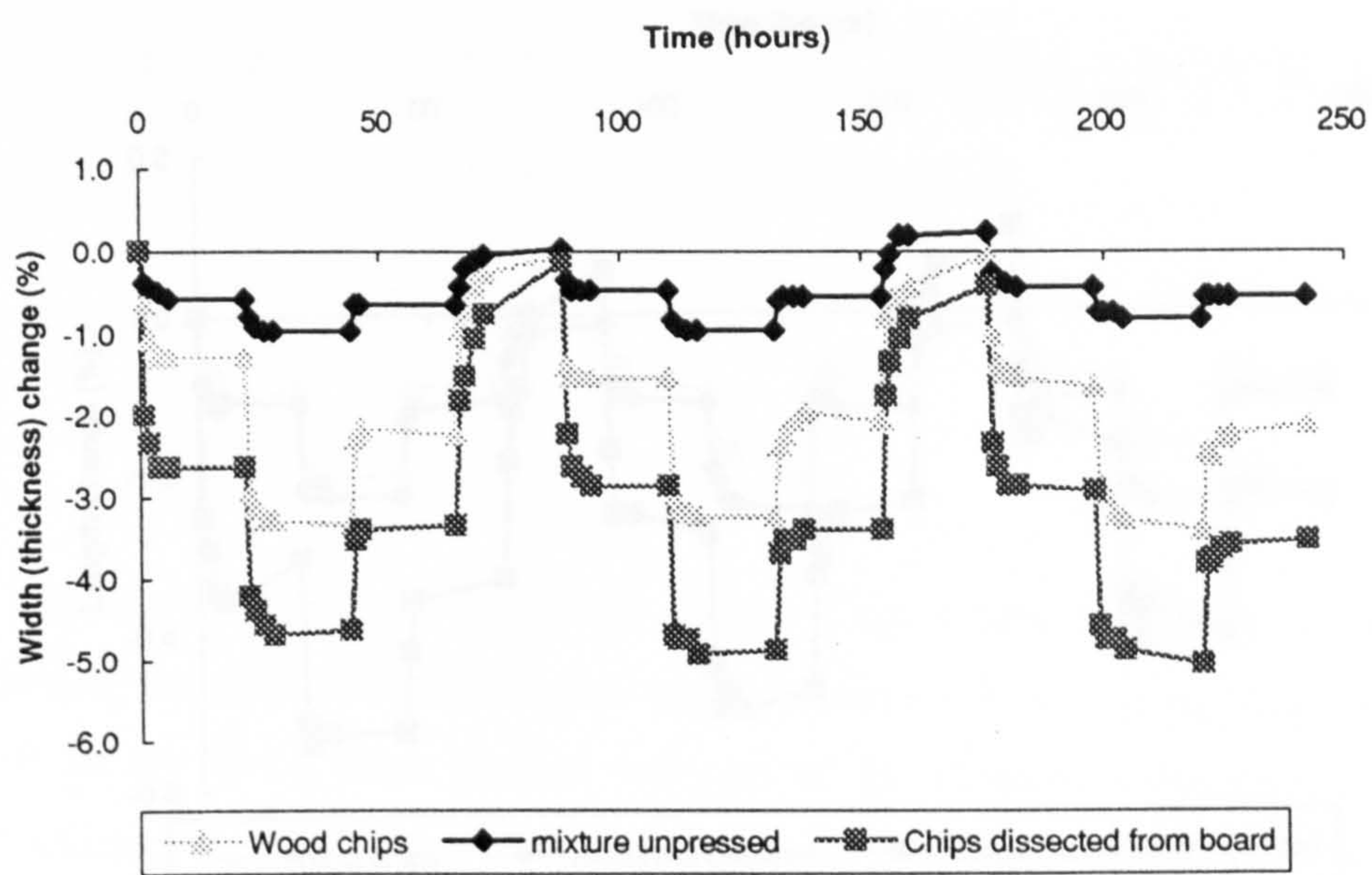


Figure 9.17A Mean width (thickness) change of chips removed from different stages of production process under cyclic RH

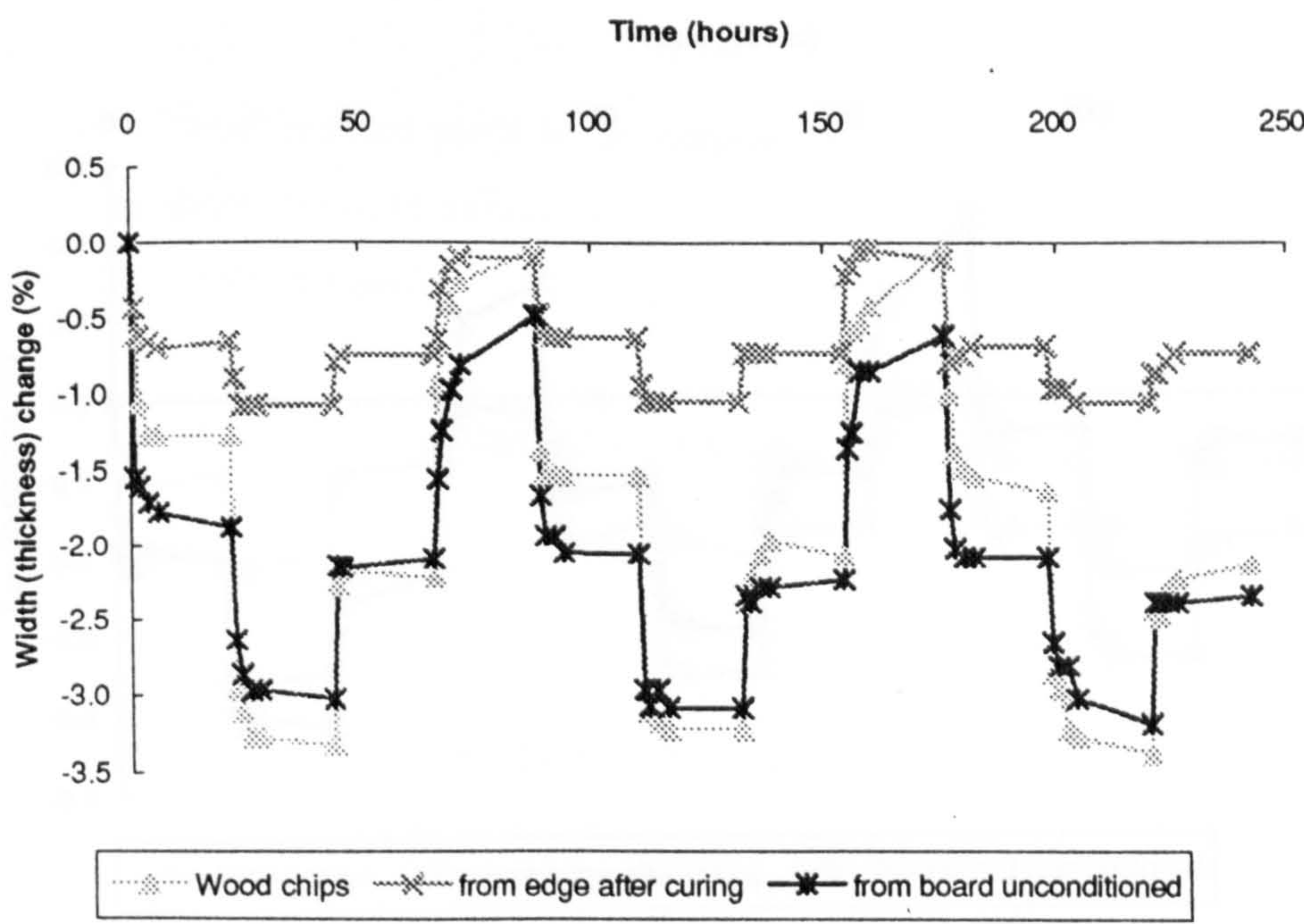


Figure 9.17B Mean width (thickness) change of chips pressed and unpressed under cyclic RH

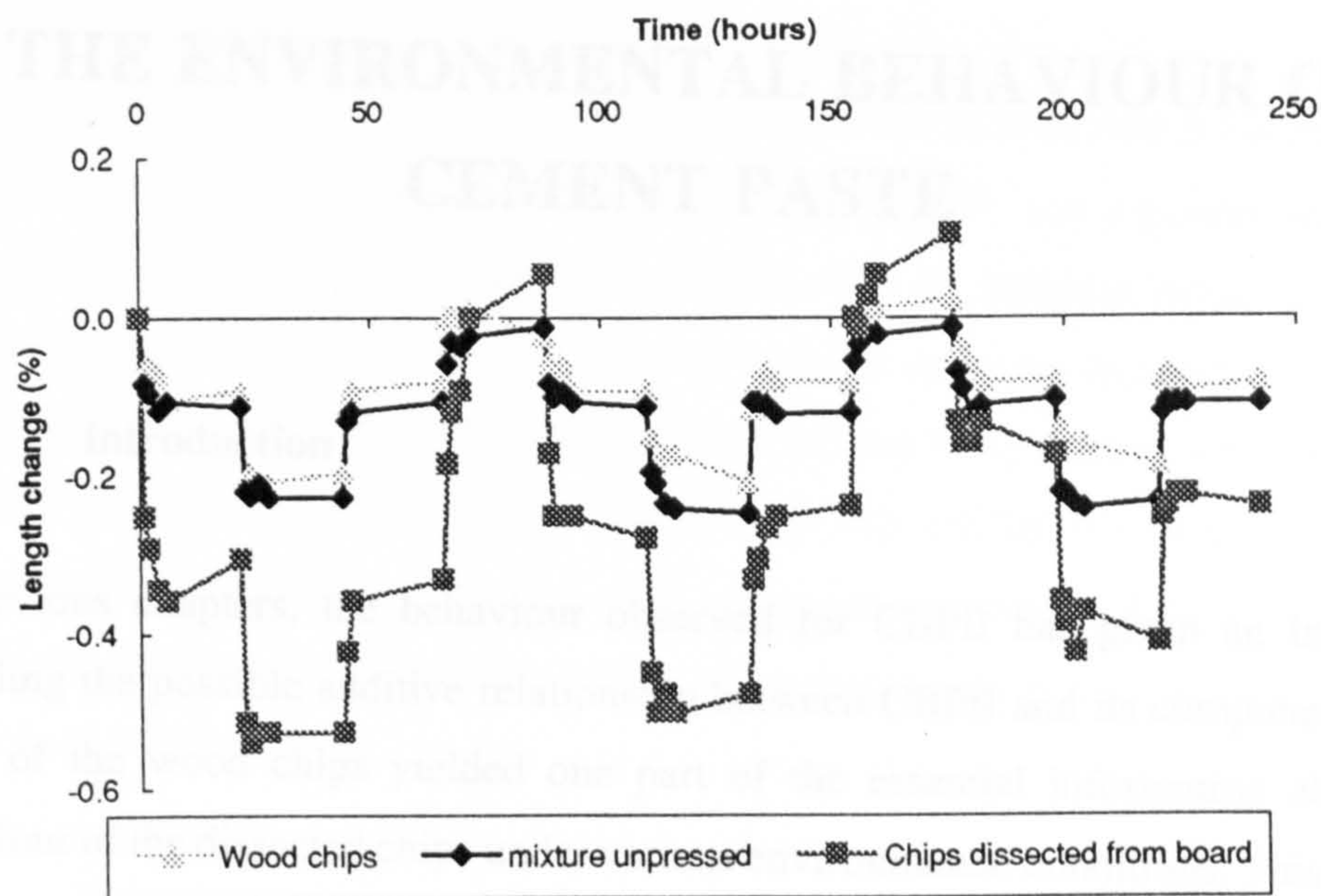


Figure 9.18A Mean length change of chips removed from different stages of the production process under cyclic RH

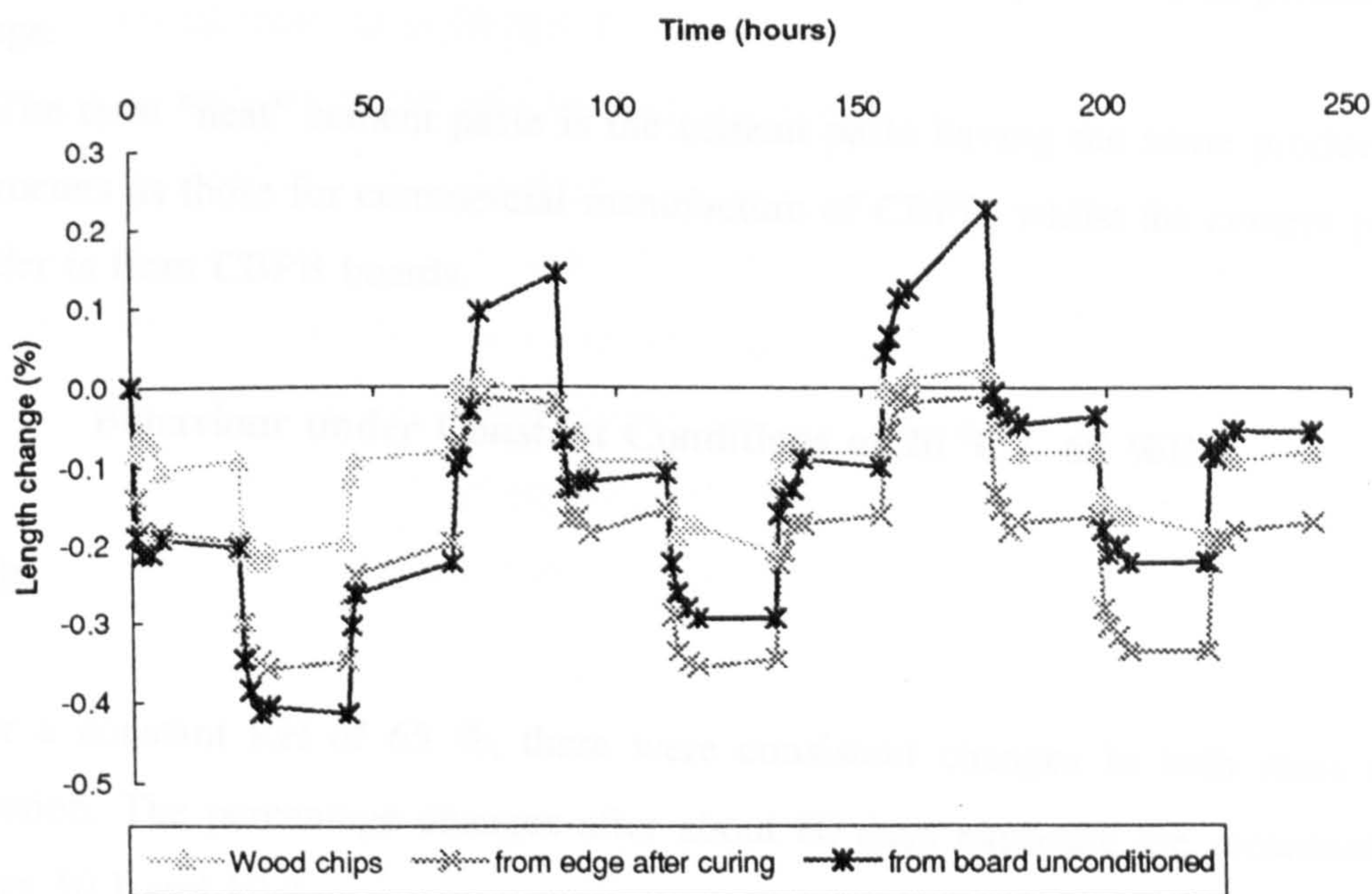


Figure 9.18B Mean length change of chips pressed and unpressed under cyclic RH

Chapter 10

THE ENVIRONMENTAL BEHAVIOUR OF CEMENT PASTE

10.1 Introduction

In previous chapters, the behaviour observed for CBPB has given an indication regarding the possible additive relationship between CBPB and its components. The study of the wood chips yielded one part of the essential information about the behaviour of the dissected chips under various environmental conditions. This chapter examines the behaviour of cement paste having the same production parameters as those for commercial manufacture of CBPB. The results were obtained by subjecting cement paste to the corresponding conditions as those for CBPB exposure, including constant RH at 65 %, single change of RH from 35 to 90 % on adsorption and from 90 to 35 %RH on desorption, and cycling of RHs between 35 and 90 %. Mass and length changes of cement paste were measured and results presented as percentage change.

The term "neat" cement paste is the cement paste having the same production parameters as those for commercial manufacture of CBPB, whilst the cement paste powder is from CBPB boards.

10.2 Behaviour under Constant Conditions of 20 °C / 65 %RH

Results

Under a constant RH of 65 %, there were consistent changes in both mass and dimension. The percentage changes after about 80 days exposure are presented in Figures 10.1 and 10.2.

Discussion

In Figures 10.1 and 10.2 it is apparent that, unlike wood chips, the mass and length of cement paste changed under constant RH. The first 80 day exposure resulted in a considerable increase in mass (about 0.71 %). In contrast with this was a significant decrease in length (about -0.013 %) after the same exposure period. The changes in both mass and dimension are linear and are in agreement with the change of CBPB under constant RH (chapter 5), though with a difference in magnitude due to the effect of the inclusion of wood chips. As mentioned before, this behaviour was most likely attributable to the carbonation of cement paste, which will be discussed in the next chapter.

10.3 Behaviour on both Adsorption (35 - 90 %RH) and Desorption (90 - 35 %RH)

Results

Figure 10.3 and Figure 10.5 show the changes in mass and length of "neat" cement paste on moving from 35 to 90 %RH. The change in mass of cement paste powder was included for comparison and verification, Figure 10.4.

Changes in the mass and dimension of "neat" cement paste on moving from 90 to 35 %RH are given in Figures 10.6, 10.7 and 10.8, whilst Figure 10.7 is the change in mass of cement paste powder when dissected from CBPB.

The relationship between mass and dimensional change of "neat" cement paste is plotted in Figure 10.9 for adsorption, and in Figure 10.10 for desorption. Again O, A / A' and B / B' represent the same points as on Figures 10.3, 10.5, 10.6 and 10.8.

Discussion

It can be seen that 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 (OA') and AB (A'B'). The points A / A' for the materials tested are located at 27 days. The results show that changes in both mass and length not only were in agreement with those of the cement paste studied in the cementitious area (chapter 2), but also were similar to those of CBPB. A large proportion of the change occurred at the beginning of exposure. After about 27 days, the changes in the length of cement paste on moving from 35 to 90 %RH and in mass of cement paste on moving from 90 to 35 %RH were very slight, or not observable in some cases, depending on the counterbalance between two processes. This counterbalance, at 90 %RH (long term exposure), is between the shrinkage of carbonation and swelling, because prolonged immersion induces tensile stresses in inter - solid bonds, disrupting some of the weak links and causing further adsorption, and, at 35 %RH (long term exposure), is between the increase in the weight of gram molecule and decrease in the mass due to water evaporation, including that released by the carbonation reaction and the physical part of water. However, an increase in the mass of cement paste continued consistently under adsorption, though the degree of change significantly slowed down. Mass increased by 4.37 % in the stage OA and by 4.76 % for OB, whilst it was 0.064 and 0.061 % for the length increase. In contrast, the decrease in length of cement paste under 35 %RH exposure gradually continued over the whole period of exposure tested. Decrease in mass of cement paste was -1.45 % for the stage OA' and -1.42 % for OB', whilst decrease in length of cement paste under desorption was -0.093 % and -0.107 % for the stages OA' and OB' respectively. This indicates that both mass and dimensional changes are associated with the moisture in cement paste but are not due solely to the movement of water in to or out of the cement paste. The changes at the later stages of exposure at 90 %RH are thought to be dominated by the condensation of moisture and at 35 %RH, to be dominated by the carbonation of cement paste.

The most interesting results, which not only interpret the mechanisms of dimensional change of cement paste but also show great agreement with the results arising from the CBPB, are the relationship between mass and dimensional changes of cement paste, Figures 10.9 and 10.10. On adsorption, on moving samples from 35 to 90 %RH, it is observed that the plot is linear at the beginning of exposure (up to about the first three day exposure), after which the slope of the curves decrease and

continues as "A" is approached, and then the increase in mass did not bring about an increase in length. It is apparent that an increase in length of cement paste on adsorption was due firstly to an increase of bound / adsorbed water as soon as it was exposed, and then 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 is a dominant mechanism, producing no increase in length but a considerable increase in the mass of cement paste.

A very distinct change in the relationship of mass and dimension of cement paste under desorption occurred after 27 days exposure: point "A" in Figure 10.10. Both OA' and A'B' are linear, but the slopes of the lines in the two stages are completely different. In the region OA', mass decrease occurs somewhat gradually with length decrease, showing a dominant effect of the movement of adsorbed water in the cement paste. The formation of menisci in the pores imposed a compressive stress on the cement paste, causing a commensurate shrinkage in cement paste. The region A'B' shows a very great contraction for unit mass change, contrasting with slight increase in the mass. This is the evidence of carbonation of cement paste resulting in an increase in mass and decrease in dimension.

Comparison of Figures 10.3 with 10.4 or of Figures 10.6 with 10.7 shows that "neat" cement paste made in the laboratory is very similar to that in CBPB (or with the cement paste powder in test), with very similar changes in both mass increase and decrease under adsorption and desorption respectively. It can be suggested that in the case of analysis of mass change, both "neat" cement paste and cement paste powder are suitable.

10.4 Behaviour under Cyclic RH Conditions

Results

The resulting change in mass of cement paste under cyclic RH are shown in Figure 10.11, and Figure 10.12 is the plot for cement paste powder. The change in length is presented in Figure 10.13.

The relationship between mass and length change is given in Figure 10.14 for

one complete cycle following 90 - 65 - 35 - 65 - 90 %RH.

Discussion

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 (Figures 10.11 to 10.13). It is apparent that changes in both mass and length were irreversible, with the mass of cement paste consistently increasing and the dimension decreasing with the number of cycles. After one and two cycles, the mass increased by 1.04 % and 1.57 % respectively, whilst the dimension decreased by -0.023 % and -0.033 % respectively, with respect to the values at 65 %RH on adsorption. The trend of these changes is similar to that of CBPB, but with a greater degree of irreversibility. The phenomenon is obviously attributable to the carbonation and stabilization of cement paste.

Like changes in CBPB, the change of cement paste is dependent on the level of RH to which it is exposed. The ranking of the degree of mass change for cement paste is: the change on moving from 65 to 90 %RH > that on moving from 65 to 35 %RH > that on moving from 90 to 65 %RH > that on moving from 35 to 65 %RH, it was about 0.068 : 0.024 : 0.015 : 0.015 (% / %RH change) in the first cycle. For length, the change on transferring from 65 to 35 %RH > that on transferring from 35 to 65 %RH > that on transferring from 90 to %RH > that on transferring from 65 to 90 %RH, and it was about 15.67 : 10.33 : 9.88 : 7.08 ($\times 10^{-4}$ % / %RH change) 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. This is clearly illustrated in the relationship between mass and dimensional change, in Figure 10.14, which is similar to that of CBPB.

The curves in Figure 10.14 show that under desorption from 90 %RH to 65 %RH and then to 35 %RH, there was a steady decrease in length of "neat" cement paste with mass decrease. 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. At the beginning of exposure from 90 %RH to 65 %RH, the dominant movement was in capillary water (decrease of the meniscus radii in channels and capillary

cavities due to reduction in relative humidity which 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 - at this time reduction in relative humidity caused formation of air bubbles in even smaller 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. This could be confirmed in the previous section.

The adsorption part of the curve is complicated by the discontinuity at the second stage of 65 %RH adsorption. Decrease in the slope of the plot of length versus mass change indicates that another process was taking place, producing a different relationship between length and mass change.

Comparison of Figures 10.11 with 10.12 again shows the similarity in the property between the cement paste powder and "neat" cement paste.

10.5 Sorption and Dimensional Change Isotherms (Hysteresis Loop)

In Figure 10.15 the adsorption and desorption of cement paste over the first complete cycle is presented. The hysteresis isotherm for length change of "neat" cement paste on first complete cycle is illustrated in Figure 10.16.

Discussion

It had been shown that the behaviour of cement paste is dependent of sorption history (Figures 10.11 and 10.13). The difference between adsorption and desorption gave rise to the hysteresis loop. The result indicates that, like the results observed in cementitious studies, the curve of desorption did not intersect with the curve of adsorption at the ultimate point due to the discontinuity of adsorption part of isotherm, which was regarded as the first and the secondary hysteresis respectively in cementitious area (Feldman and Sereda, 1964). The intersection between the curve

of adsorption and desorption lies between the RH of 65 and 90 %RH. Before intersection, the change in adsorption was lower than that in desorption, but the mass was higher under adsorption than under desorption after intersection, showing a significant effect of other processes at this stage of exposure.

A comparison of the loop arising from cement paste powder and that arising from "neat" cement paste shows that a small amount of wood powder may be contained in the cement paste powder. The value arising from cement paste powder is slightly higher than that arising from "neat" 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.

Unlike the loop for mass change, the loop of length change was different. The curve of adsorption was unable to reach the curve of desorption. The dimensions of cement paste are unable to recover to their original values.

The shape of hysteresis loops for mass change suggests that the hysteresis loops are moving upward with the cycles, whilst that for length change indicates that hysteresis loops are moving downward with the cycles.

10.6 Interim Conclusions 7

1) Comparison of the behaviour of cement paste powder with that of "neat" cement paste having the production parameters for the manufacture of CBPB showed that the features of "neat" cement paste were very close to that of cement paste in the CBPB.

2) The behaviour of "neat" cement paste was similar to that of CBPB for all results but the degree of change of cement paste at various conditions was no greater than that of CBPB, due to moisture or its combined effects.

3) Change associated with "neat" cement paste not only reflected the changes of RH but also reflected the effect of carbon dioxide in the air environment.

4) Under constant RH of 65 %, there was a consistent increase in mass and decrease

in dimension of "neat" cement paste, showing a structural change of cement paste due to carbonation or other consolidation process.

5) Changes in both mass and dimension of "neat" cement paste under a single change in RH (both adsorption and desorption) can be divided into two distinct stages, with a significant change at the beginning of exposure and a slight or consistent change afterward, depending on mass or dimension change, and on sorption history. The first stage was 27 days for the materials tested.

6) At the second stage of exposure, substantial increase in the mass of cement paste occurred under adsorption on moving from 35 to 90 %RH, whilst a decrease in length under desorption on moving 90 to 35 %RH, indicating that both mass and dimensional changes were not due solely to the movement of water into or out of the cement paste. Mass increase was dominated by the condensation of moisture, whilst length decrease was dominated by the effect of carbonation.

7) The mass change under desorption and length change under adsorption were not observable at later stages of exposure due to a counterbalance between two processes i.e. between carbonation shrinkage and immersion swelling under 90 %RH, and between increase in molecular weight and decrease because of water release under 35 %RH.

8) The relationship between mass and length under desorption was linear but with an abrupt change of slope at 27 days. Under adsorption, a linear relationship only occurred during the first 3 days for the material tested, after which the slope decreased up to 27 days. At the final stage, mass increase made no increase in length, illustrating the movement of different types of water and confirming the effects of other processes during the exposure.

9) Under cyclic RH exposure, the mass consistently increased and the dimension decreased with the number of cycles, showing the existence of carbonation over cycling in normal air environments.

10) The change of "neat" cement paste was dependent on the level of RH.

11) In one complete cycle: 90 - 65 - 35 - 65 - 90 %RH, $\Delta L / L$ to $\Delta M / M$ was linear for the whole range of desorption, showing that the movement of capillary, gel and small amount of adsorbed water caused commensurate shrinkage. This was similar to results for other porous materials.

12) A discontinuity in the adsorption part of the curve of $\Delta L / L$ to $\Delta M / M$ was observed. This is related to processes other than simple physical adsorption.

13) The difference in change of cement paste between adsorption and desorption gave rise to a hysteresis loop. The shape of the loop was similar to that of CBPB. The loop for mass change intersected between 65 and 90 %RH, supporting the result for the relationship between length and mass change where a significant increase in mass brought about no increase in length at late stage. The shape of the loop for mass indicates that the hysteresis loops for mass change will be moving upward with cycles.

14) The loop for length change was unable to intercept each other between adsorption and desorption curves, showing the dimension could not recover to its original values. The shape of the loop for length change implies that the hysteresis loops of length change will be moving downward with cycles.

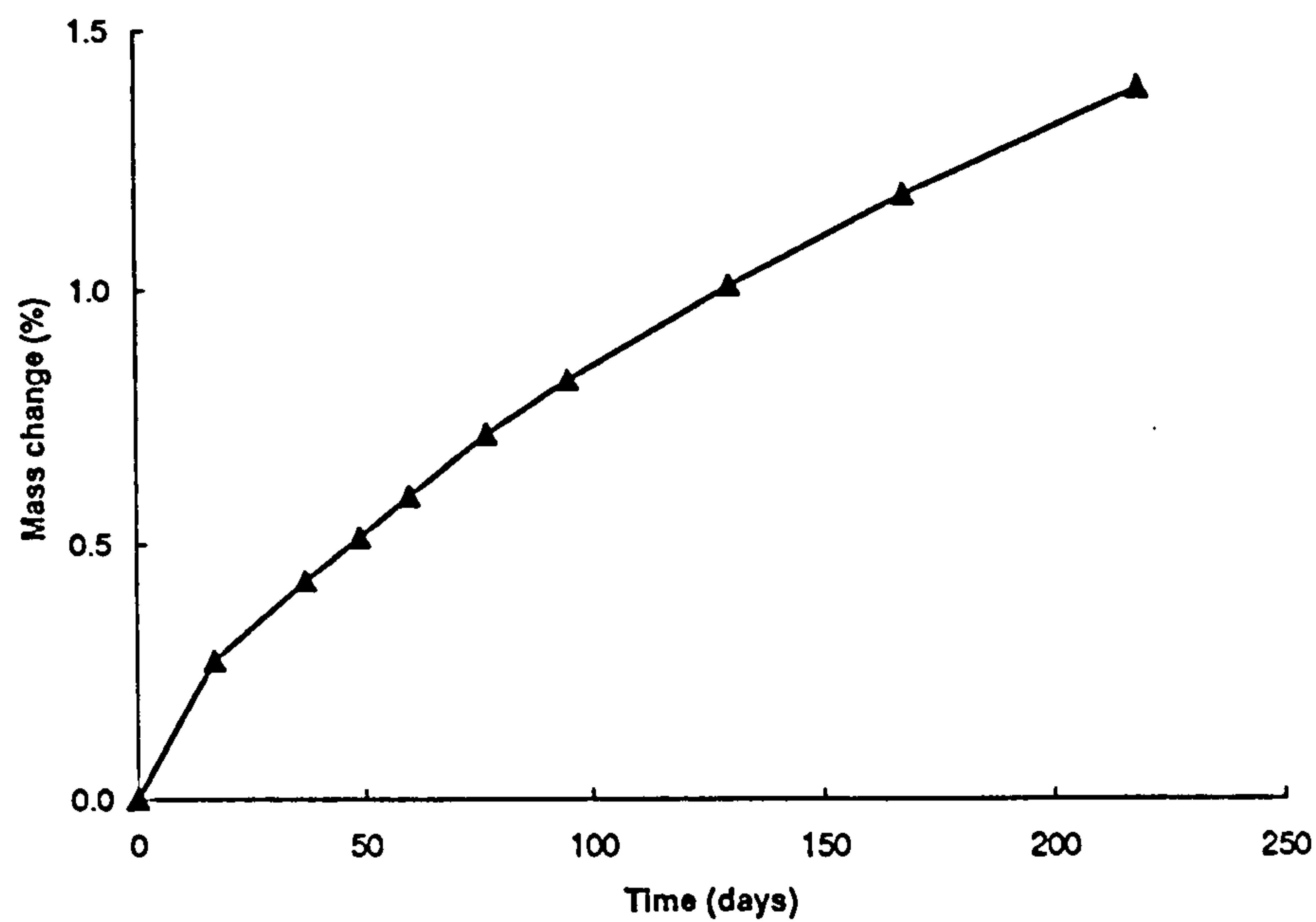


Figure10.1 Change in mass of neat cement paste under constant air environment of 20 °C / 65 %RH

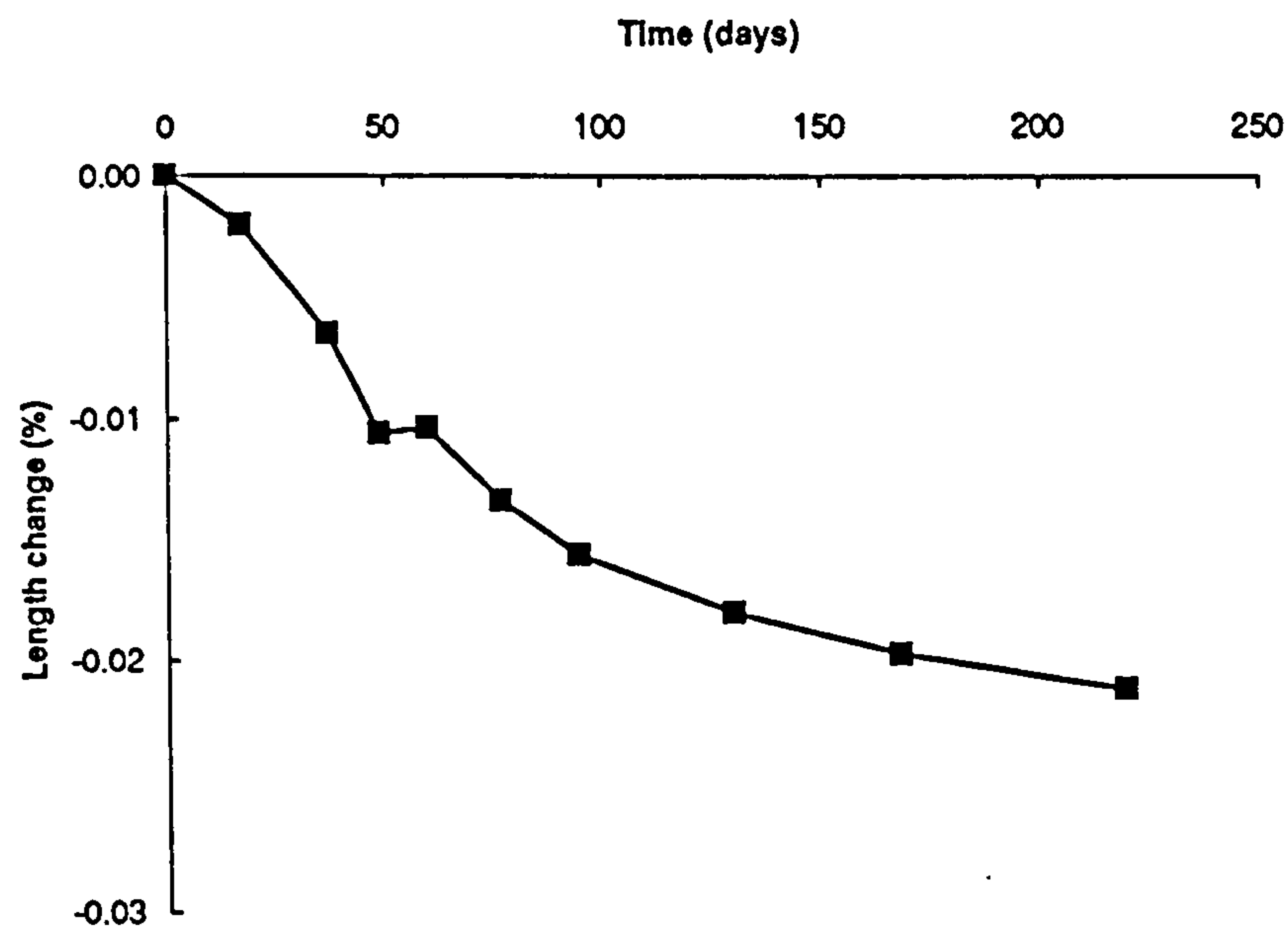


Figure10.2 Change in length of neat cement paste under constant air environment of 20 °C / 65 %RH

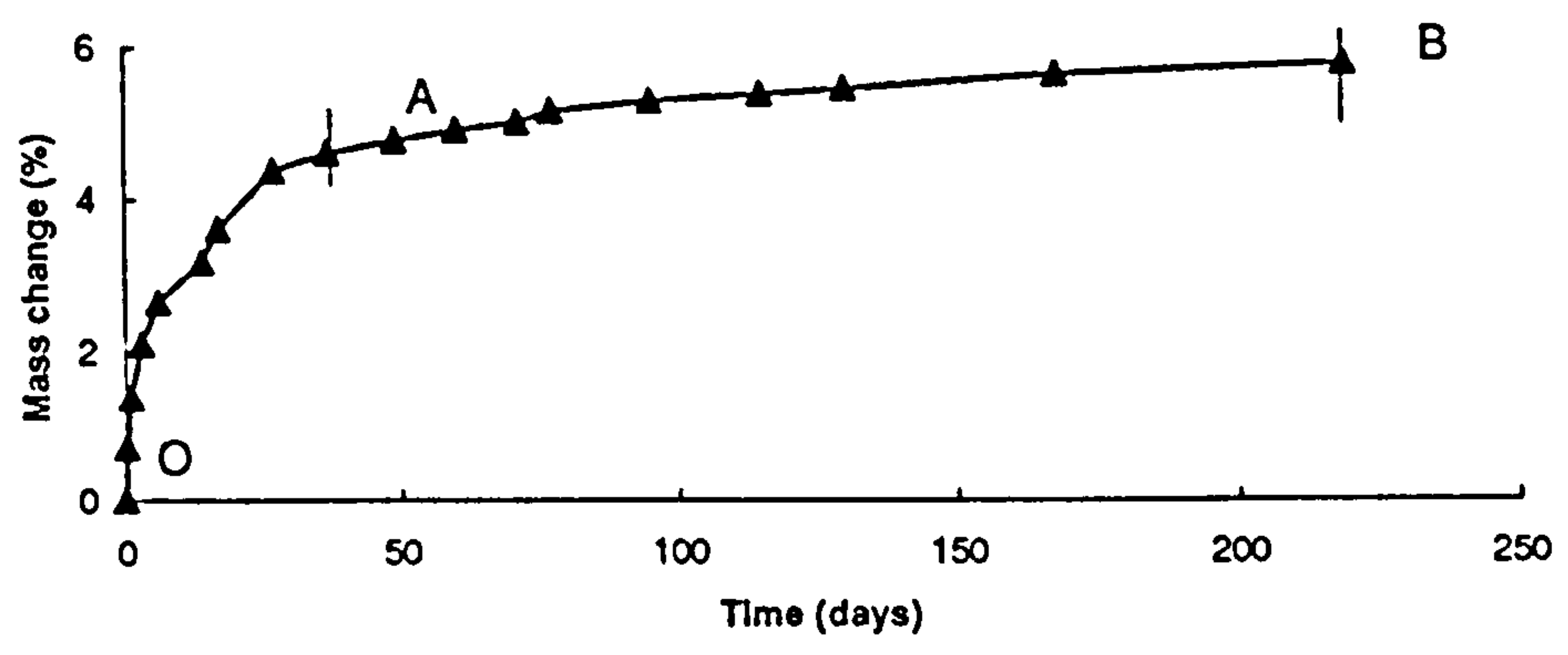


Figure10.3 Change in mass of neat cement paste under normal air in moving from 35 to 90 %RH

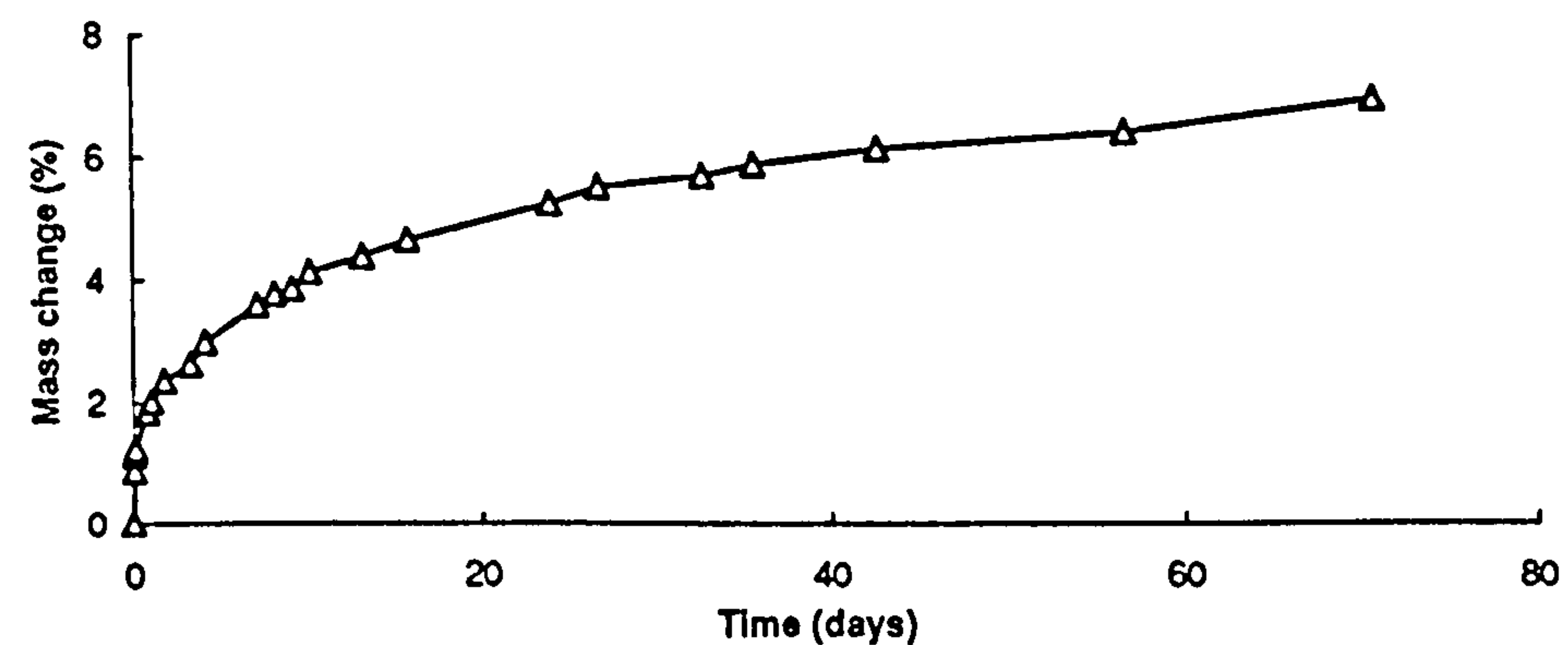


Figure 10.4 Change in mass of cement paste powder under normal air in moving from 35 to 90 %RH

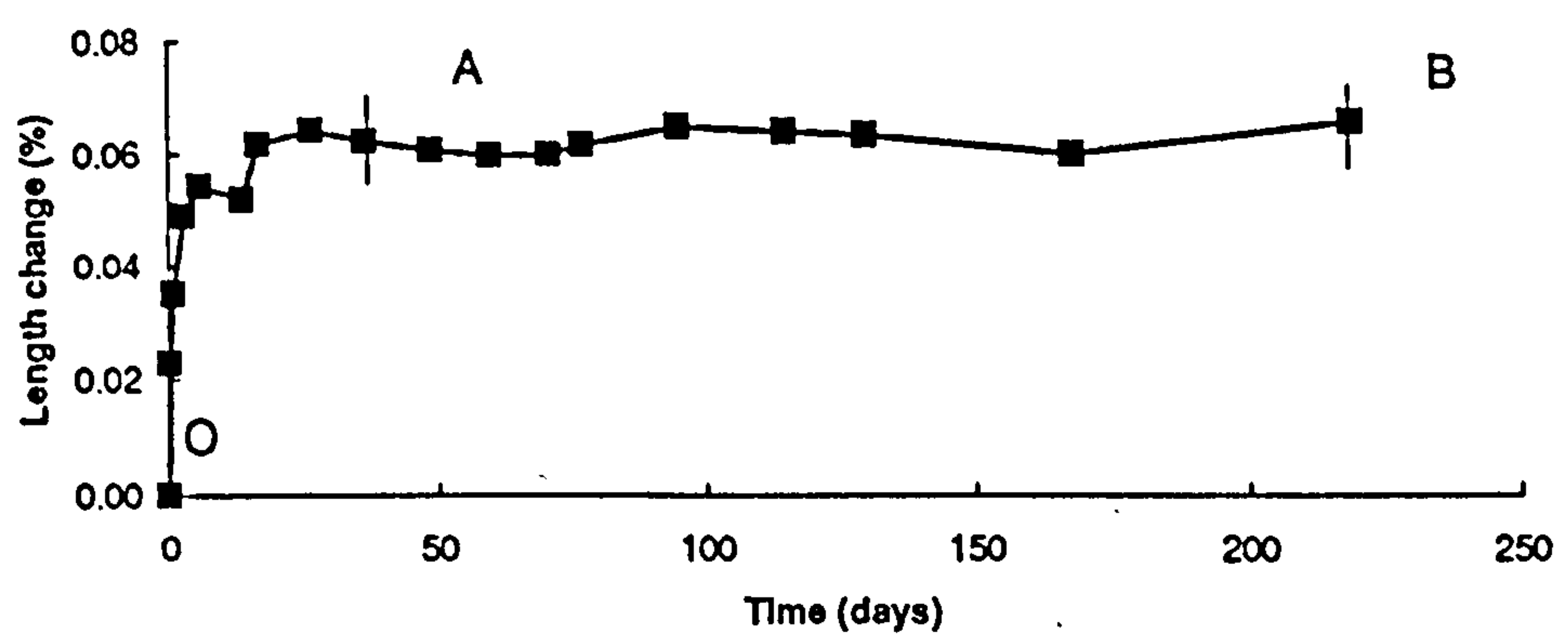


Figure10.5 Change in length of neat cement paste under normal air in moving from 35 to 90 %RH

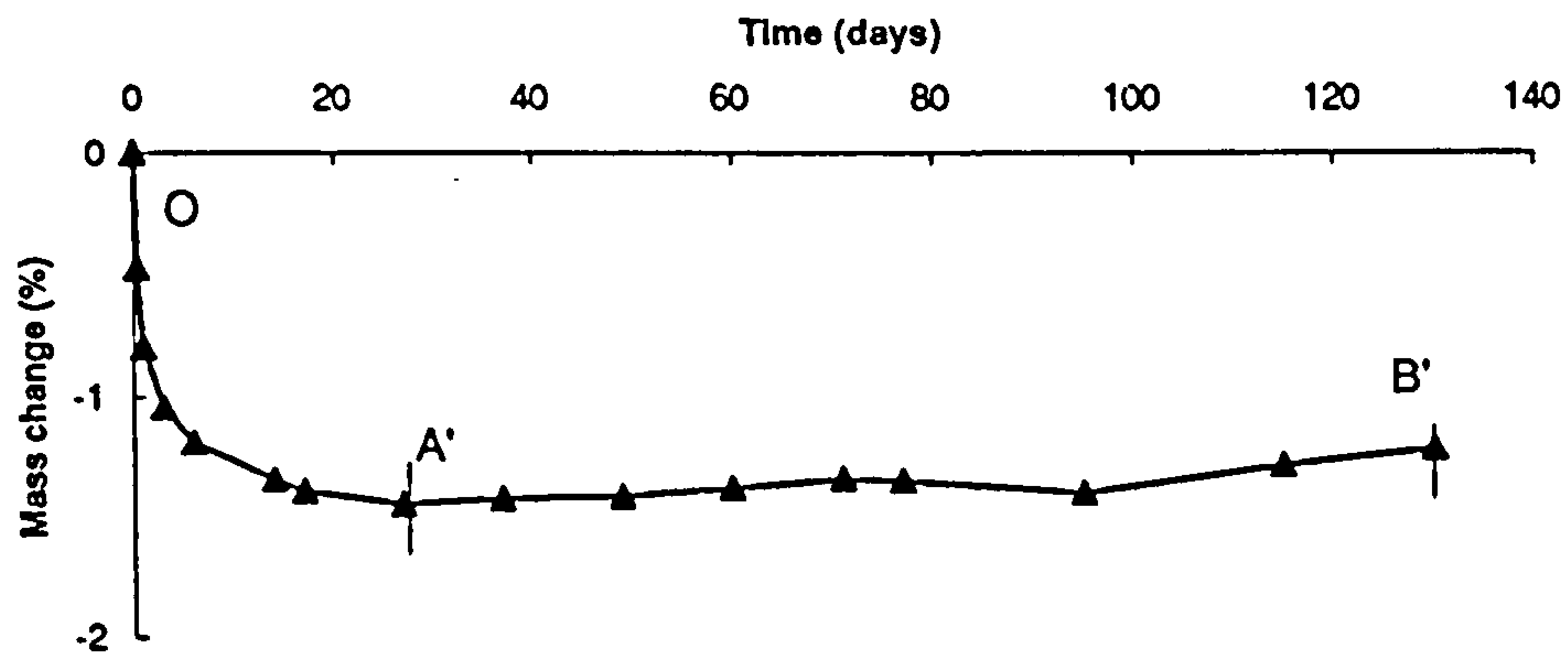


Figure10.6 Change in mass of neat cement paste under normal air in moving from 90 to 35 %RH

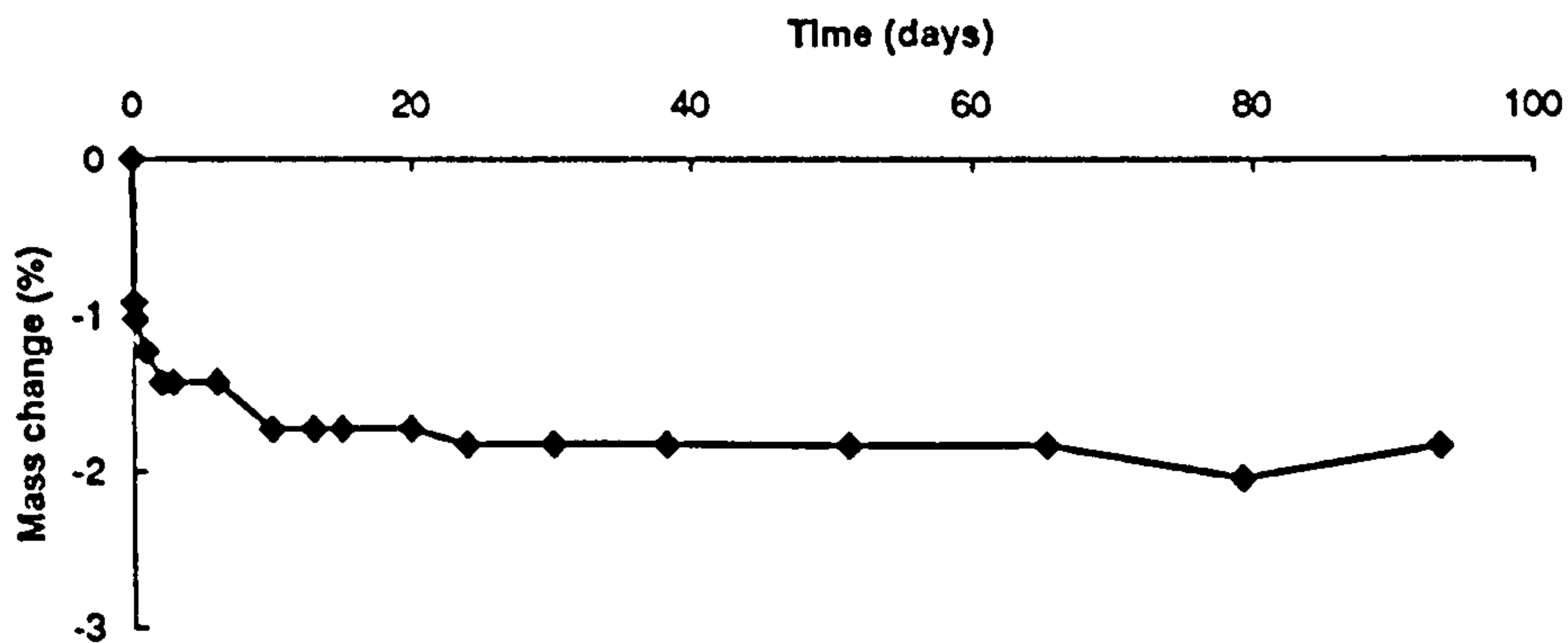


Figure 10.7 Change in mass of cement paste powder under normal air in moving from 90 to 35 %RH

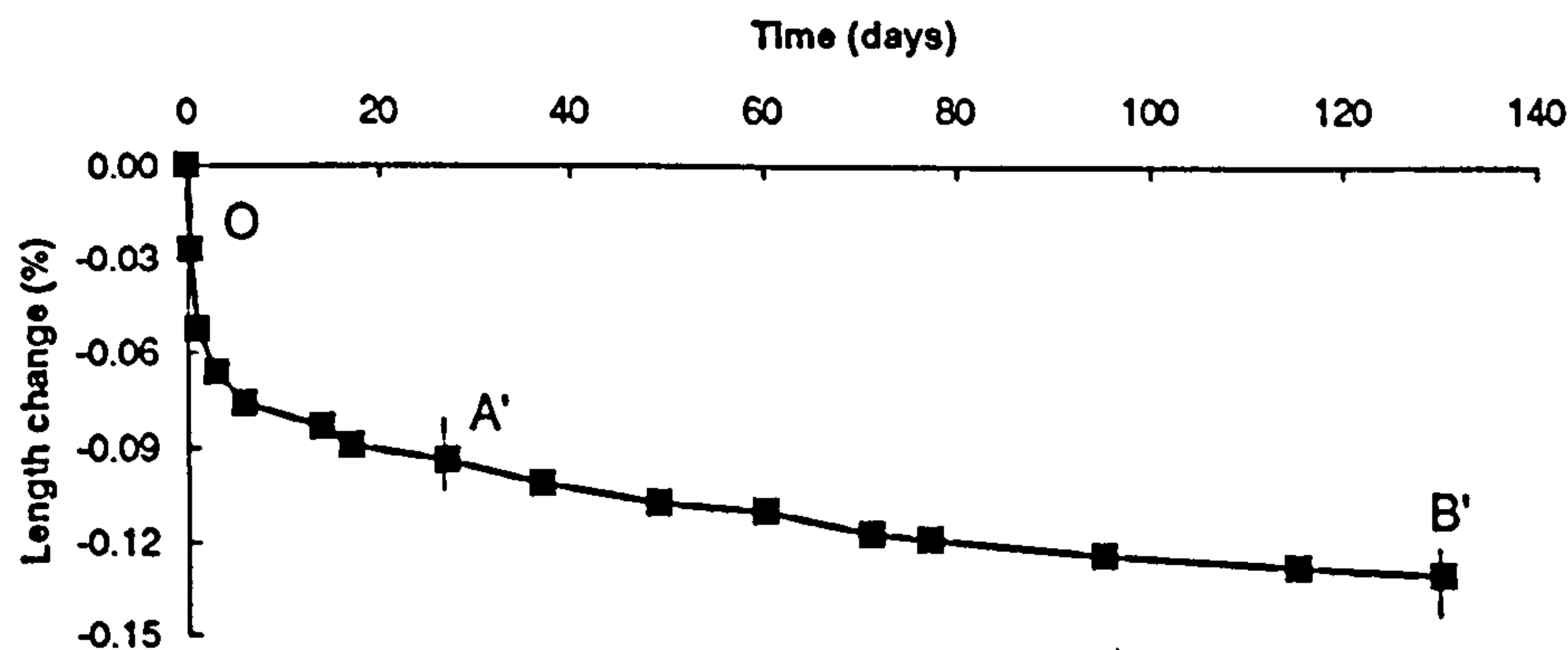
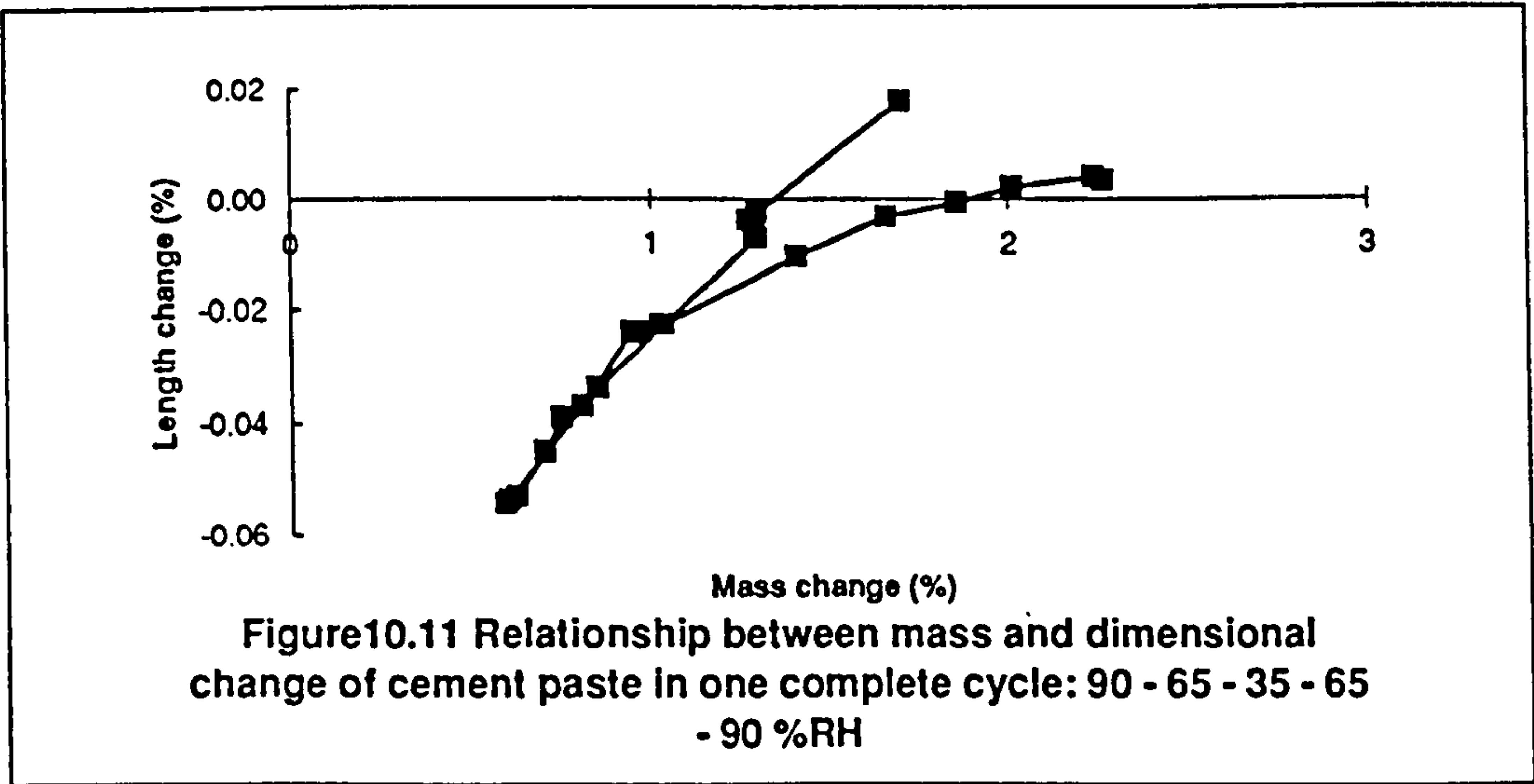
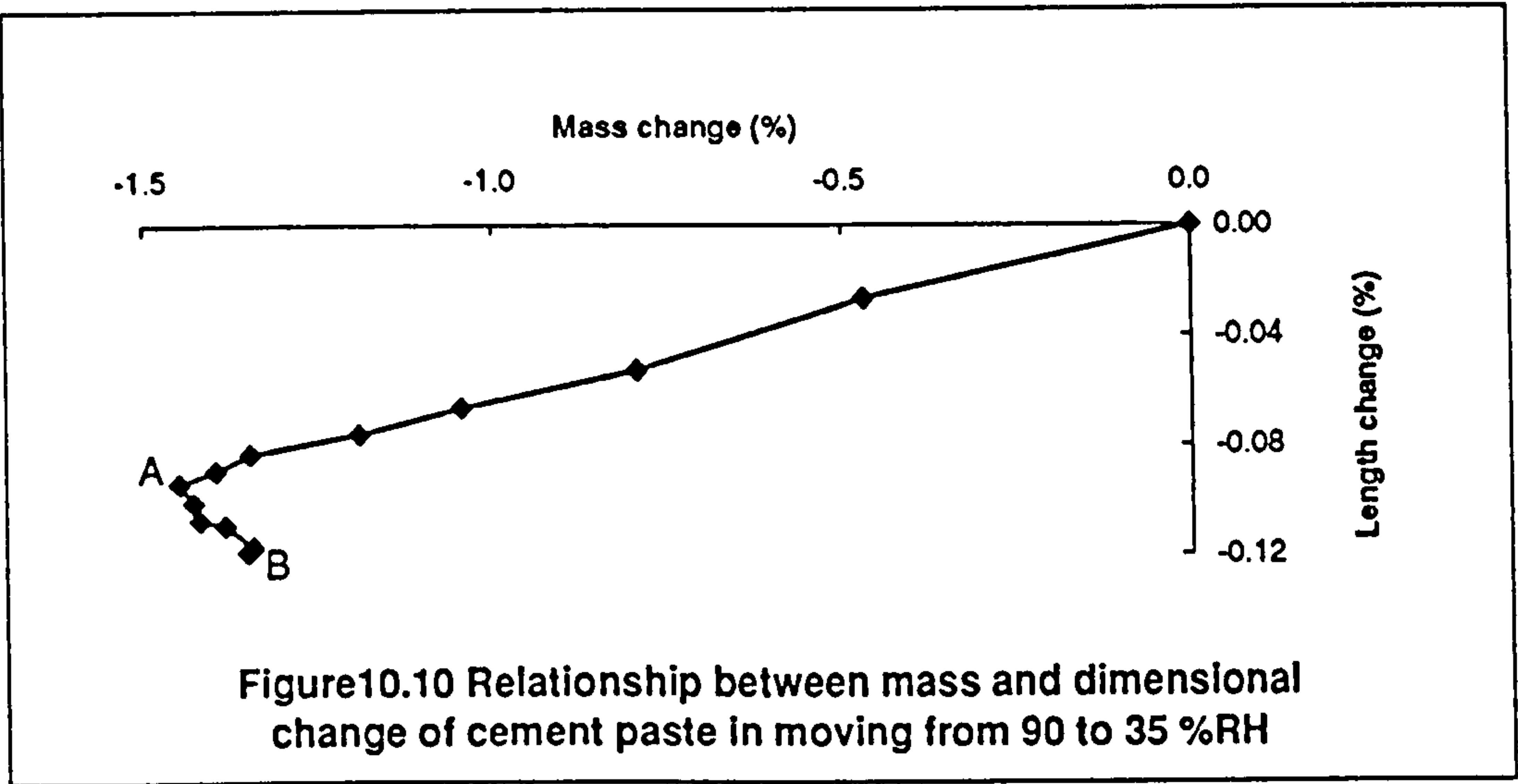
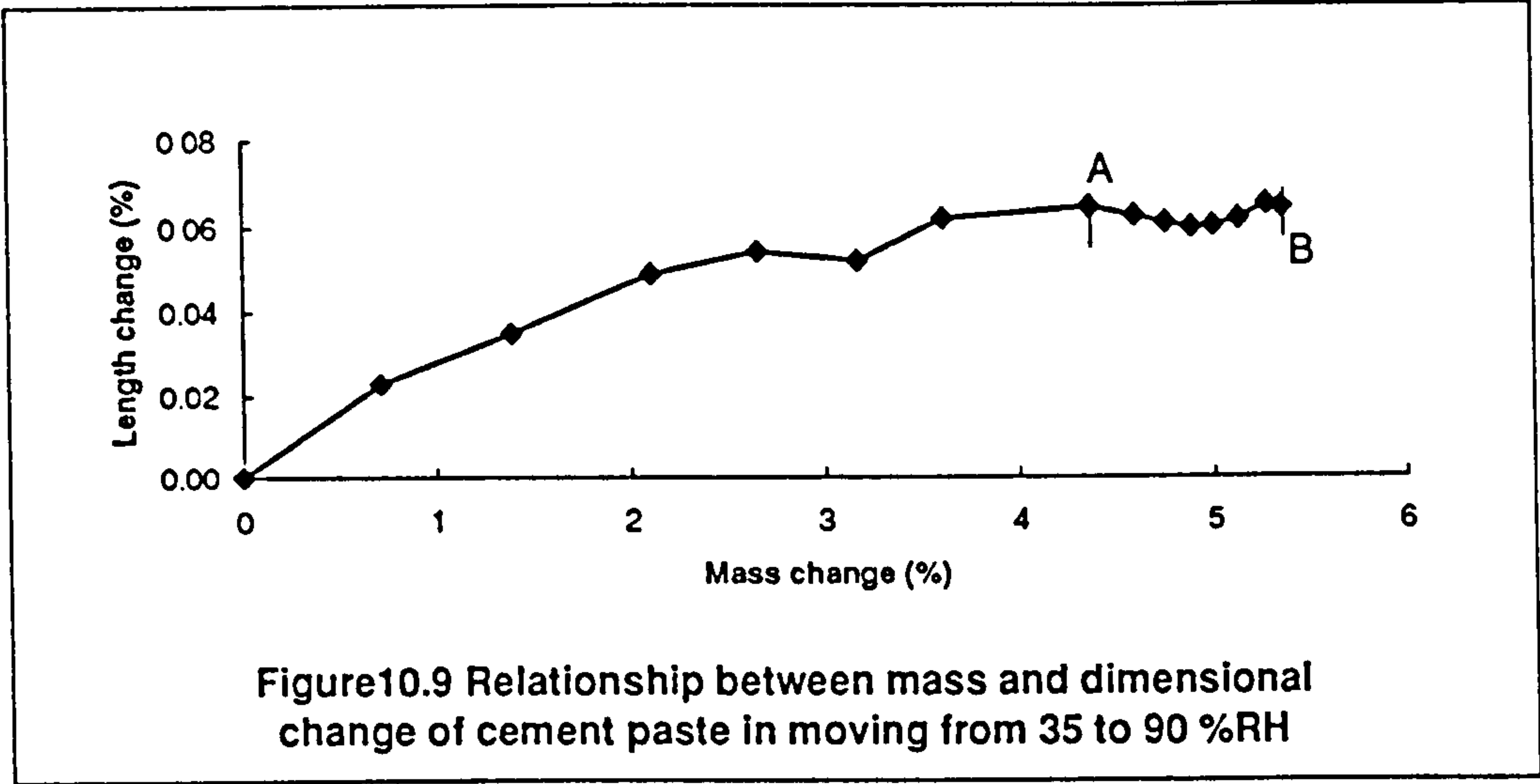
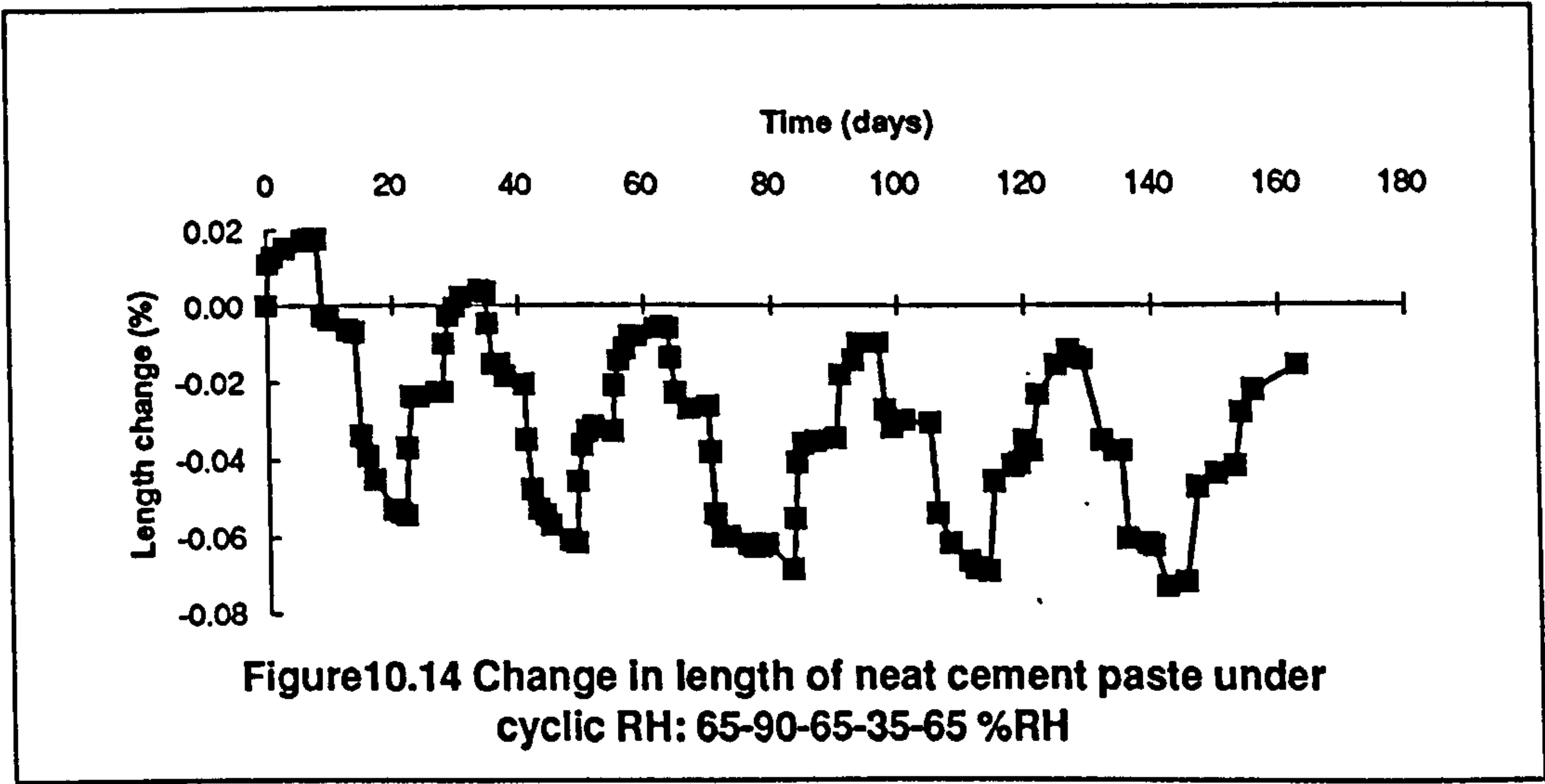
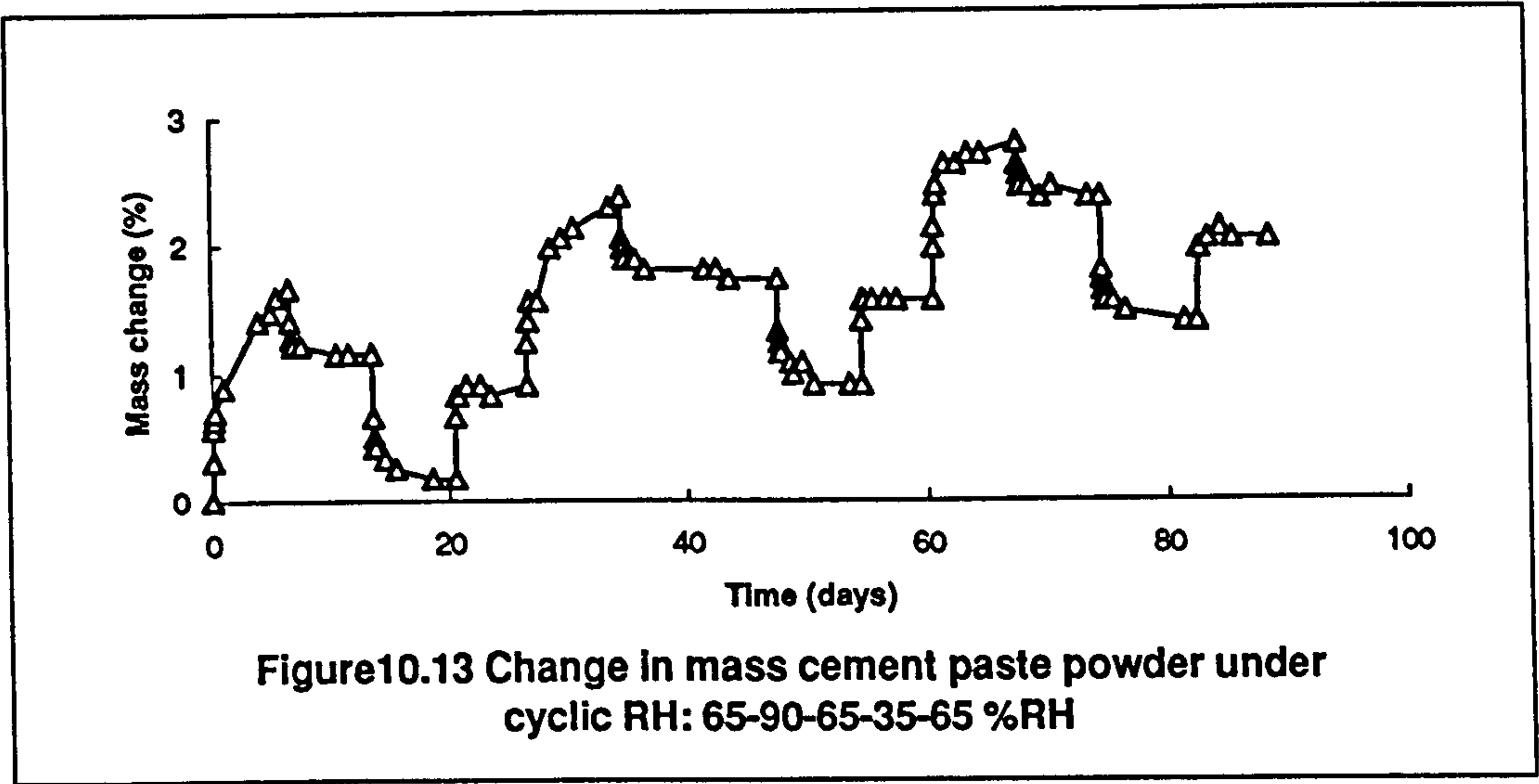
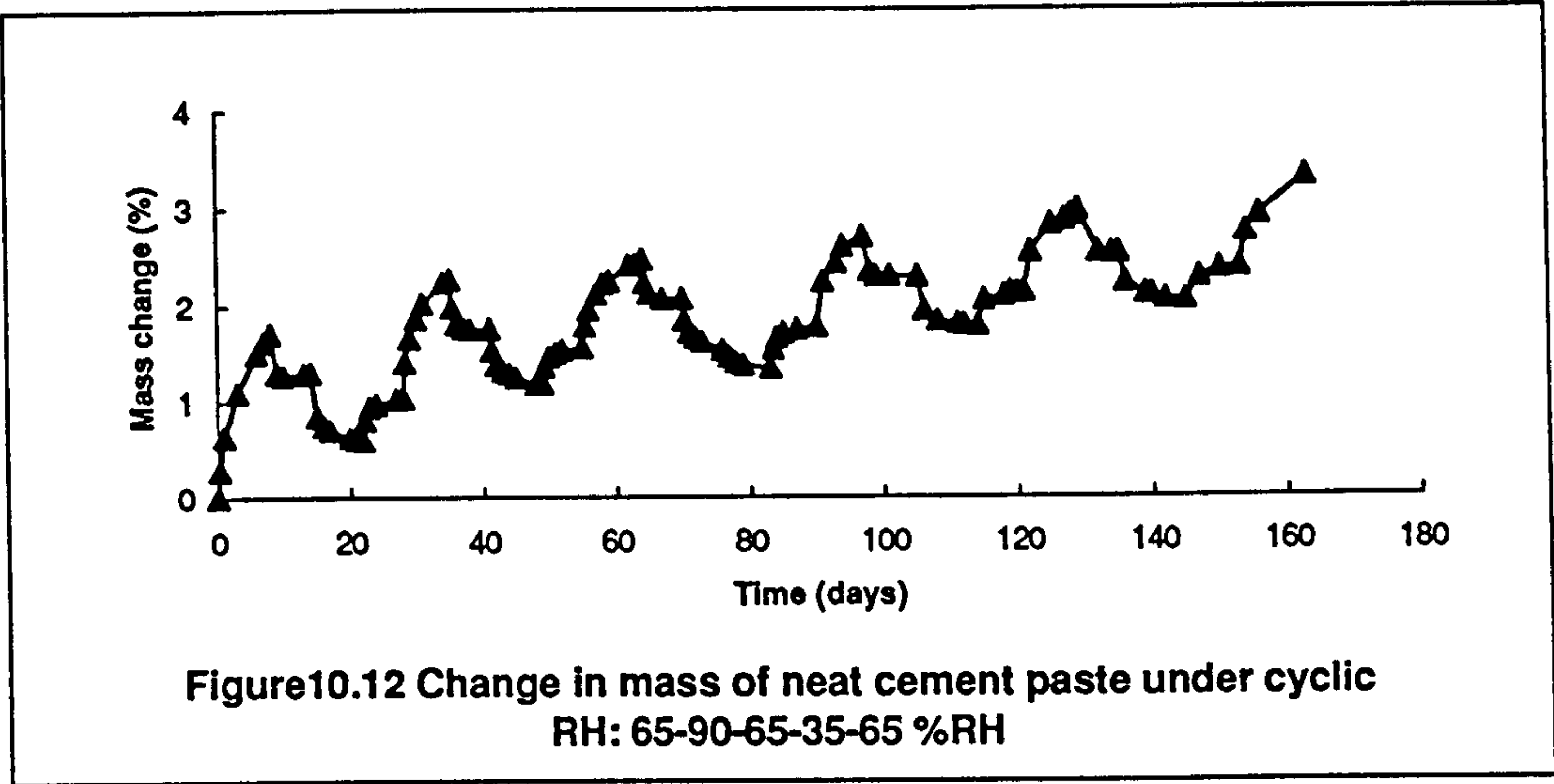


Figure10.8 Change in length of neat cement paste under normal air in moving from 90 to 35 %RH





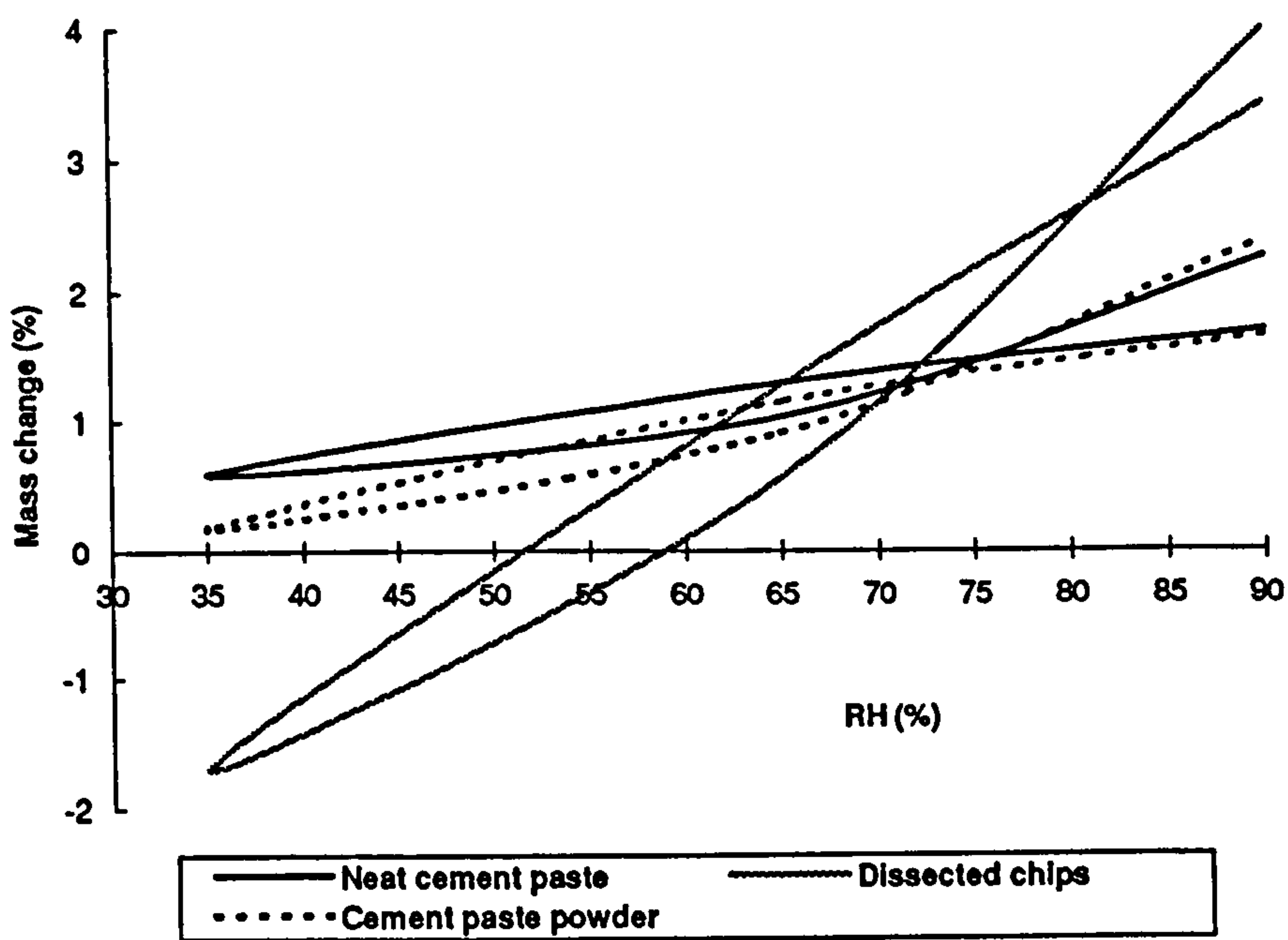


Figure 10.15 Adsorption and desorption of neat and powder cement paste in first complete RH cycle

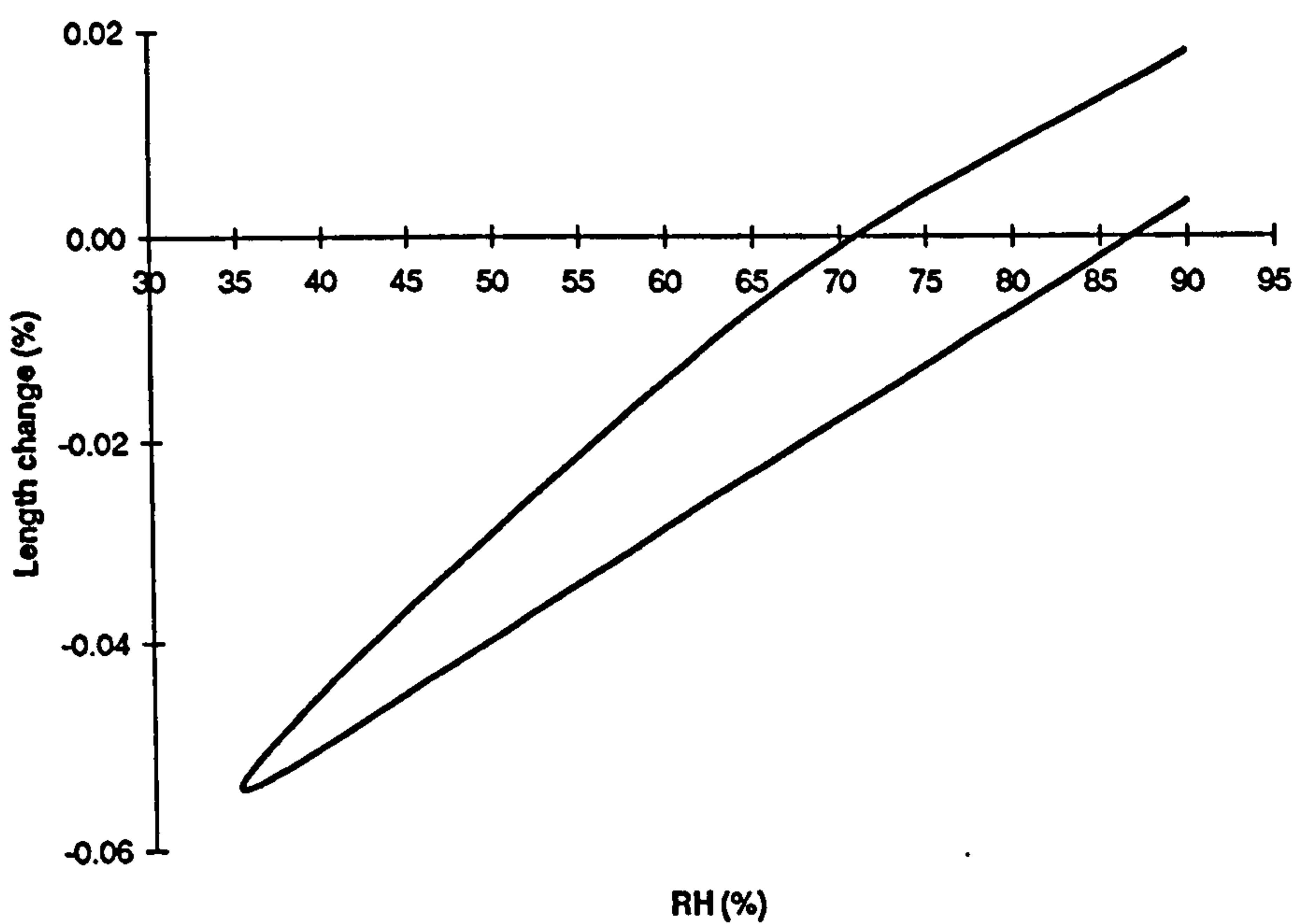


Figure 10.16 Length hysteresis isotherm of neat cement paste in one cycle: 90-65-35-65-90 %RH

Chapter 11

CARBONATION AND CARBONATION INDUCED SHRINKAGE OF CBPB

11.1 Introduction

The significance of carbonation and carbonation induced shrinkage of Portland cement products has been of special interest in the cementitious area for a long time. It has been observed that both carbonation and carbonation induced shrinkage are greatly dependent on the RH of exposure and the density of materials. The pores filled with water hindered the penetration of carbon dioxide because of the low rate of diffusion of CO_2 in water, whilst the reaction of carbon dioxide with water molecules was absent in completely dried pores. Lightweight concretes are more susceptible to carbonation and carbonation effects because of their usually higher permeability. The problem of shrinkage is further aggravated by the higher compressibility of the aggregate.

Evidences of excessive increase in the mass and shrinkage of dimension of CBPB have been illustrated in this study when exposed to various air conditions. It was considered that part of these changes was due to the carbonation of cement paste in CBPB.

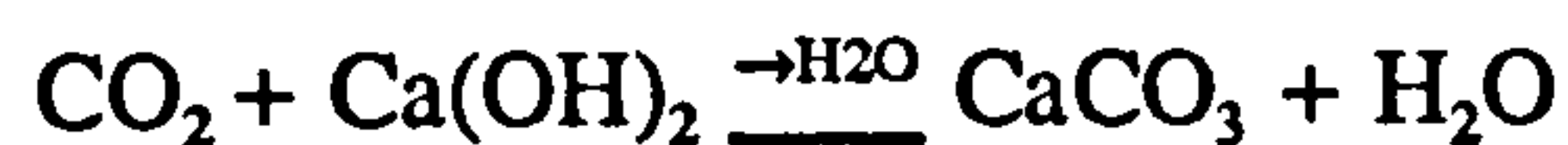
This chapter was carried out to evaluate the carbonation and carbonation induced shrinkage of CBPB or its component, cement paste, with reference to the influence of carbon dioxide in normal air environment. The results will supplement information regarding the behaviour of CBPB and lead to a better interpretation of the instability of CBPB.

11.2 Mechanism of Carbonation of CBPB

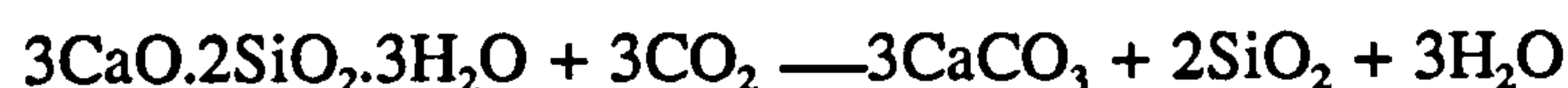
The mechanism of carbonation of CBPB is likely to consist mainly of gaseous diffusion combined with chemical interaction. The chief chemical interaction is the

reaction of CO_2 in the air (about 0.03 % by volume) with Ca(OH)_2 liberated during cement hydration and with CSH. This process results in decomposition of the hydration products of the cement paste in CBPB to form various minerals and water.

The representative functions are:



and



Carbonation proceeds inwards from the exposed CBPB surface along a front roughly parallel to it. This can be confirmed from the study of the density profile of CBPB (chapter 4). In terms of the structure of CBPB, carbonation not only took place in the cement paste in the CBPB but also may be strengthened in the interfacial region due to the less dense microstructure typical of the bulk matrix and the large volume of calcium hydroxide contained. The loose structure of wood chips in CBPB may provide pathways for carbon dioxide and enhance their reaction.

11.3 Carbonation and Subsequential Shrinkage of CBPB and its Cement Paste under Constant RH Condition

Results

Carbonation and carbonation effects on neat cement paste are presented in Figure 11.1 and 11.2. Carbonation and carbonation effects on the corresponding CBPB are illustrated in Figures 11.3, 11.4 and 11.5.

Discussion

In Figures 11.1 and 11.2, it is apparent that carbonation took place in cement paste within CBPB under normal air exposure. The resulting phenomenon was that the mass of cement paste consistently increased and the dimension decreased under a constant RH of 65 %. Over a period of exposure of about 80 days, the mass increased by about 0.7 %, whilst the length decreased by about -0.013 %. The slight increase in mass and decrease in length of cement paste subjected to the CO_2 - free

environment were due possibly to further hydration by virtue of the long time period required for the complete hydration of cement paste. Therefore changes due to carbonation were probably very slightly lower than the values indicated.

Under the same exposure, the phenomena pointed out in cement paste also occurred in the changes of CBPB (Figures 11.3, 11.4 and 11.5), showing a consistent increase in mass of CBPB and decrease in both length and thickness with exposure period. Note that wood chips remain constant under constant RH, providing that chemical degradation does not influence the values tested. The changes in CBPB were deduced to be due to the carbonation of cement paste within CBPB. In fact, a decrease in mass of CBPB under a CO_2 - free atmosphere confirmed that there existed degradation of wood chips due to the alkali solution, causing a loss of mass.

Comparisons of the trends of changes in Figures 11.1 and 11.2 with Figures 11.3 - 11.5 indicate that curves A in Figure 11.3 and 11.4 and 11.5 are not the total changes of CBPB due to the carbonation under 65 %RH normal air environment. The value for mass change of CBPB should, at least, be equal to the addition of A and B to a curve C in Figure 11.3. The values for dimensional changes of CBPB should be given by B subtracted from A, being plotted as curves C in Figure 11.4 and 11.5.

It appears that increase in mass of CBPB due to carbonation was less than that of cement paste, the former being about 0.35 % whilst the latter was about 0.51 %; decrease in length was less than that of cement paste whilst decrease in thickness was greater than that of cement paste. These results reflect not only the percentage contribution but also effect of structure and stresses during their changes. It was concluded that the difference in the change between the length and thickness of CBPB was not solely due to the structure and anisotropic property of wood chips, but had a significant influence from the stress distribution.

11.4 Carbonation and Carbonation Induced Shrinkage of Cement Paste and CBPB under a Single Change of RH

Results

Mass and length changes of cement paste on moving from 90 to 35 %RH are

presented in Figures 11.6 and 11.7, which include changes under normal and free - CO_2 air environments.

The changes of CBPB under the same conditions are given in Figures 11.8, 11.9 and 11.10 for mass, length and thickness respectively.

Corresponding values arising from materials on moving from 35 to 90 %RH are plotted in Figures 11.11 to 11.15 respectively.

Discussion

In Figures 11.6 and 11.7 it is shown that changes of cement paste, in both mass and length, were very similar at the first part of the decrease in RH, but at the later stages of exposure, there was a divergence between the changes under normal and CO_2 - free air environments. Carbonation seemed not to occur at the beginning (or at least was much greater at later stages than that at early stage of exposure in moving sample from 90 to 35 %RH). The difference in the behaviour between two stages of exposure is apparently due to different moisture profiles in the cement paste. Carbonation is accompanied by a release of water and time is required to extract water by drying. At the beginning of exposure, the cement paste was nearly saturated though the ambient RH was 35 % and the rate of carbonation was very low due to the low rate of carbon dioxide diffusion. This is in agreement with results on other cementitious materials observed by Schubert (1976), who found that periodic re - wetting significantly reduced carbonation due to a lower rate of carbon dioxide diffusion through the partially saturated pores of the cement paste matrix; and by Meyer (1968), who concluded that variable moisture conditions can cause a change in the shape of the carbonation depth versus time curve, with the rate of carbonation significantly decreasing with increase of moistening.

Comparisons of the changes under normal air with those under CO_2 - free air show that the behaviour of cement paste was due dominantly to the moisture change on moving from 90 to 35 %RH. However, carbonation shrinkage had a significant effect on the total decrease in length of cement paste at later stages of exposure.

Comparisons of differences between A and B in Figure 11.1 with that in Figure 11.6, or of the differences between A and B in Figure 11.2 with that in Figure 11.7

show a close relationship between carbonation and RH. Significant changes in both mass and length of cement paste occurred under constant 65 %RH, whilst only a marginal difference was found in the mass change and a slight difference in length change between normal and CO₂ - free air environment on moving samples from 90 to 35 %RH.

The trends of changes of CBPB under the same frame of RH change are similar to those of cement paste. Ultimate values of changes over the period tested were very close between CBPB under normal and free - CO₂ air environments. Although the behaviour on prolonged exposure has not been studied due to limited time, from chapter 5 and 6 it is predicted that decreases in dimensions of CBPB will gradually continue, and mass will slightly increase with exposure period under normal air environment.

In terms of change history, the rate of change in the early stages of exposure, whether in mass or dimensions, was very different between the two environmental conditions, with a much higher rate of change of CBPB under normal air than under CO₂ - free air. The reason for this is still unknown.

On adsorption, i.e. on transferring samples from 35 to 90 %RH, the slight carbonation which occurred was reflected in mass and length changes of neat cement paste, with a higher change in mass and a lower change in length under normal air than under CO₂ - free air (Figures 11.11 and 11.12). Carbonation cannot still be reflected clearly in the changes of CBPB on moving from 35 to 90 %RH over the period tested. There was a significant difference in the rate of change of CBPB under between normal and CO₂ - free air environment at early stages of exposure: as on desorption, the rate of change of CBPB under CO₂ - free air was much lower.

Unlike the changes due to the carbonation, the changes due to moisture movement were greater for CBPB than for cement paste (comparison of Figure 11.6 with Figure 11.8 or of Figure 11.7 with Figures 11.9 and 11.10).

11.5 Carbonation and Carbonation Induced Shrinkage of Cement Paste and CBPB under Cyclic RH Conditions

The carbonation and carbonation shrinkage of neat cement paste are illustrated in

Figures 10.11 and 10.13. Those for CBPB can be evaluated in Figures 11.1, 11.2 and 11.3.

In these Figures, consistent increase in mass and decreases in dimensions show the effect of carbonation of CBPB under cyclic RH, assuming that other mechanisms were not significant. As discussed above, the carbonation of CBPB is strongly dependent on the RH, with carbonation being less under both ultimate RH. It is evident that changes of mass and dimensions of cement paste, or of CBPB due to carbonation, under cyclic RH, should lie between the maximum and minimum change values.

In Figure 10.11 it may be noted that the maximum change in mass due to carbonation of cement paste after two cycles (returning to 65 %RH) was about 1.6 % which was about three times higher than that under constant RH at 65 %RH (with the same period of exposure); the change in length of cement paste under cyclic RH was also about three times (-0.03 %) higher than that under constant 65 %RH (Figure 10.13). Evidently, the degree of carbonation for "neat" cement paste is not greatest under 65 %RH. In the cementitious area it lies between 50 and 75 %RH.

Values in Figures 11.1, 11.2 and 11.3 confirm that the greatest carbonation of CBPB under normal air environment does not lie at a RH of 65 %RH. However, the values arising from cyclic RH were only slightly higher than those arising from constant 65 %RH exposure, Figure 5.1 and 5.2. The divergence between neat cement paste and CBPB may be attributable to the effect of moisture held in wood chips.

11.6 Interim Conclusions 8

- 1) Carbonation and carbonation induced shrinkage took place in CBPB or its component, cement paste, under normal air environment, which contains carbon dioxide. The carbonation proceeded inwards from the exposed CBPB surface along a front roughly parallel to it, although it may be concentrated in some local area (interfacial region).

- 2) Carbonation and carbonation shrinkage were essentially dependent on RH, and required the presence of water and an intermediate moisture content for maximum

shrinkage. A significant reduction in carbonation of CBPB or its cement paste occurred at the ultimate RH.

3) Under the constant RH of 65 %RH tested, the changes of CBPB, in both mass and dimensions, due to carbonation were less than those of its cement paste, showing the percentage contribution of components in CBPB.

4) The changes of CBPB due to the combined effects of moisture movement and carbon dioxide were greater than those of cement paste.

5) The decrease in the thickness of CBPB due to carbonation was much greater than that in length of its "neat" cement paste, suggesting that the difference between the change in length and thickness of CBPB under various exposures was not due solely to the structure and anisotropic nature of wood chips, but could be affected by stress distributions during the changes.

6) Under long term exposure, the values in the changes of CBPB due to carbonation may be supplemented by the degradation of wood chips which may reduce the mass and dimensions.

7) The change due to carbonation at 35 %RH or 90 %RH exposure can clearly be reflected in cement paste at later stages of exposure, but not in CBPB over the period tested. However, the effect can be deduced by combining the results in chapter 6.

8) It is evident that change of CBPB under ultimate RH exposure was dominated by the effect of moisture change. However, at 35 %RH exposure, carbonation had a significant effect on the total decrease in dimensions.

9) Under single change RH, the trends of changes of CBPB were similar to those of its cement paste. However, it is unknown if the rate of change of CBPB under CO₂ - free air environment was much lower than that under normal air at the beginning of exposure.

10) Under the same exposure period, the changes of both cement paste and CBPB due to carbonation under cyclic RH was higher than those under constant RH of 65 %RH, indicating that the greatest carbonation did not occur at 65 %RH.

11) The difference in the change of CBPB due to carbonation between normal and free - CO₂ air exposure was less significant than that of cement paste, indicating that the moisture held in wood chips may have an influence on the carbonation of CBPB.

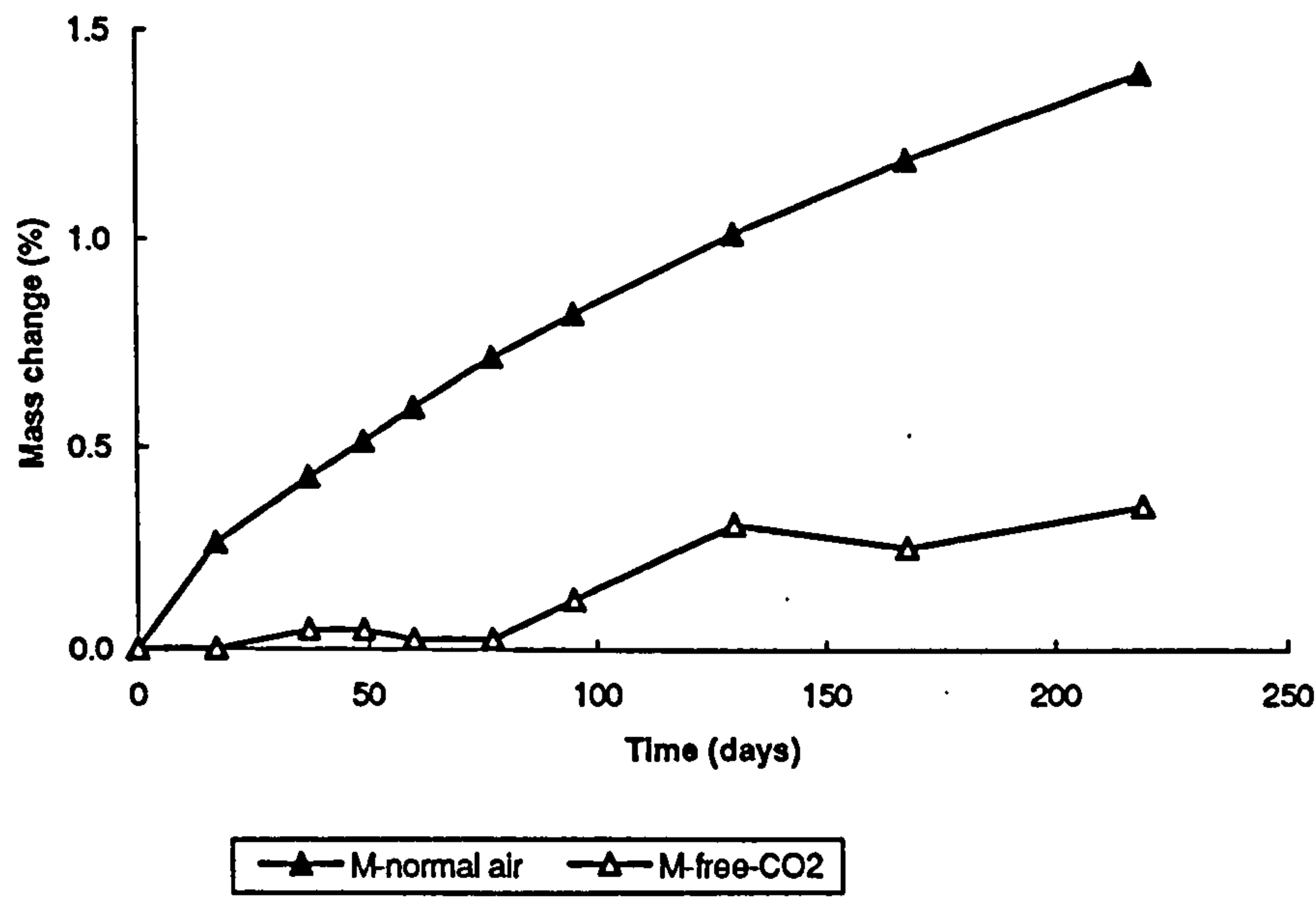


Figure11.1 Change in mass of neat cement paste under normal and CO₂ - free air at constant 65%RH

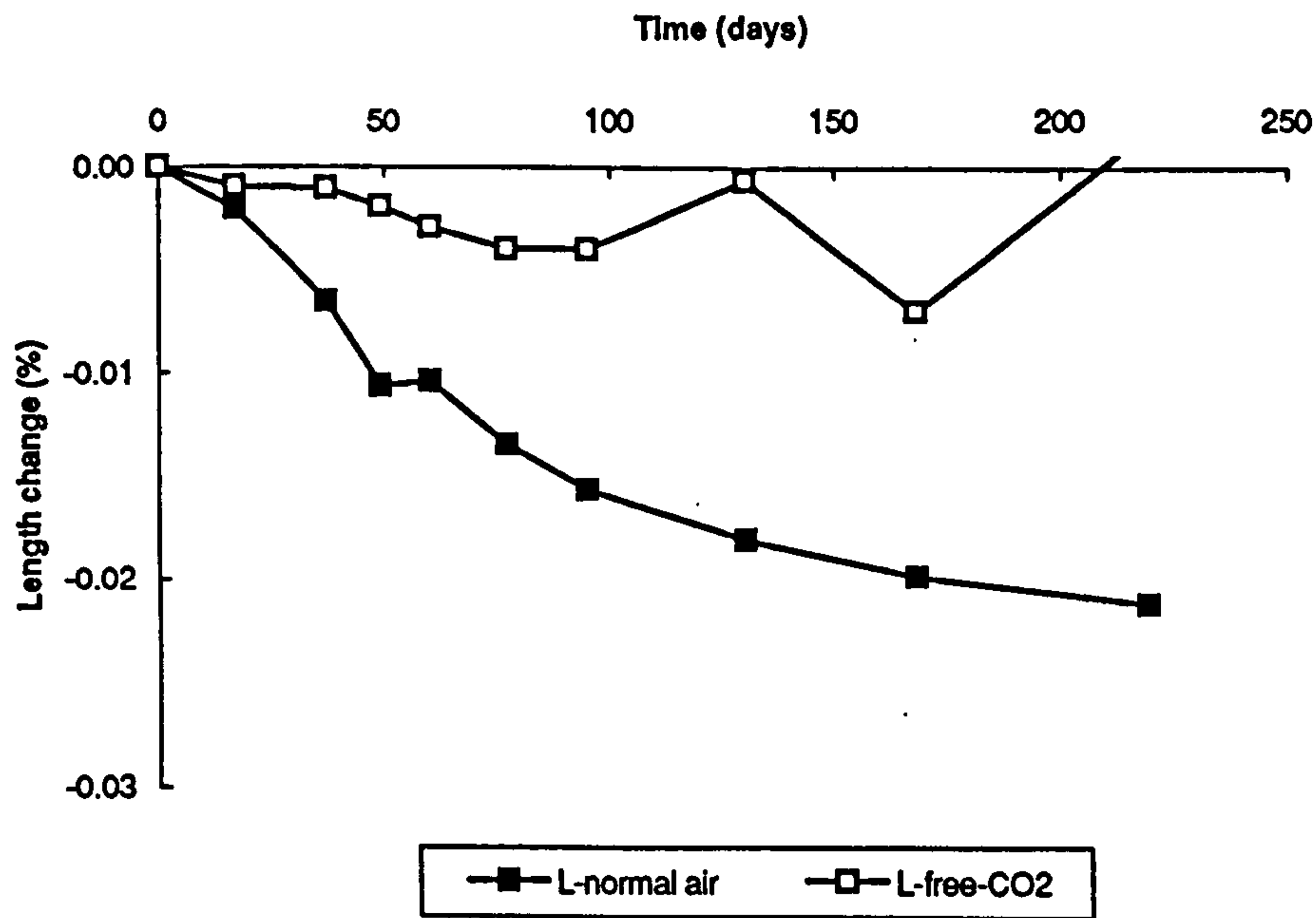


Figure11.2 Change in length of neat cement paste under normal and CO₂ - free air at constant 65 %RH

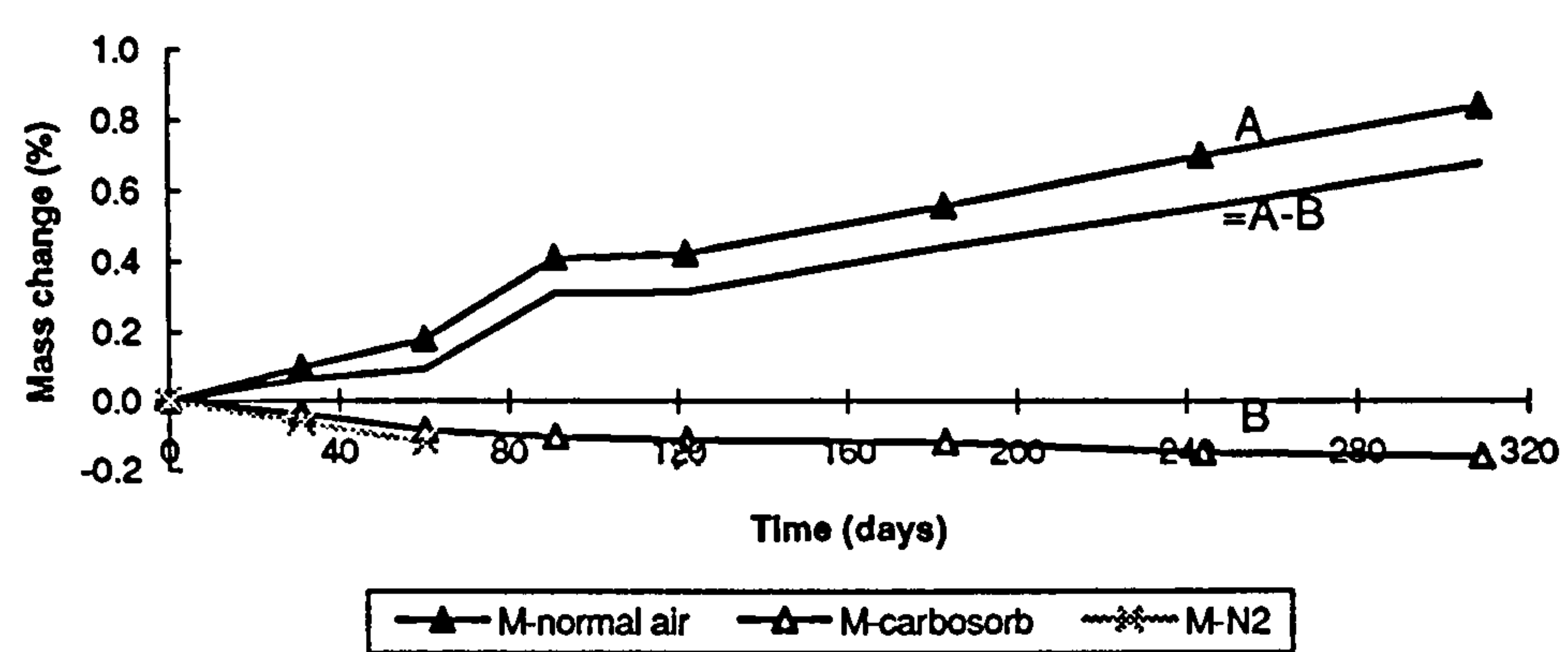


Figure 11.3 Change in mass of CBPB under normal and CO₂ - free air at constant RH 65 %RH

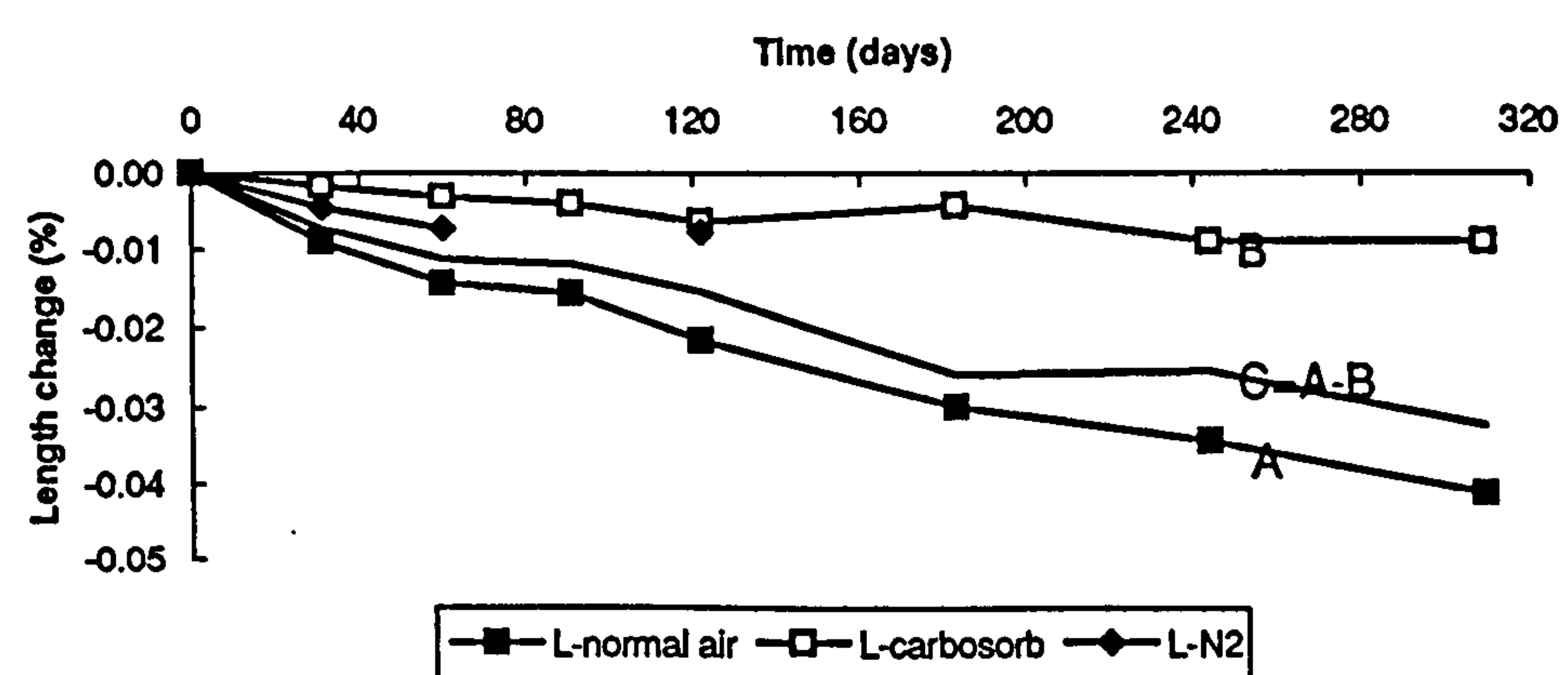


Figure 11.4 Change in length of CBPB under normal and CO₂ - free air at constant RH 65 %RH

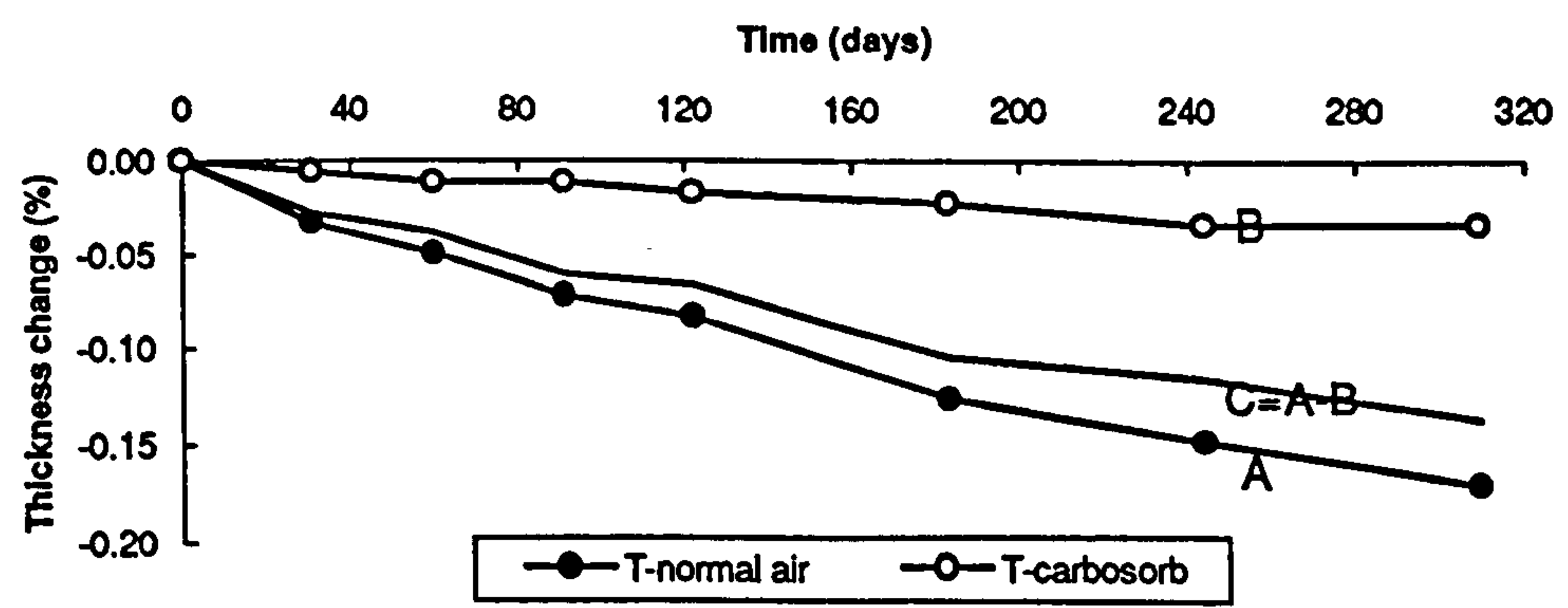
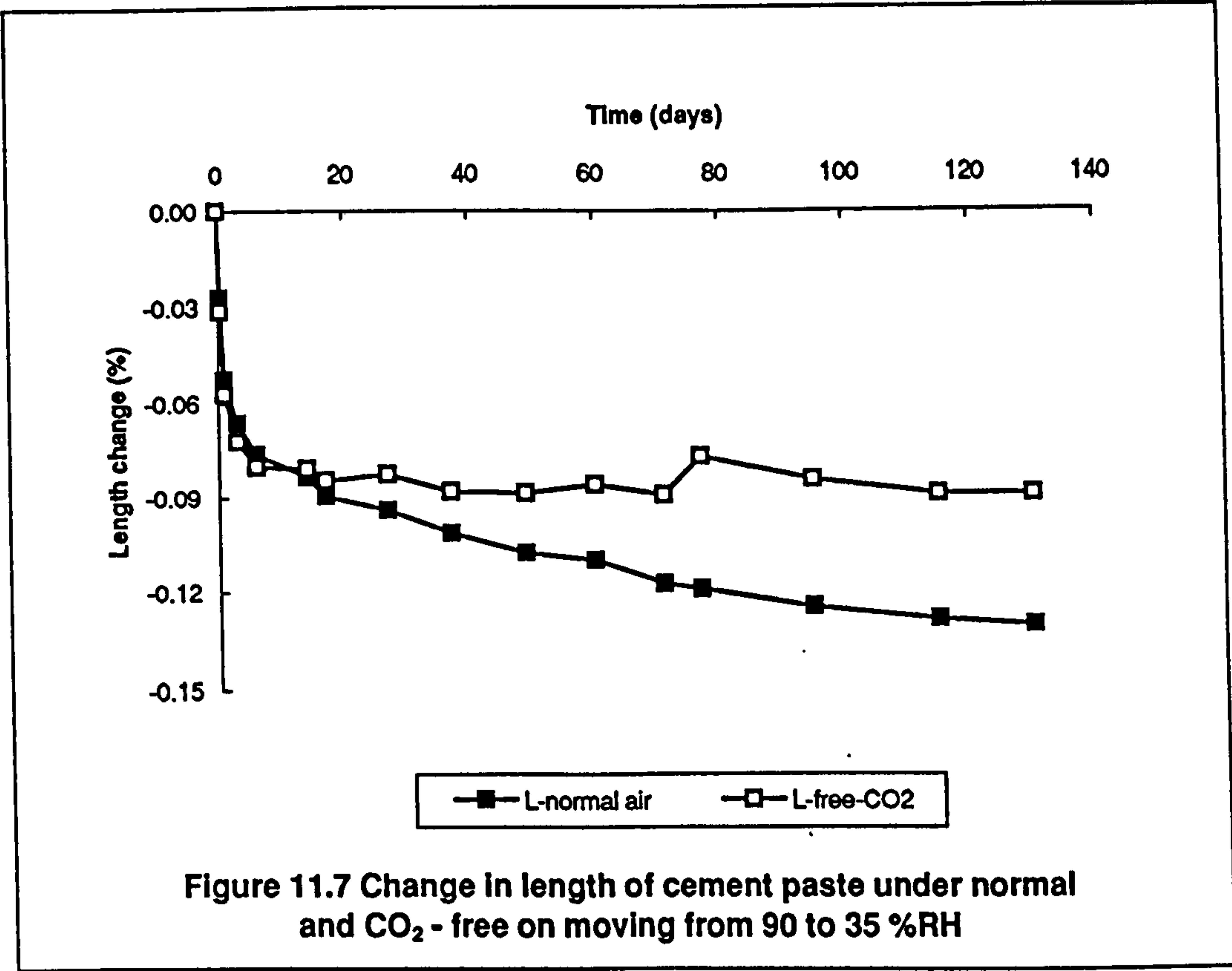
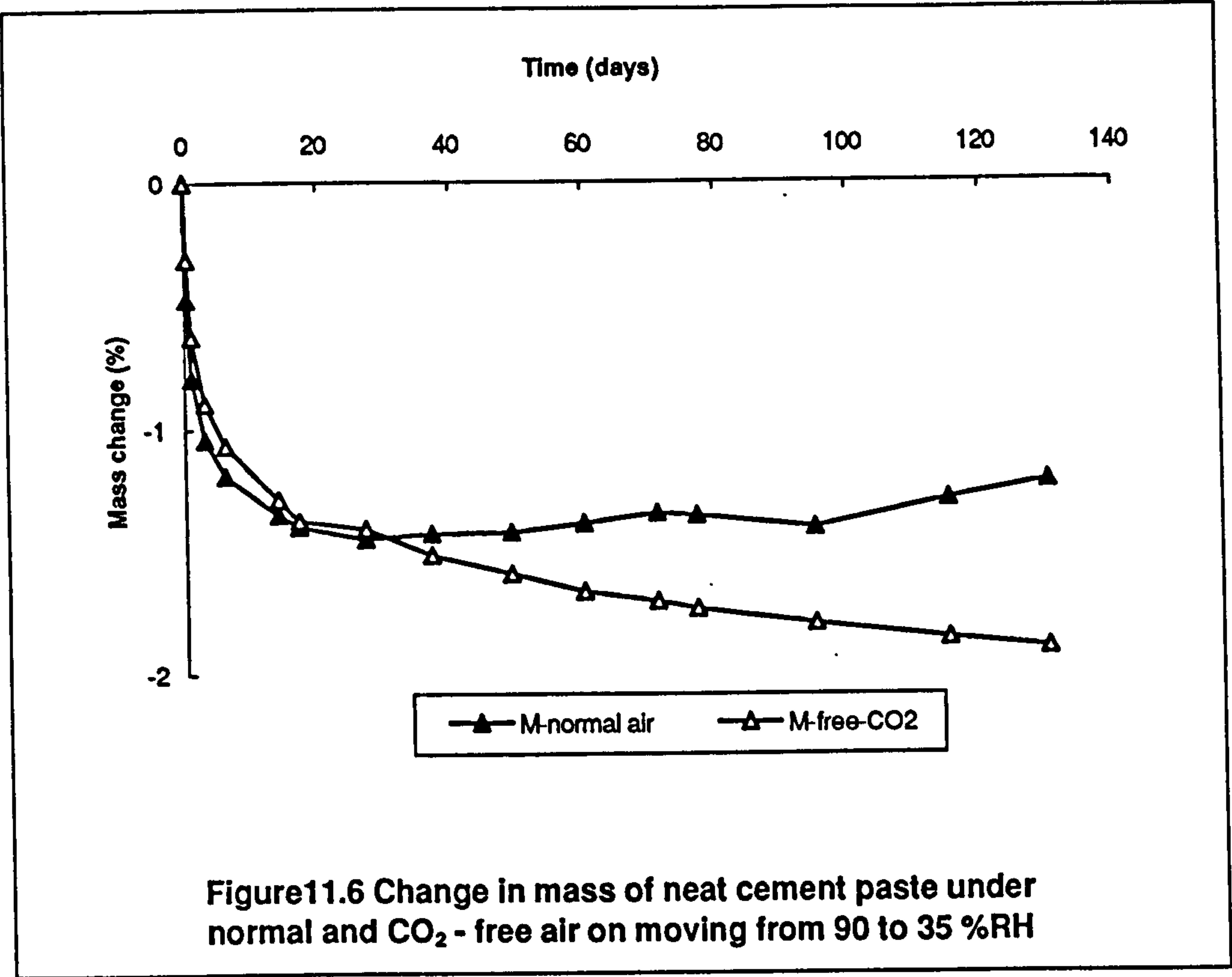
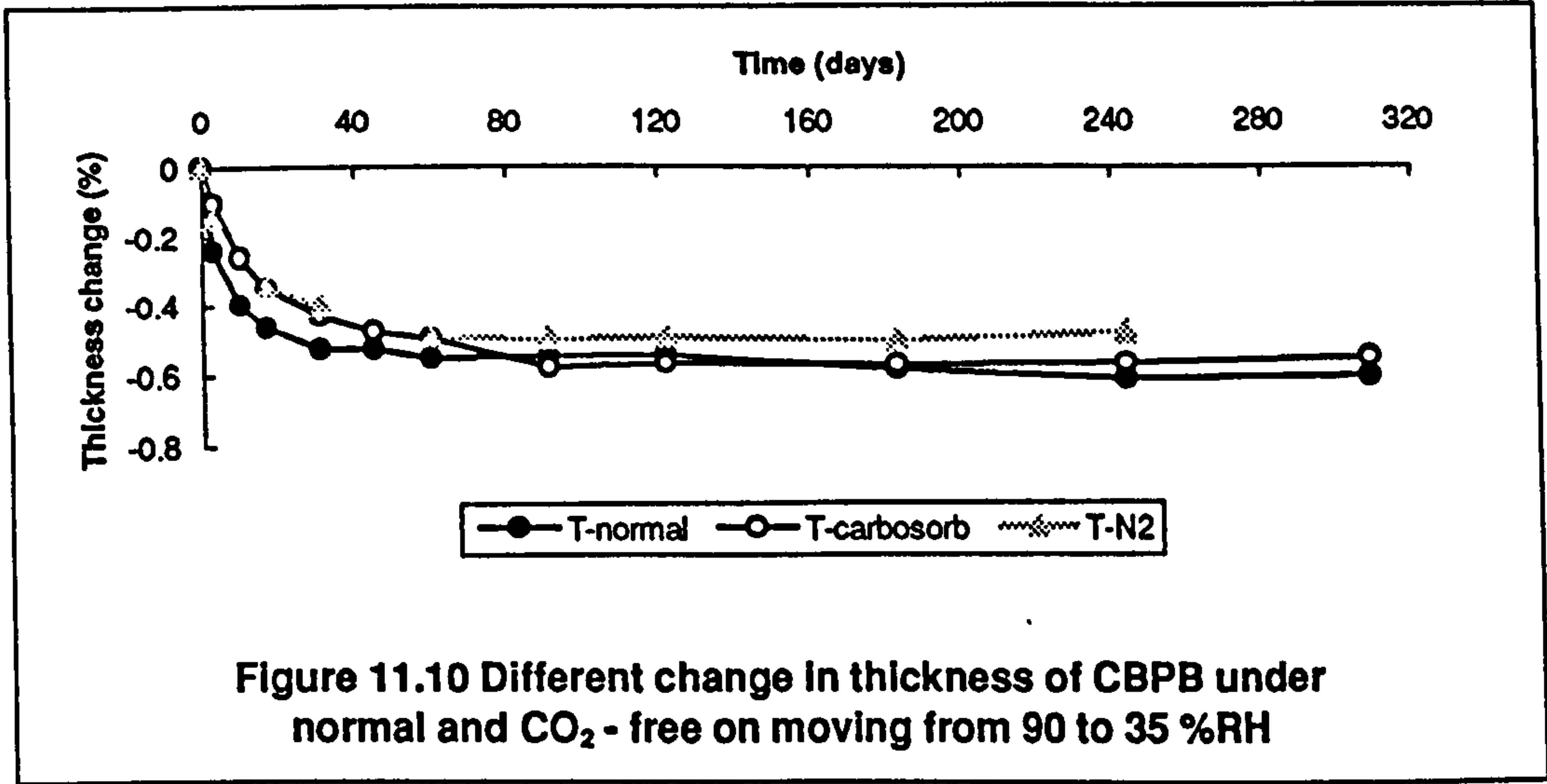
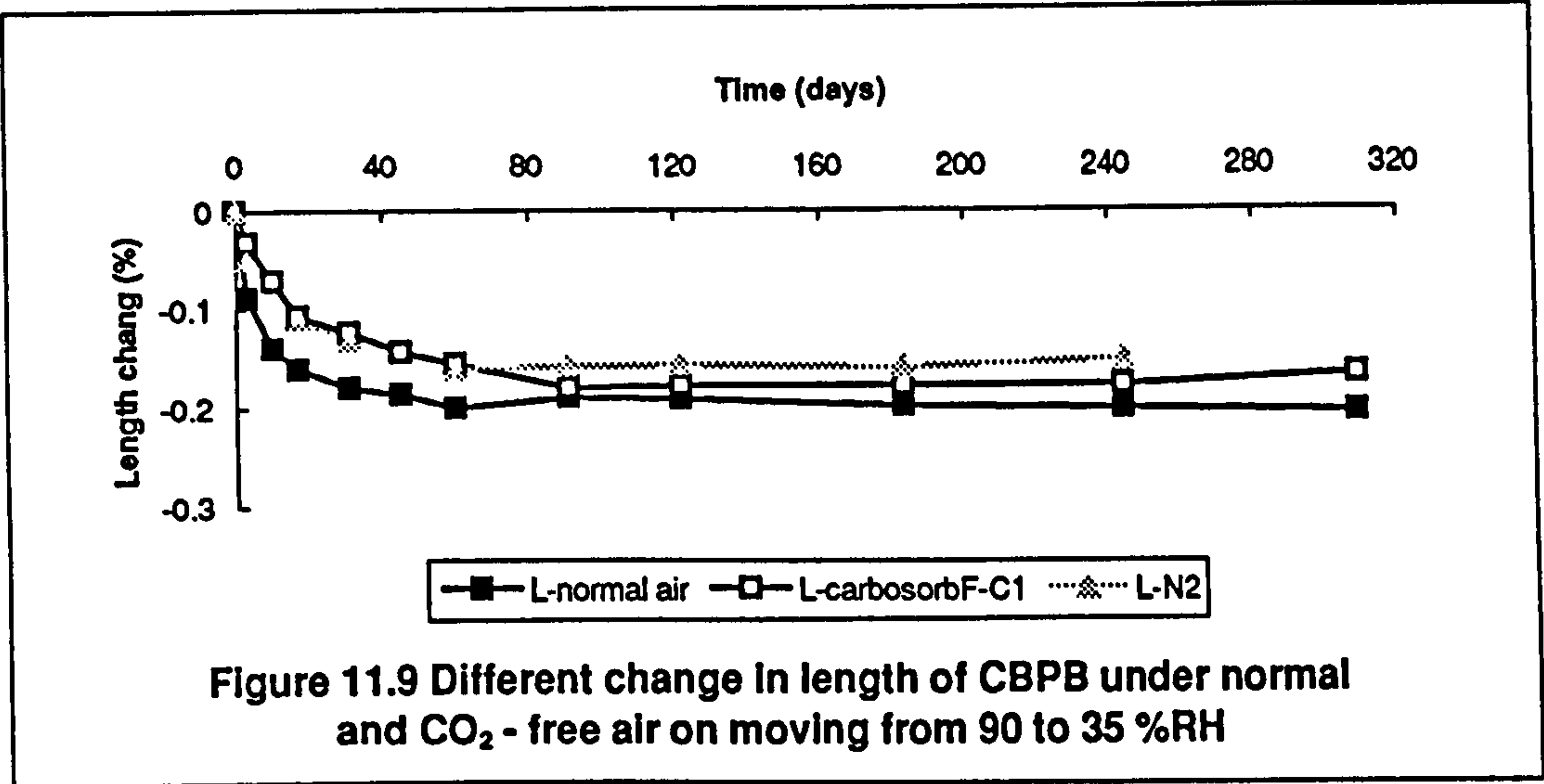
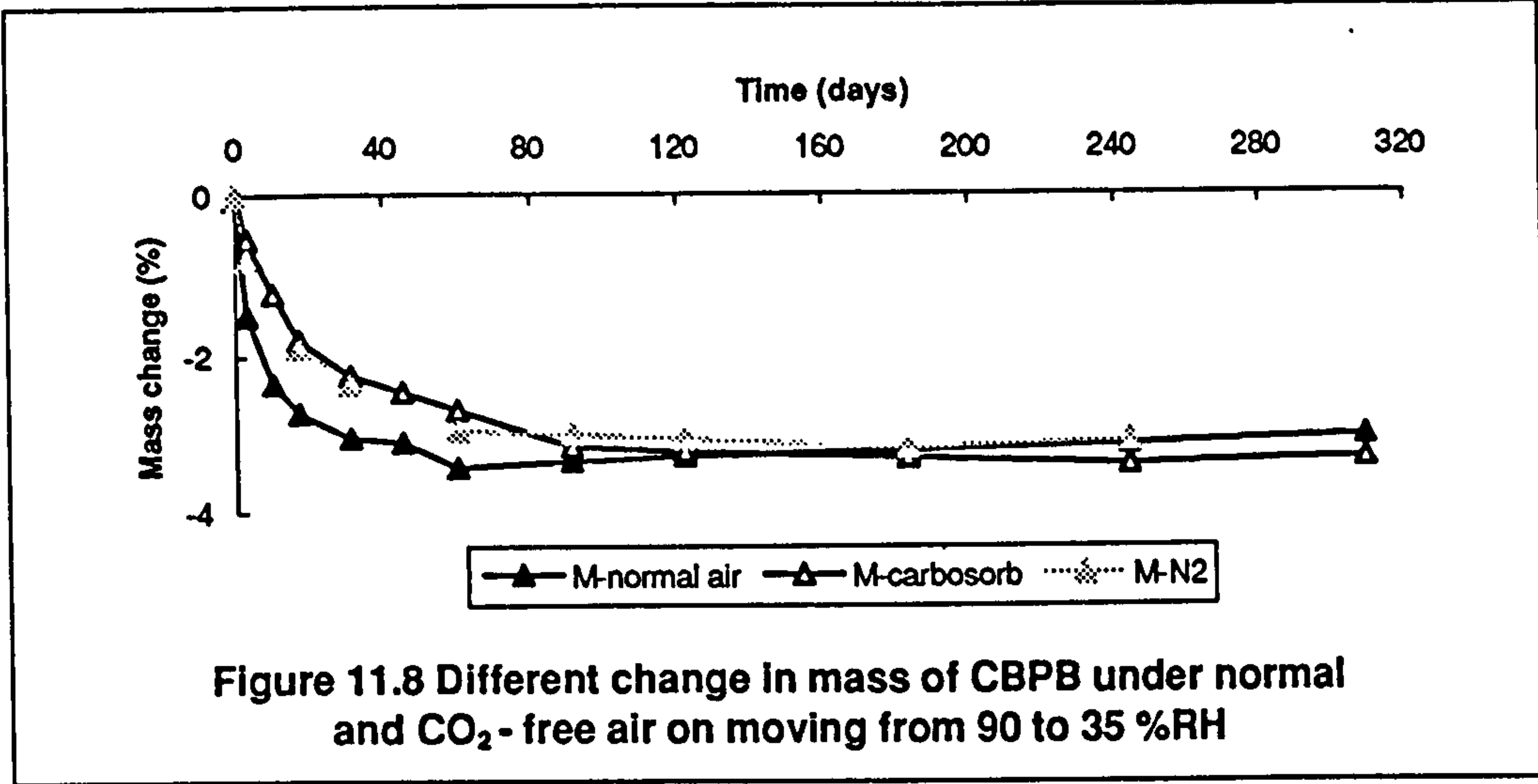
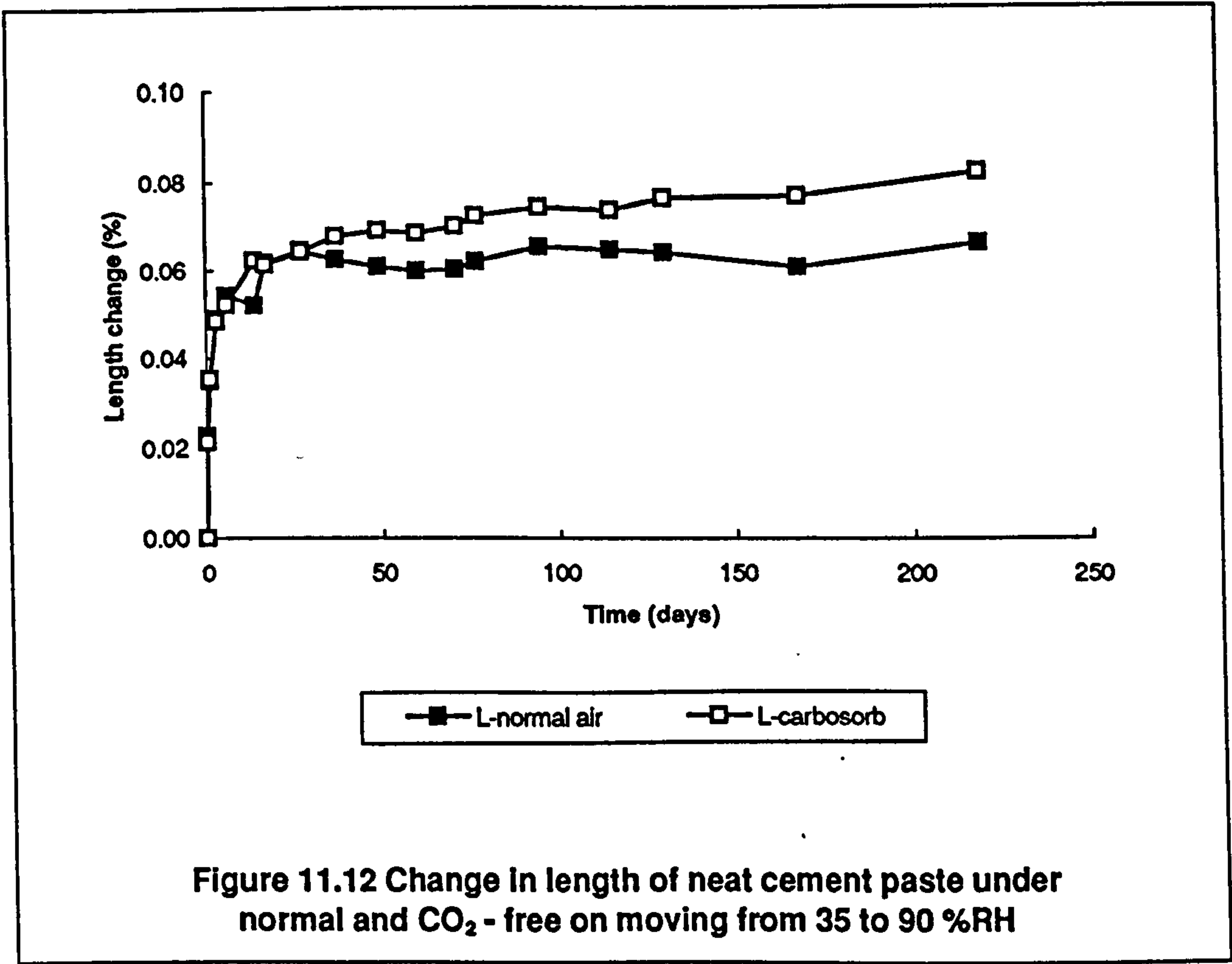
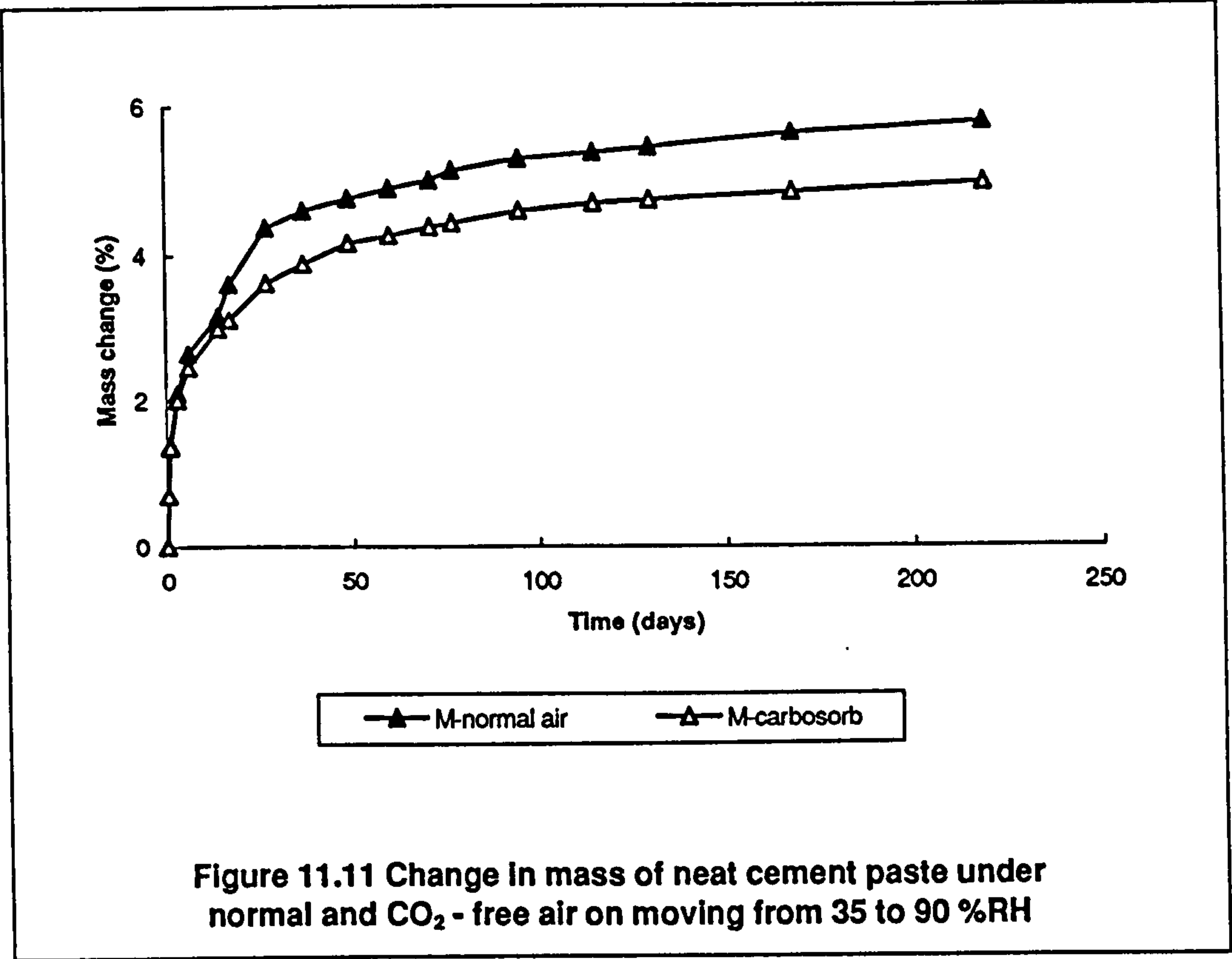
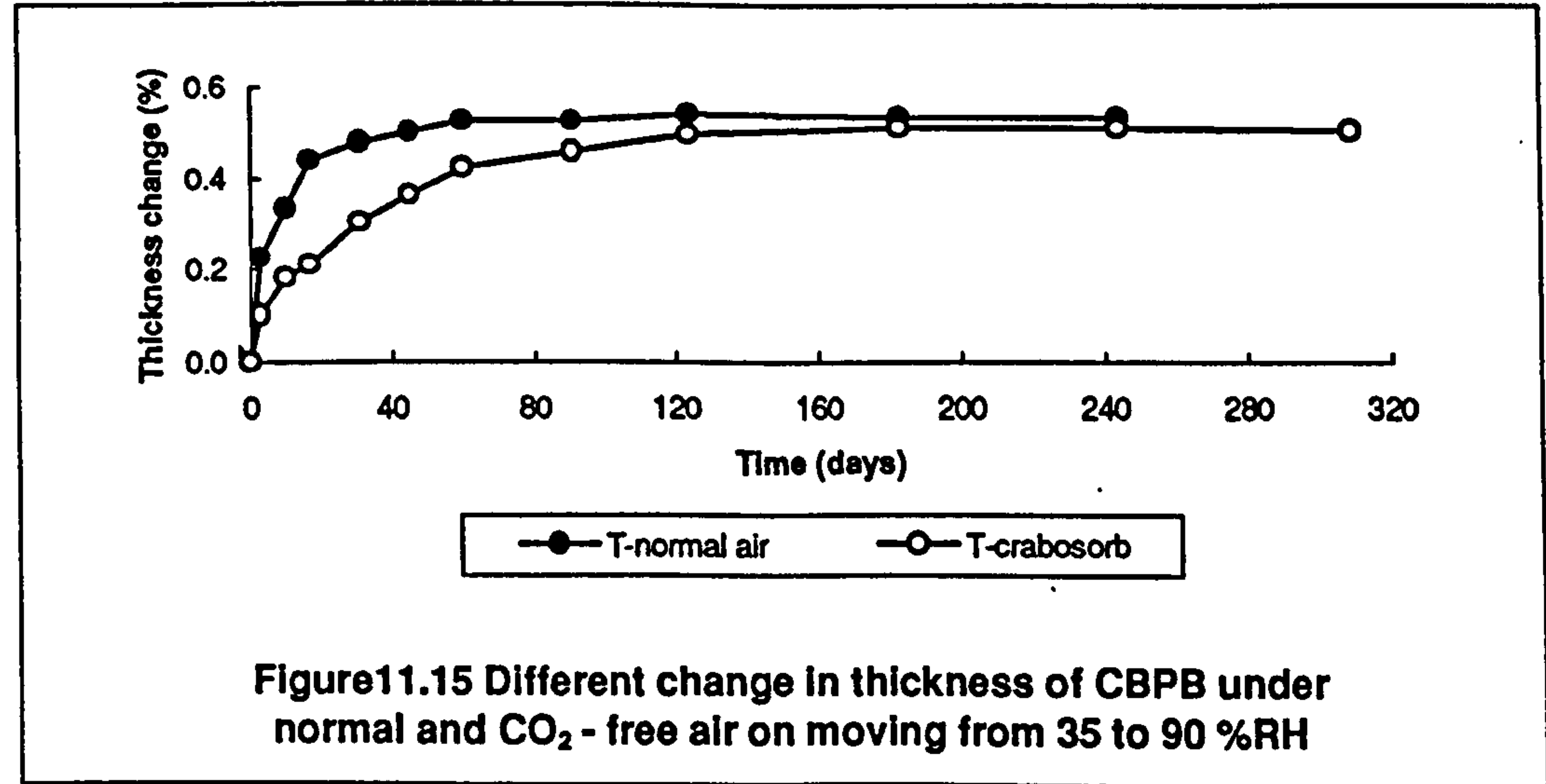
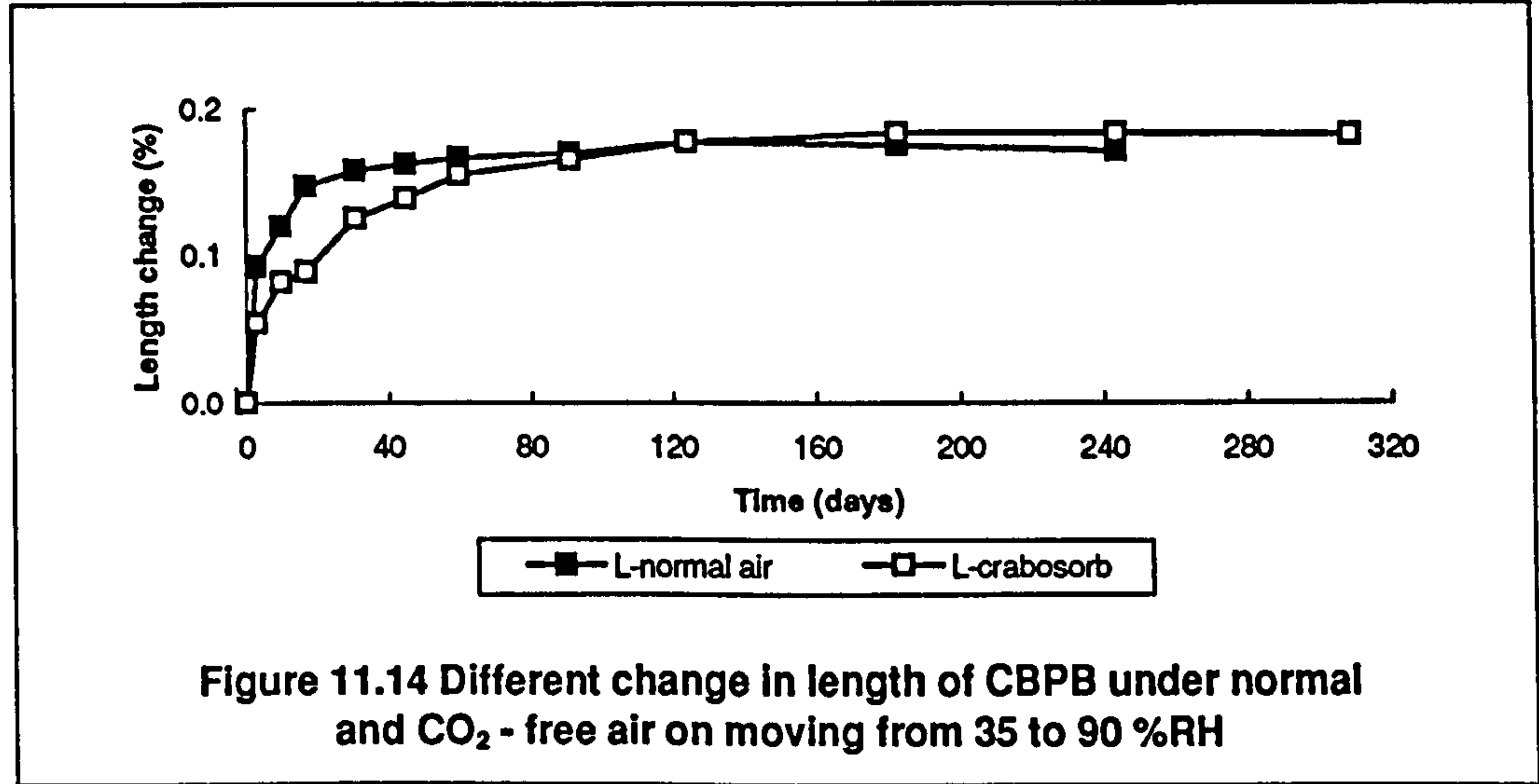
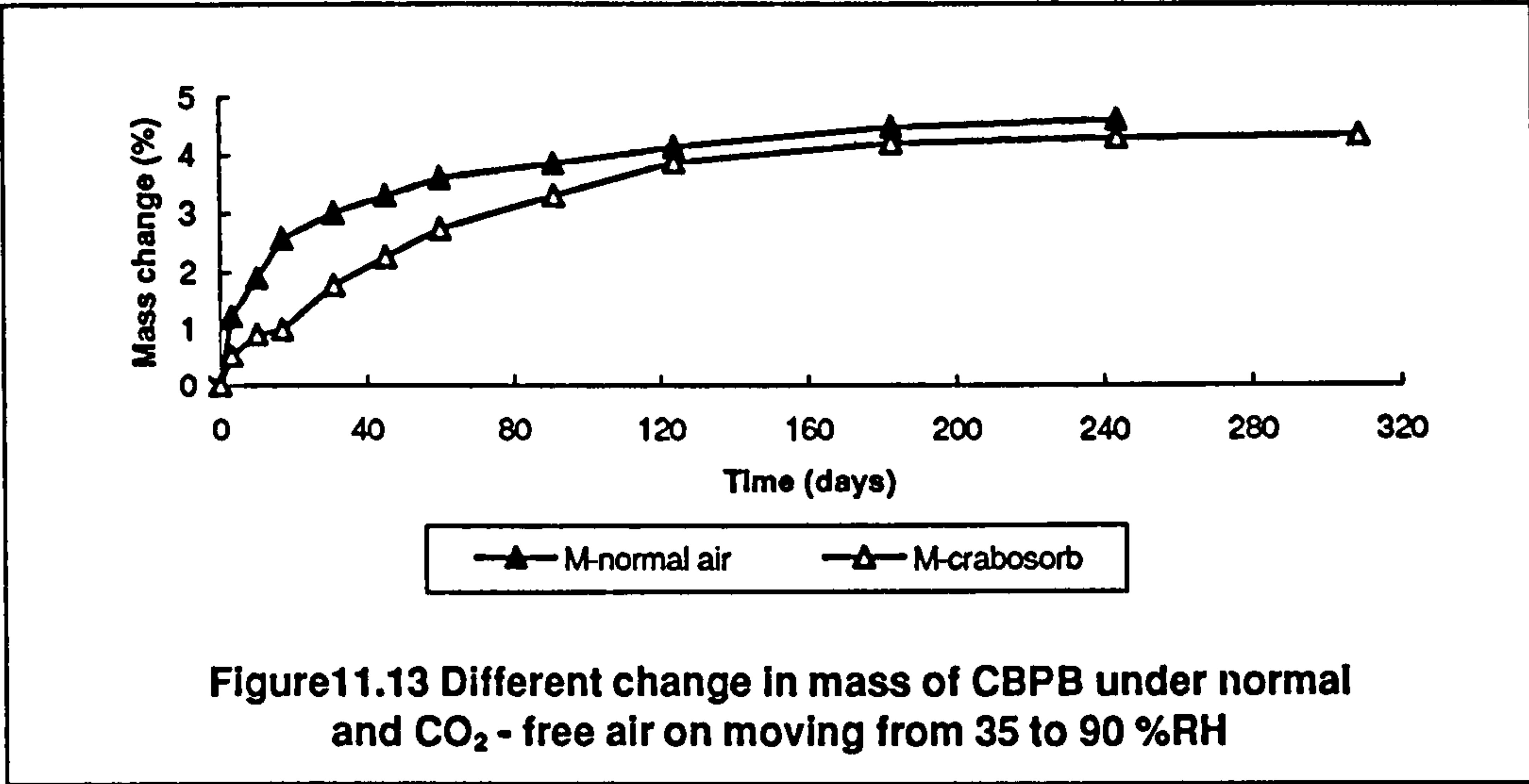


Figure 11.5 Change in thickness of CBPB under normal and CO₂ - free air at constant RH 65 %RH









Chapter 12

MECHANISMS OF DEFORMATION OF CBPB

12.1 Introduction

In previous chapters, it has been shown that CBPB adsorbs moisture when it is under higher RH and desorbs moisture as it is subjected to the lower RH. It will shrink under desorption and swell under adsorption. The magnitude of the change varies with the direction of samples, length or thickness, and the range of RH.

Drying shrinkage of cement paste may involve length changes up to 5 %, the shrinkage of wood normally ranging from 0.1 % to 10 % depending on various conditions. However, it should be noted that longitudinal shrinkage is always an order of magnitude less than transverse, while in the transverse plane radial shrinkage is usually some 60 - 70 % of the corresponding tangential figure.

CBPB may be regarded as a two - phase composite material in which the discontinuous phase is the wood chips and the matrix phase is the hardened cement paste. Accordingly, the deformation of CBPB is determined by deformation of the cement paste and by that of wood chip. All factors which affect the deformation of both wood chips and cement paste also affect the deformation of CBPB. The summary of the factors is given as Figure 12.1 which have been discussed in different chapters. This chapter deals with the mechanisms of sorption and deformation of CBPB under the supposed model of structure.

12.2 Mechanistic Model of CBPB

The structure of both cement paste and wood chips under the microscope is very complex. For the cement paste, both microcrystalline and colloidal materials are visible, with the colloidal material occurring as an amorphous mass enclosing microcrystalline $[\text{Ca}(\text{OH})_2]$ and un - hydrated residuals of the original cement grains. Pores in the cement paste include both gel pores and capillary pores. For wood chips,

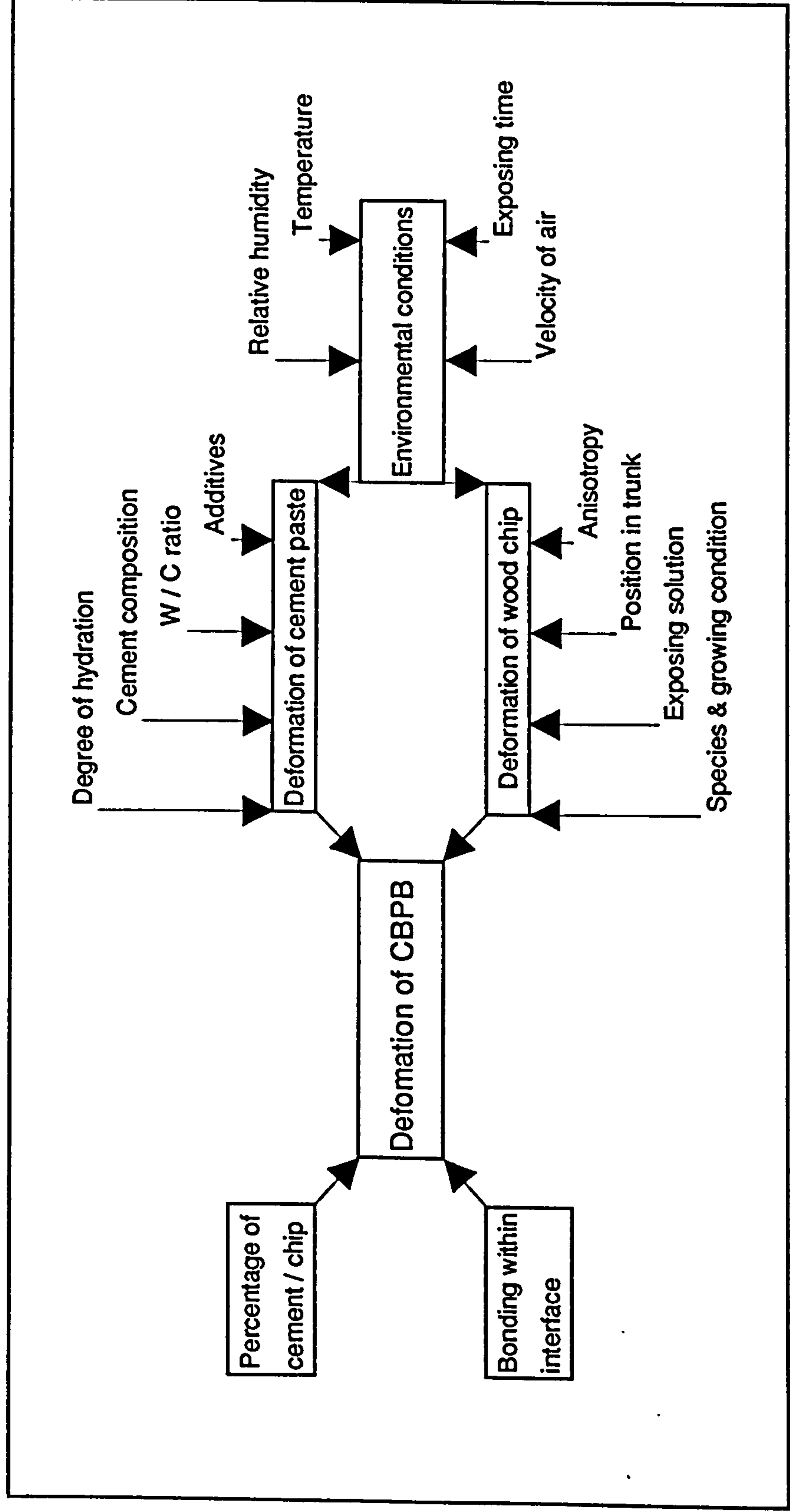


Figure 12.1 Schematic representation of factors affecting deformation of CBPB

the structure is comprised of cells which, for softwood, consists of both tracheids and parenchyma. Overall 90 - 95 % of cells are aligned in the vertical axis, whilst the remaining percentage is present in bands. The lumen are connected by pores of different kinds.

The interface between the cement paste and the wood chips consists of an initially water - filled transition zone which does not develop the dense microstructure typical of the bulk matrix and contains a large volume of calcium hydroxide crystals deposited in large cavities. Under scanning electron microscopy there is very close contact between the peripheral fractured lumen cell walls of wood substrate and solid hydrated cement paste products but no evidence of any hydrated or unhydrated cement constituents penetrating non - fractured cell lumen within the wood substrate was found. Generally the complete cells immediately adjacent to the cement are deformed, being nearly flattened.

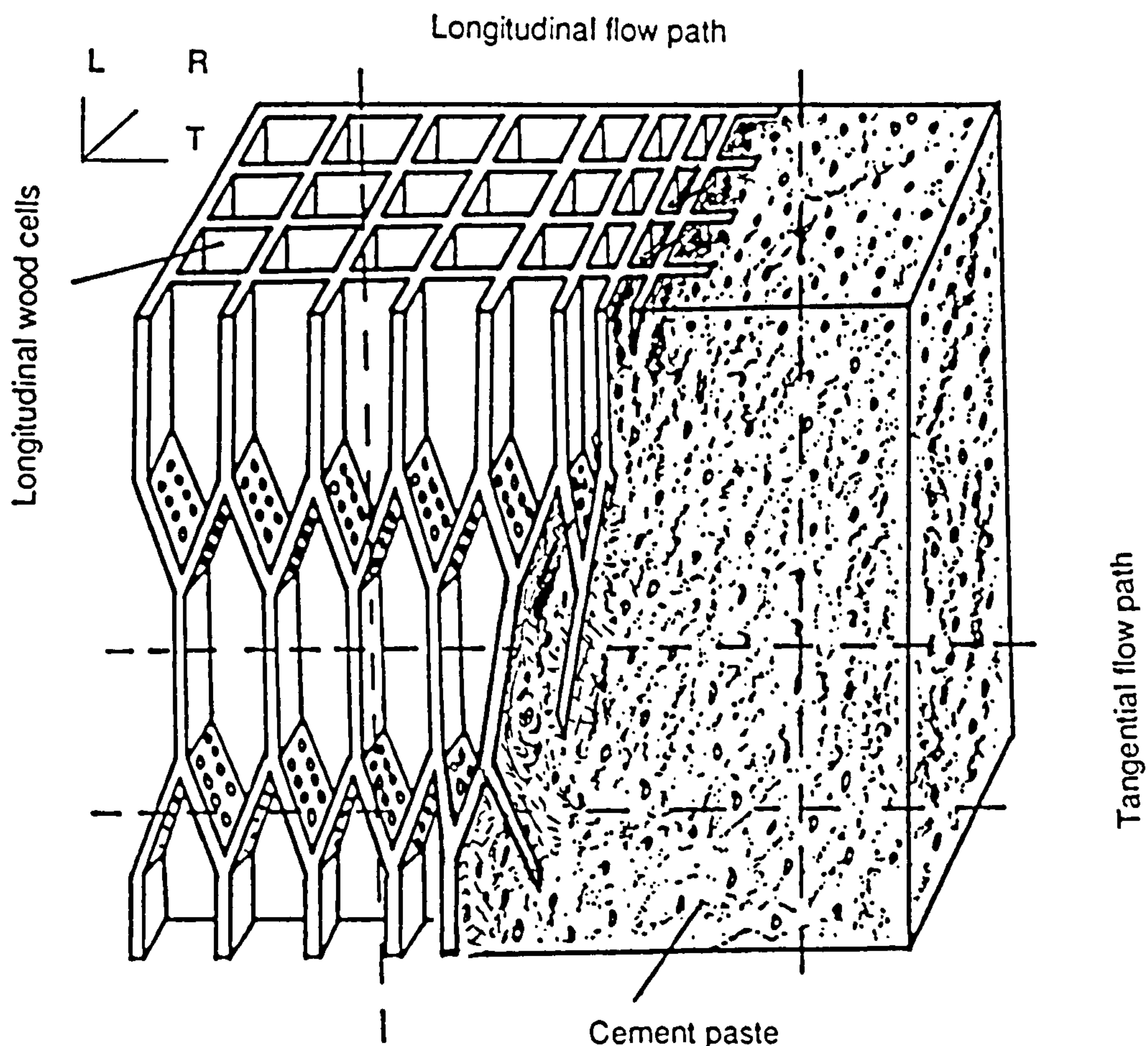


Figure 12.2 Mechanistic model of the structure of CBPB

Based on the above facts, a mechanistic model of CBPB consisting of softwood chips and cement paste is illustrated in Figure 12.2. As can be seen, the blocking / filling of the interconnecting pits on the wood cells by the liquid cement paste may play an important role in the movement of moisture. In Figure 12.2, the model presents both cross sectional and tangential sections with respect to the wood chip. The radial section is similar to the tangential section with the exception of the ray cells which are not included. For the model, all pits of soft wood are assumed to be located on the tapered overlapping portions of square longitudinal cells. Compared to the lumen of wood, gel pores in the cement paste are too small to be shown at the same scale, only some of capillary pores can be shown.

It is evident that sorption of CBPB not only occurs separately in wood chips and cement paste, but are also complicated by the interfacial region. The lumen and other voids of wood chips adjacent to the cement paste is deformed and the void space is fully or partly filled with cement paste. The transportation of moisture through the CBPB may depend on the conditions at this area and be dominated by the component which is more resistant to the moisture movement.

Further details of both wood cell wall and C - S - H (calcium silicate hydrate) which is the principal constituent of the cement gel can be referred to in chapter 2 in which the models are included.

12.3 Water in CBPB Corresponding to the Level of RH Tested

Considered with respect to the model described above, water in the CBPB can be classified as follows:

- 1) Free water - which is present both in the cement paste and the wood chips in CBPB. It exists in the cell cavities / pores beyond the range of the surface forces of the solids in the CBPB. In wood chips, this water is at a moisture content above the fibre saturation point (fsp).
- 2) Adsorbed / bound water - which occurs in both cement paste and wood chips. It has been proposed that this water is taken up on internal sorption sites attractive to water. It is confined between adjacent crystallite surface and adsorbed on the surface of the crystallites. Characteristic of another part of water is different between the

constituents of wood chips and cement paste. For wood it is bonded to the matrix constituents (hydrogen bonding) and to the hydroxyl groups of the cellulose molecules in the non - crystalline regions. Corresponding to this is that part of water called:

3) Chemical water in cement paste - it is combined in the hydrated cement compounds and as such is part of the solid. This type of water in cement paste cannot be removed during normal drying.

When CBPB is soaked in water, all gaps and pores and cavities, whether in wood chips, cement paste or their interface, are filled, though the duration required may depend on the structure of the interface between the wood chip and cement paste.

At 90 %RH, capillary condensation could occur at those pores having radii less than $0.01\ \mu\text{m}$. In theory, lumen in wood chips are too large (about $8 - 35\ \mu\text{m}$, for the Sitka spruce in the CBPB used). Some capillary pores in cement paste and the interfacial area play a major role in determining the moisture content. However, in terms of the complex shape of large cavities and deformation of wood cells, and partial filling of cement paste in the lumen of wood cells in the interfacial region, a small amount of water may be included in the ends of the cells or some large size of other cavities as Figure 12.3.

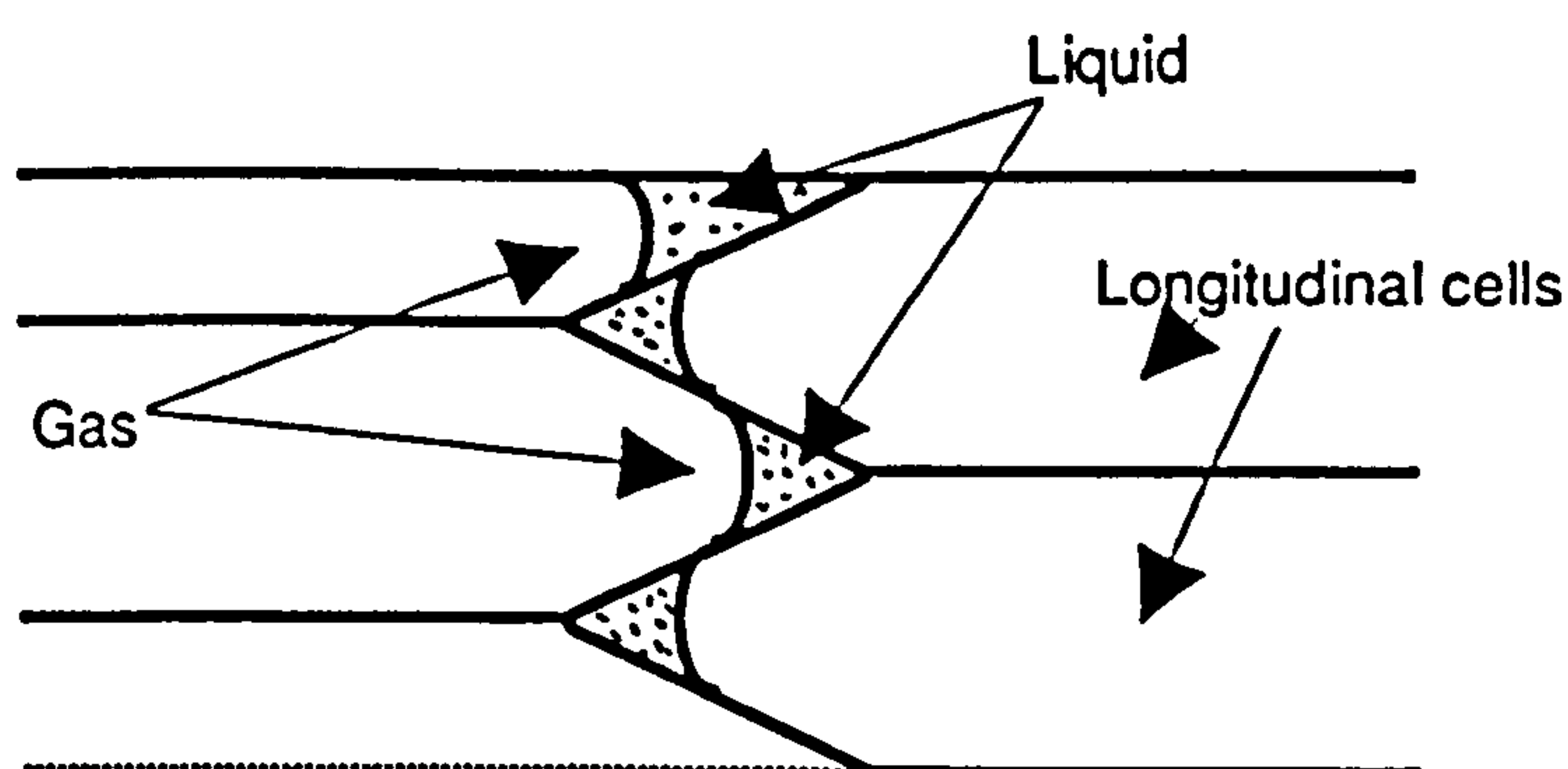


Figure 12.3 Assumed moisture location in lumens

At 65 %RH condensation can only occur in pores smaller than about $0.002\ \mu\text{m}$. The majority of moisture is absorbed in the cell walls of wood chips and in gel pores (about 0.0015) of the cement paste and some tiny cavities in the interfacial area.

At 35 %RH $0.001\ \mu\text{m}$ pores of radii are required to condense moisture, if it

occurs. It is thought that moisture is strongly restricted to the surface of crystalline or other matrix constituents.

12.4 Deformation Mechanisms of CBPB with Respect to Moisture Changes

The following is an attempt to explain the deformation mechanisms by means of a comprehensive hypothesis based on the features of cement paste and wood, and referring to existing facts regarding the structure of CBPB (especially in the interfacial area) and the results described in previous chapters. It is based on cement paste in CBPB due to its more irregular structure and supplemented with the wood chip organised in a very regular pattern.

Physical deformation can be attributable to at least four mechanisms, and involves all types of evaporable water confined in the small spaces within the CBPB (described above). It is apparent that these mechanisms will occur at different levels of RH.

Water immersion (Complete saturation) When CBPB is immersed in water or is at its initial stage before drying (environmental exposure), it can be regarded as saturated. The whole system is probably subject to a slow swelling process balanced by tension in the solid phase. It is believed that at the initial moment of exposure (prior to any active shrinkage mechanism set in), the wet material contracts slightly due to the relief of these tensile stresses.

RH - 99.9 - 90 %RH At the commencement of desorption a fairly large weight loss is accompanied by only a small amount of shrinkage. Meniscus formation in channels and capillary cavities (the radius of pores ranging from 1 μm to 0.01 μm) subjects the whole system to elastic shrinkage due to increases in tensile forces in the water. However, as can be seen in the aforementioned discussion, this function exists in the corner of lumen in wood cell wall, capillary pores of cement paste or other cavities, and the loss of this water plays little role in shrinkage since the forces involved are small. This mechanism, based on the relationship between RH and pore radius, is in agreement with the discoveries by Roper (1965).

RH - 90 - 40 %RH Below 90 %RH menisci can only exist in pores ranging from 0.01 to 0.0011 μm , as appear in the gel pores of cement paste and in the porous

zone of the interface but may disappear in the wood chips in CBPB. Further reduction in RH causes the formation of air bubbles in even smaller pores, with a corresponding increase in the tensile forces in the water and elastic contraction of the cement paste. For wood chips, the non - crystalline material in the cell wall (varying from 8 % to 33 %) results in marked shrinkage due to the drying out of the water - reactive matrix, the microfibrils come into closer proximity with a commensurate increase in interfibrillar bonding and decrease in overall dimensions. Such change are reversible, or almost completely so. At RH approaching 40 %RH, menisci disappear even in the cement paste, tending to relieve all elastic contraction due to tension in the pore water. A corresponding experimental result was obtained by Roper (1965), who found that the loss of water between RH ranging from 40 to 20 % was accompanied by almost no shrinkage of the cement paste.

RH - 40 - 0 %RH With no pore water in CBPB, strong tangential tensile forces arise in the adsorbed water / bound water attracted onto the crystal surfaces. Reductions in RH increase these forces with a rise in reactive compression in the solid. This process is probably slowed down below 10 %RH, when only little adsorbed water is present.

Within this range of RH, withdrawal of adsorbed, confined water results in a spontaneous closing of the gaps occupied by the water adjacent crystal surfaces and embedded between crystal layers. The high shrinkage rate is expected at the lower range (below 10 %RH) due to the reduction in intra - crystal layer spacing. For cement paste approaching 0 %RH drying shrinkage is accompanied by some decomposition of hydrated products due to liberation and expulsion of chemically - bound hydroxylic water from within the crystal lattice.

In the reverse process, dry CBPB expands with increasing RH. It probably begins with water adsorbed onto crystal surfaces, relieving the tangential compression. Filling of all voids with pore water could only be effected by complete immersion.

12.5 Deformation Mechanism of CBPB with Respect to Carbonation of CBPB

As discussed in chapter 11, CBPB under CO₂ - contained air will react with carbon

dioxide, and deformation of CBPB occurred (as carbonation shrinkage) which was usually attributed to water released as the product of the reaction between carbon dioxide and hydroxides or hydrates. The features of carbonation can be summarised as follows:

Firstly carbonation can occur even at the low CO_2 concentrations.

Secondly carbonation is closely related to RH and has a dramatic effect on dimension (shrinkage). Maximum shrinkage occurs at about 50 to 75 %RH. Some carbonation, but no carbonation shrinkage occurs at 100 %RH and below 25 %RH.

Thirdly carbonation is accompanied by a decrease in the amount of non - evaporable water in the cement paste.

Fourthly carbonation shrinkage is almost completely irreversible.

Fifthly carbonation shrinkage is a separate phenomenon from drying shrinkage and is superimposed upon the drying shrinkage when CBPB is drying.

12.6 Deformation of CBPB with Respect to Degradation of Wood Chips within CBPB

The wood chips within CBPB are surrounded by cement paste which is highly alkaline in the presence of moisture. It is well known that the solution of strong bases is capable of removing the great part of extractives and dissolving considerable quantities of wood components, especially the hemicelluloses, causing loss of weight of materials. In referring to the structure of wood and the function of the three components, the loss of any part of the components of wood would result in a different volume change as the surrounding condition changes. Consequentially the deformation of CBPB will be supplemented by the dimensional change of wood chips due to the alkali attack.

12.7 Reversible and Irreversible Processes of Deformation in CBPB

The mechanisms above, covering the whole RH range, can be classified into two types of deformation:

1) Reversible processes;

2) Irreversible processes.

The reversible processes involve pore water and adsorbed water for which shrinkage deformation is mainly an elastic response of solids to compressive stresses induced by surface tension in the liquid phase, especially for gel pores in cement paste. However, the processes also involve the closing up of the microfibrils. Re-wetting of the dry CBPB relieves these stresses and results in the penetration of moisture into non - crystalline material in the cell wall, and the system recovers elastically.

During the expulsion of water between adjacent surfaces, the contraction of small inter - solid substance occurs and is accompanied by the increase in the bonding forces or by the formation of new chemical or physical bonds. These processes are most intensive at lower RH levels. Raising the RH would not result in full recovery of these gaps, owing to the inability of water molecules to reoccupy the newly closed original spaces. However, it should be noted that prolonged immersion would induce tensile stresses in inter - solid bonds, disrupting some of the weak new links and permitting further recovery.

In view of the structure of the wood cell wall, the differences in contact angle of the advancing and receding capillary water front within the cell cavities and the irreversible inelastic exchange of hydroxyl groups between neighbouring cellulose molecules may contribute to the irreversible deformation of CBPB.

Irreversibility is also possible at higher RHs. Under prolonged hydrostatic compression, the adsorbed confined water may squeeze out slowly, reducing the small inter - solid gaps.

The deformation of CBPB is not governed exclusively by the quantitative pattern of water loss or gain, but also depends on the mode of stress imposed on the solids and the restraining effect of the structure as a whole. It is apparent that an irreversibility appears due to the mechanical stress induced in the interface by the difference in the deformation between the wood chip and cement paste, if the bonding strength between the cement paste and wood is strong enough to withstand the stress. Compression and tension stress on wood chips may attain the smaller and larger dimension respectively.

Over the whole range of RH exposure, the carbonation of cement paste and

degradation of wood chips manifest themselves in the irreversibility of deformation.

Thus, a complete desorption - adsorption cycle over the whole range of RH will show definite hysteresis. However, the subsequent shrinkage - swelling cycles would produce progressively smaller irreversible effects due to the tendency of stabilization of material.

The results obtained from this study, described in previous chapters, support the above deformation hypothesis. For example, the results of chapter 8 illustrated the mechanisms of deformation as in Table 12.1.

Table 12.1 Mechanisms corresponding to the different stages of drying deformation

Stage	Deformation	Proposed mechanisms
OA	low shrinkage rate	capillary water
AB	steady shrinkage rate	bound / adsorbed water, carbonation and degradation
BC	shrinkage rate increase	supplemented by carbonation and degradation
C'D	steady shrinkage rate	bound / adsorbed water, carbonation and degradation
DE	high shrinkage rate	little adsorbed water & inter- / intra-crystalline water, carbonation
EF	low swelling at beginning of wetting	opposite processes counterbalancing each other

PART 3

MODELLING THE

BEHAVIOUR OF CBPB

AND

APPRAISING CBPB AS

A COMPOSITE

Introduction

The work on the behaviour of CBPB and its components over the various conditions described in part 2 has generated abundant data. Based on this, the instability of CBPB has been fully understood and qualitatively interpreted.

In this part of the thesis, the distribution and orientation of wood chips, and the individual area and shape of constituents of CBPB have quantitatively been analyzed under SEM with the aid of image analysis.

The data of part 2 have been manipulated to develop universal formulae which attempt to predict the behaviour of CBPB and its constituents (dissected chip and laboratory cement paste) over various conditions. The formulae for constant and a single change of RH can then be applied to cyclic RH conditions.

By combining the numerical results of image analysis with the universal formulae of two components, some of the work described in this part derived an universal model for the behaviour of CBPB using the rule of mixtures. Experimentally determined and predicted values have been compared to verify the CBPB as a composite and the applicability of the rule of mixtures.

Notation

D	Diffusivity of CBPB
D_f	Final dimension of wood
D_i	Initial dimension of wood
ΔD_p	Dimensional change of cement paste in CBPB
ΔD_{cp}	Dimensional change of CBPB
ΔD_w	Dimensional change of dissected chip
E_d	Fractional change in dimensions of CBPB over various RH
E_m	Fractional change in the mass of CBPB under changing RH
E_{m3}	Fractional change in mass of CBPB in moving to 35 %RH
E_{m9}	Fractional change in mass of CBPB in moving to 90 %RH
E_{kj}	Fractional change in the mass or dimensions of dissected chips or laboratory cement paste

$E_{(t)}$	Fractional change in mass of CBPB at time, t
f	Final
i	Initial
j	" m_3 ", " m_9 ", " d_3 ", " d_9 " or " d " representing fractional changes in mass or dimensions of materials in moving to 35 %RH or 90 %RH
k	"w" or "p" representing wood or cement paste
ℓ	Half the thickness of CBPB
ℓ_0	Initial depth of carbonation
ℓ_t	Depth of carbonation at time, t
ΔL_{cp}	Length change of CBPB
L_f	Final length of CBPB
L_i	Initial length of CBPB
$\Delta L(T)_{cp}$	Change in length or in thickness of CBPB
$L(T)_f$	Final length or thickness of CBPB
$L(T)_i$	Initial length or thickness of CBPB
n	The relaxation term
M_f	Final mass of CBPB
M_i	Initial mass of CBPB
M_{wf}	Final mass of dissected chip
M_{wi}	Initial mass of dissected chip
M_t	Mass at time, t
ΔM_p	Mass change of cement paste in CBPB
ΔM_{cp}	Mass change of CBPB
ΔM_w	Mass change of dissected chip
S	Dimensional change (percent) of wood from green to oven dry
t	Duration of exposure
ΔT_{cp}	Thickness change of CBPB
T_f	Final thickness of CBPB
T_i	Initial thickness of CBPB
ΔY_{kj}	Mass or dimensional change of dissected chip or cement paste at various conditions
Y_{kjt}	Final mass or dimensional change of dissected chip or cement paste at

	various conditions
Y_{kji}	Initial mass or dimensional change of dissected chip or cement paste at various conditions
A_x, B_x, C_x and G_x	Coefficients related to the feature of materials and environmental conditions
e_R	Mean transverse modulus of elasticity of wood
e_L	Longitudinal modulus of elasticity of wood
e_p	Modulus of elasticity of cement paste
$e_{w\alpha}$	Modulus of elasticity of wood chip at three principal directions of CBPB
e_θ	Modulus of elasticity of wood chips at θ direction
e_φ	Modulus of elasticity of wood chips at φ direction
G_{LR}	Mean transverse shear modulus of wood
m_{kf}	Mass fraction of cement paste or wood chip
m_{pf}	Mass fraction of cement paste
m_{wf}	Mass fraction of wood chips
M_{cpj}	Mass change of CBPB at the various conditions tested
M_{pjf}	Final mass change of cement paste at corresponding conditions
M_{pji}	Initial mass change of cement paste at corresponding conditions
M_{wjf}	Final mass change of wood chips at corresponding conditions
M_{wji}	Initial mass change of wood chips at corresponding conditions
V_{kf}	Volume fraction of wood chip or cement paste in unit mass of CBPB
V_{LR}	Mean transverse Poisson's ratio of wood
V_{pf}	Volume fraction of cement paste in unit mass of CBPB
V_{wf}	Volume fraction of wood chip in unit mass of CBPB
ρ_{cp}	Density of CBPB
ρ_k	Density of wood chip or cement paste
$\sigma_{cp\alpha}$	Overall stresses of CBPB at three principal directions
σ_L	Stress in the longitudinal direction of wood
$\sigma_{R(T)}$	Mean stress in the transverse direction of wood
$\sigma_{LR(T)}$	Mean shear stress in the transverse direction of wood
σ_p	Stress in cement paste

$\sigma_{w\alpha}$	Stress in the wood chips at three principal directions of CBPB
σ_{θ}	Stress in the wood chips at θ direction
σ_{φ}	Stress in the wood chips at φ direction
$\epsilon_{cp\alpha}$	Strain in CBPB
ϵ_p	Strain in cement paste
$\epsilon_{w\alpha}$	Strain in wood chip
α	Angle between the longitudinal direction of wood chips and surfaces or edges of CBPB
θ	Angle between wood chips and edge (length direction) of CBPB
φ	Angle between wood chip and vertical coordinate

Chapter 13

BEHAVIOUR PREDICTION OF CBPB AND ITS COMPONENTS UNDER VARIOUS CONDITIONS

13.1 Mass and Dimensional Changes of CBPB under Constant RH

As discussed earlier, even under constant (normal) environment (20 °C / 65 %RH) the mass and dimensions of CBPB change with increasing exposure period. These changes (Figures 5.1, 5.2 and 5.3), have been thought to be most likely due to the carbonation of cement paste in CBPB. Quantitative formulae will now be derived to validate the quantitative interpretation.

Theoretical background

It is well known in cementitious area that the depth of carbonation is roughly proportional to the square root of the duration of exposure:

$$l_t = l_0 + C_c \sqrt{t}$$

According to the main chemical interaction of carbonation: $\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}$, increase in the density of CBPB is proportional to the depth of carbonation over an unit square area. Therefore, increase in the mass of CBPB would be proportional to the duration of exposure. This relation can be written as:

$$\Delta M_p = A_p + B_p t \quad 13.1$$

Considering CBPB as a two phase material, then

$$\Delta M_{cp} = \Delta M_p + \Delta M_w \quad 13.2$$

Under constant RH the change of mass of the wood is negligible (perhaps remaining

constant), and the mass of the CBPB can be expressed as:

$$\Delta M_{cp} = B_{m0}t + C_{m0} \quad 13.3(1)$$

Examination of the models

An experimentally produced and a simulated curve for the change in the mass of laboratory cement paste is presented in Figure 13.1. It is apparent that the results from the laboratory cement paste are in agreement with the results gained from the cementitious study (section 2.6.3): there was an excellent correlation between the mass increase with exposure time. The increase in mass due to carbonation was proportional to the duration of exposure.

Similarly the change in mass of CBPB under a constant RH of 65 %RH is given in Figure 13.2. A comparison of the experimentally determined value with that produced using Equation 13.3(1) shows an excellent correlation: the R^2 value is given in Table 13.1.

As for mass change, the dimensional changes of CBPB can be written as:

$$\Delta L_{cp} = B_{l0}t + C_{l0} \quad 13.3(2)$$

$$\Delta T_{cp} = B_{t0}t + C_{t0} \quad 13.3(3)$$

The results for the dimensional changes of cement paste and CBPB are presented in Figure 13.3 and 13.4.

From the values of R^2 it is clear that a better correlation can be obtained after slight adjustment. Whether for change in mass or length or thickness, the changes can be described by:

$$\Delta M_{cp} = A_m t^2 + B_m t + C_m \quad 13.4(1)$$

$$\Delta L_{cp} = A_l t^2 + B_l t + C_l \quad 13.4(2)$$

$$\Delta T_{cp} = A_t t^2 + B_t t + C_t \quad 13.4(3)$$

Comparison between the experimental values and those produced using Equation 13.4 (Table 13.1) shows a wholly satisfactory outcome.

13.2 Mass and Dimensional Changes of CBPB under a Single Change of RH

13.2.1 Theoretical Background and Model Development

CBPB is supposed to be a composite material and there are at least three reasonably distinct components of the total porosity: the internal porosity of the wood chips, the porosity of the cement gel matrix and the voids produced by the packing geometry of the constituent particles (cement paste and wood chips). The behaviour of CBPB primarily depends on the properties of cement paste and wood chips. According to their drying behaviour, both wood and cement paste are divided as the hygroscopic porous materials, being one of three groups: non-hygroscopic porous materials, hygroscopic porous materials and hygroscopic non-porous materials (Brakel, 1980). The hygroscopicity of wood is attributed to the absorption of water vapour in the cell wall constituents, whilst it is generally thought that cement paste owes its hygroscopicity to surface and capillary condensation on its very large internal area.

Diffusion processes for hygroscopic porous materials have been studied in great depth, it being found that they basically comply with Fick's law. In this case, the process of attaining equilibrium is assumed to be an exponential function of time (Morton and Hearle, 1962; Crank, 1975). The diffusivity can then be calculated as follows, based on Fick's law (Crank, 1975):

$$D = \frac{\pi l^2}{4} \left(\frac{dE}{d\sqrt{t}} \right)^2 \quad 13.5$$

The fractional mass change:

$$E_{(t)} = \frac{M_t - M_i}{M_f - M_i} \quad 13.6$$

The Fickian part of fractional mass change:

$$E_{(t)} = 1 - \frac{8}{\pi^2} \sum \left[\frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D t}{4l^2}\right) \right] \quad 13.7$$

There have been several reports of non-Fickian sorption in both wood and concrete (section 2.2.3). Such effects are caused by internal relaxation which slows down the sorption process (Crank, 1975). The effect has very long time scales and seems to almost govern the adsorption process in wood at high RH. In CBPB materials, condensation at high RH can occur since the relative vapour pressure over a concave air - water meniscus is less than unity (section 2.3), particularly in cement paste where the pore system consists of minute pores which can hold large amounts of water. In addition, an increase in the mass of CBPB due to carbonation of cement paste also occurs under changing RH during sorption of CBPB, these disturbances mainly acting during the later stages of the sorption. Non - Fickian sorption in CBPB can be seen from the calculation based on Equation 13.5 (Figure 13.5). The Figure shows that the diffusivity of CBPB was not constant but was time - dependent.

As the sorption is thought to be governed both by Fickian and non-Fickian processes, the sorption may be modelled as a sum of a number of uncoupled processes. Many theories and models have been proposed for polymers and wood. One of them is to model the result of sorption measurements in the form of the fractional weight change. Accordingly the physical model for CBPB can be written as:

Fractional change of CBPB = Fickian part of the fractional mass change + non - Fickian part of fractional mass change.

According to the main non - Fickian part of mass change of CBPB (the results arising from CBPB under constant RH as described earlier), the mathematical model for CBPB can be proposed to be: -

$$E_m = A_{mI} + B_{mI}t + G_{mI}\exp(C_{mI}t) \quad 13.8$$

where

$$A_{mI} + G_{mI} = 0 \quad 13.9$$

This Equation can then be rewritten as:

$$E_m = A_{m1} + B_{m1}t - A_{m1}\exp(C_{m1}t) \quad 13.10(1)$$

In the model, the term " $A_2 - A_{m1}\exp(C_{m1}t)$ " is related to the Fickian effect, and the term " $A_3 + B_{m1}t$ " represents the main non - Fickian effect. $A_2 + A_3 = A_{m1}$.

In terms of the dimensional change (proportional to the mass change) which will be discussed in later section, the mathematical models for the length and thickness changes of CBPB are also proposed to be of the same form as that for the mass change (Equation 13.10), i.e.

$$E_d = A_{d1} + B_{d1}t - A_{d1}\exp(C_{d1}t) \quad 13.10(2)$$

13.2.2 Numerical Solution of the Equation and Comparison with Experimental Results

A comparison of fractional mass change of CBPB for different RH regimes given as Figure 13.6 indicates that the fractional mass change of CBPB was independent of the level of the RH change. The curves arising from transferring the CBPB from 90 to 35 %RH and from 65 to 35 %RH are very close, as are the curves arising from transferring from 35 to 90 %RH and from 65 to 90 %RH. However, there was a great difference between these two groups of curves, which is thought to be due to the condensation of moisture under high RH. This distinct phenomenon occurs in cement paste at RH over 80 %RH.

The result above is confirmed in the fractional changes in dimension of CBPB (Figures 13.7 and 13.8). The fractional changes in dimension, whether in the length or the thickness, were very close for all RH change regimes. Of most interest is that the curve for the mean fractional change in length coincides with that in thickness (Figure 13.9). It is clear that:

- 1) the behaviour of CBPB will comply with the theory described above;
- 2) the proposed models for both mass and dimensions are appropriate;
- 3) condensation under high RH didn't affect the fractional change in dimension, the fractional changes in dimensions were every similar over various change RH;

4) the mass change of CBPB on adsorption under high RH should be considered separately.

Programs were written using FORTRAN 77 to develop the analytical expressions of fractional changes of both mass and dimension of CBPB and its tested constituents. The results are:

For fractional change in mass of CBPB without significant condensation,

$$E_{m3} = f_3(t) = 1.0016 - 1 \times 10^{-4}t - 1.0016e^{(-1.258 \times 10^{-1}t)} \quad R^2 = 0.99 \quad 13.11$$

For fractional change in mass of CBPB with significant condensation (90 %rh),

$$E_{m9} = f_9(t) = 6.157 \times 10^{-1} + 1 \times 10^{-3}t - 6.157 \times 10^{-1}e^{(-6.196 \times 10^{-2}t)} \quad R^2 = 0.99 \quad 13.$$

For fractional change in dimensions, whether in length or in thickness,

$$E_d = g(t) = 9.005 \times 10^{-1} + 3 \times 10^{-4}t - 9.005 \times 10^{-1}e^{(-1.078 \times 10^{-1}t)} \quad R^2 = 0.99 \quad 13.13$$

A comparison of experimentally determined fractional changes with numerically calculated data is presented in Figures 13.10 and 13.11. It is apparent that there exists an excellent correlation between the experimental and modelled results.

13.2.3 Evaluation of Mass and Dimensional Changes and Model Verification

Now that the fractional changes in both mass and dimension have been given, together with the initial and final values of changes (Table 13.2) the change in mass and dimensions of CBPB can be calculated as a function of sorption time:

$$\Delta M_{cp} = 100 \left(\frac{M_f}{M_i} - 1 \right) E_{3(or9)} \quad 13.14(1)$$

$$\Delta L_{cp} = 100 \left(\frac{L_f}{L_i} - 1 \right) E_d \quad 13.14(2)$$

$$\Delta T_{cp} = 100 \left(\frac{T_f}{T_i} - 1 \right) E_d \quad 13.14(3)$$

The experimental curves (markers) and model curves of the changes in mass and dimensions of CBPB are both presented in Figures 13.12, 13.13 and 13.14. The correlations are tabulated in Table 13.2. It may be seen that the predicted values are very close to the experimentally derived mass and dimensional changes during sorption, the correlation coefficients lying between 0.94 and 0.99. This also confirms that flow in CBPB is governed by both Fickian and non - Fickian effects, and that the models developed are appropriate.

13.3 Mass and Dimensional Changes of CBPB under Cyclic RH

When CBPBs are cycled between different RHs, the movement of CBPB is made up of the changes due to cyclic moisture and the attack of CO₂ on cement paste or alkali attack on wood chips. These changes have been qualitatively described as the cyclic and accumulated changes.

13.3.1 Accumulated Change with Time / Number of Cycles

The prediction given in section 13.1 shows that there is a consistent change of both mass and dimension of CBPB subjected to a constant RH. Assuming that the cyclic RH does not affect the structure of CBPB, the model in section 13.1 will be applicable for the changes of CBPB under cyclic RH.

The experimentally determined maximum values of accumulated changes of 12 mm CBPB at 35, 65 and 90 %RH (based on the maximum values after

preconditioning in 90 %RH) were applied to Equations 13.4 (Figures 13.15 - 13.17). Corresponding fits for 18 mm CBPB are illustrated in Figures 13.18 - 13.20. The coefficients are given in Table 13.3. An excellent correlation between experiment and theoretical predictions was obtained.

It is apparent that the trend of accumulated changes of CBPB with cycles, whether in mass or dimensions, was very similar to that under constant RH. The models from section 13.1 are thus applicable. A comparison of the curves fitted shows that the forms of curves through 35, 65 and 90 %RH are very similar, whether in mass or dimensional changes. However, in comparison with those under constant environmental condition, the rate of change was much more significant due to the effect of cyclic RH (section 2.6.3.3). This result indicates that the mechanisms of the change in CBPB under atmosphere exposure, resulting in the accumulated changes of both mass and dimensions, are probably the same for all levels of RH. Nevertheless, 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 consistent change was plotted as a function of the number of cycles (Figures 13.21 - 13.23). Logarithmic functions of the number of cycles are found to be the best predictors for mass increase and dimensional decreases. The coefficients of the Equations are also included in Table 13.3. The degrees of fit are very high for mass and dimensional predictions.

By comparing the adsorption curves (and earlier equations) with the desorption curves, differences owing 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 Figures 13.15 - 13.17 with 13.18 - 13.20 shows that the trend of accumulated change of two types of CBPB was very similar, but the amount of the percentage change was different - the higher change occurred in 18 mm CBPB. The percentage change seems to be proportional to the thickness of CBPB.

13.3.2 Cyclic Change

Based on the models developed in section 13.2, a prediction in the change of 18 mm CBPB under cyclic RH has been carried out. The simulated curves and experimental data are plotted in Figures 13.24, 13.25 and 13.26. The applicability of the models is confirmed. In the Figures, there is a deviation, the degree of predicted changes from one condition to another being slightly lower than the experimentally determined values. This is because the final change values of CBPB (before moving to next condition) do not reach to the level required.

13.4 The Relationship between Dimensional and Mass Change under Various Conditions

13.4.1 Under Constant Conditions of 20 °C / 65 %RH

Based on mass and dimensional changes of CBPB (Equation 13.3), the functions of change can be rewritten as:

$$\Delta M_{cp} = f(t), \quad \Delta L_{cp} = g(t), \quad \Delta T_{cp} = h(t)$$

Therefore,

$$\begin{aligned} \frac{d(\Delta L_{cp})}{d(\Delta M_{cp})} &= \frac{d[g(t)]}{d[f(t)]} = \frac{g'(t)}{f'(t)} = \frac{B_{\theta}}{B_{m0}} \\ \frac{d(\Delta T_{cp})}{d(\Delta M_{cp})} &= \frac{d[h(t)]}{d[f(t)]} = \frac{B_{\theta}}{B_{m0}} \end{aligned} \quad 13.15$$

Thus, the relationship between the length and mass change is:

$$\Delta L_{cp} = \frac{B_{\theta}}{B_{m0}} \Delta M_{cp} + C_7 \quad 13.16$$

and between the thickness and mass change is:

$$\Delta T_{cp} = \frac{B_{\infty}}{B_{m0}} \Delta M_{cp} + C_8 \quad 13.17$$

The experimental data and calculated values are plotted in Figure 13.27. The result verifies the above discussions.

13.4.2 Under a Single Change of RH

13.4.2.1 Theoretical Background

The relationship between mass and dimensional changes of hydrated cement paste

The qualitative relationship between the dimensional change and the amount of water held by the paste has been studied by many workers. It was concluded (Roper, 1965) that when cement paste dries, the curve of the relationship between shrinkage and mass decrease consists of four sections of different slopes, each of which is well represented by a straight line. At the commencement of desorption a fairly large weight loss is accompanied by only a small amount of shrinkage. Water of this type is all removed before a p / p_0 value of 0.85 is attained. The second type of water is more important from the shrinkage viewpoint and is lost within a p / p_0 range from 0.4 to 0.9. Within this range a substantial proportion of the entire shrinkage occurs. A third type of water is lost within a p / p_0 ranging from 0.2 to 0.4. Its removal from the paste is accompanied by almost no shrinkage. Finally the removal of the fourth type of water takes place between a p / p_0 from 0 to 0.2, when the slope of the shrinkage and mass decrease curves is at its maximum. The corresponding mechanisms have been detailed in chapter 12.

When CBPB was subjected to 35 %RH or 90 %RH, water movement in the cement paste of CBPB could be treated as the second type of water. The relationship between dimensional and mass change of cement paste in CBPB can be expressed as:

$$\Delta D_p = A_9 \Delta M_p + C_9 \quad 13.18$$

The relationship between mass and dimensional change of wood

Over the testing range 35 %RH to 90 %RH the equilibrium moisture content of chips is under fiber saturated point (section 2.2.2) (about 8 % and 29 % under 35 and 90 %RH respectively for the dissected chip in the experiment). The relationship between dimensional and mass change can be simplified as (USDA, 1974):

$$\Delta D_w = A_{10} \Delta M_w + C_{10} \quad 13.19$$

from Equations:

$$D_f = D_i [C_6 (M_{wf} - M_{wi})]$$

for moisture ranging from 6 to 14 %, and from

$$D_f = \frac{D_i (M_{wf} - M_{wi})}{30 \left(\frac{100}{S} - 1 \right) + M_{wi}}$$

when moisture is not ranging within 6 to 14 %.

The relationship between mass change and dimensional change of CBPB

Provided that moisture is the only main factor affecting the mass and dimensional change of CBPB, from the relationship of dimensional and mass change in cement paste, together with that in wood chips, the relationship of dimensional and mass change of CBPB may be expressed as:

$$\Delta D_{cp} = A_{11} \Delta M_{cp} + C_{11} \quad 13.20$$

In terms of the sorption mechanisms of porous materials, the relationship

between mass and dimensions on desorption can generally be applied to that on adsorption. However, condensation in the mini pores of cement paste is certainly expected under high RH, leading to a higher rate of mass increase compared to the lower rate of dimensional increase. This has been discussed in section 13.2. The linear relationship may not be the case under 90 %RH adsorption. The decline in the ratio of dimensional change to mass change is supposed to exist in the plots. Therefore, a modification must be made for the formulae to correspond to the subtle change in the relationship. The Equation assumed may be written as:

$$\Delta D_{cp} = A_{12} + B_{12}\Delta M_{cp} + G_{12}\exp(C_{12}\Delta M_{cp}) \quad 13.21$$

the exponential term being included to balance the reduction in the ratio of dimensional changes to mass change due to the condensation.

13.4.2.2 Verification and Solution of the Equation by Using Equation 13.14

From Equations 13.14, the relationship between dimensional and mass change of CBPB without significant condensation is:

$$\frac{\Delta L(T)_{cp}}{\Delta M_{cp}} = \frac{\left[\frac{L(T)_f}{L(T)_i} - 1\right]}{\left[\frac{M_f}{M_i} - 1\right]} \frac{E_d}{E_{w3}} = \frac{\left[\frac{L(T)_f}{L(T)_i} - 1\right]}{\left[\frac{M_f}{M_i} - 1\right]} K(t)_1 \quad 13.22$$

and that with significant condensation (on adsorption at 90 %RH) is:

$$\frac{\Delta L(T)_{cp}}{\Delta M_{cp}} = \frac{\left[\frac{L(T)_f}{L(T)_i} - 1\right]}{\left[\frac{M_f}{M_i} - 1\right]} K(t)_2 \quad 13.23$$

Where:

$$K(t)_1 = \frac{E_d}{E_{m3}}, \quad K(t)_2 = \frac{E_d}{E_{m9}}$$

The calculated $K(t)_1$ and $K(t)_2$ are plotted in Figure 13.28. It apparent that $K(t)_1$ is almost constant, thus the relationship between the dimensional change and mass change is linear for CBPB (without significant moisture condensation). The theoretically derived model, Equation 13.20, identifies with calculated equations, and the slope of line is:

$$K = \frac{\left[\frac{L(T)_f}{L(T)_i} - 1 \right]}{\left[\frac{M_f}{M_i} - 1 \right]} K(t)_1 \quad 13.24$$

Over the range of exposure time from 0 to 36 days, $K(t)_1$ is about 0.75, and from 51 to 420 days it is about 0.98. The two distinct ranges actually divide the dominant mechanisms of movement of CBPB. The former is moisture effect, and the latter is the carbonation effect. This is in agreement with results arising from CBPB subjected to constant environmental condition (section 13.4.1).

$K(t)_2$ is a function against time, t , and the function can be given as:

$$K(t)_2 = A_{13} + B_{13}t + G_{13}\exp(C_{13}t) \quad 13.25$$

The calculated data and the simulated curve using Equation 13.25 are presented in Figure 13.29, in which A_{13} , B_{13} , G_{13} and C_{13} are 1.361, -9×10^{-4} , 1.129 and -4.586×10^{-2} respectively. It is clear that the supposed model (equation 3.21) is appropriate. The relationship between dimensional and mass change of CBPB contains the exponential term. The relationship is:

$$\Delta L(T)_{cp} = \frac{\left[\frac{L(T)_f}{L(T)_i} - 1\right]}{\left[\frac{M_f}{M_i} - 1\right]} K(t)_2 \Delta M_{cp} \quad 13.26$$

The result above shows that the relationships between all the dimensional and mass changes of CBPB can be expressed in the same form:

$$\Delta L(T)_{cp} = \frac{\left[\frac{L(T)_f}{L(T)_i} - 1\right]}{\left[\frac{M_f}{M_i} - 1\right]} K(t) \Delta M_{cp}$$

It is apparent that the Equations are related to the corresponding initial and final values of changes and $K(t)$ which is dependent on the environmental condition.

13.4.2.3 Comparison with Experimental Results

A comparison of experimentally determined data with simulated calculated values in Figures 13.30 - 13.33 indicates that the present models predict the relationship between dimensional and mass change. Two points are clear:

1) For sorption without moisture condensation, the movement of CBPB is divided into two stages, the first stage being dominated by the moisture movement in the materials, and the second stage being dominated by the carbonation of CBPB. The relationships between the dimensional and mass change in both stages is linear, but the dimensional change in unit mass change was much higher in the second stage of exposure compared to that in the first stage.

2) For adsorption under high RH, condensation plays an important role in the relationship over the whole duration of exposure.

13.4.3 Under Cyclic RH

Figure 13.34 compares the experimentally determined dimensional and mass change of 18 mm CBPB in the second complete cycle with the theoretical equations given above. Like those under a single change of RH, the relationships obey the theoretical predictions regardless of the immediate 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, but from 65 to 90 %RH the relationship is exponential. This confirms the theoretical models above, and suggests that under cyclic RH the dimensional changes of CBPB are mainly influenced by the moisture content; the structural changes or chemical reactions, if of influence, do not cause an observable effect on the relationship owing to the short term duration.

13.5 Mass and Dimensional Change of Dissected Chips and of Laboratory Cement Paste under a Single Change in RH

In this section, only changes in mass and dimensions of dissected chip and laboratory cement paste in moving from 35 to 90 or from 90 to 35 %RH were predicted in order to obtain the universal formulae for modelling CBPB as a composite in chapter 15.

As qualitatively discussed in previous chapters, the trend of changes in dissected chips and laboratory cement paste, whether in mass or in dimensions, was similar to those of CBPB. It is clear that the fractional change in the mass of dissected chips and cement paste should also be divided into two groups, one with and another without significant condensation (Figures 13.35 and 13.41). However, as for CBPB, the fractional changes in dimensions all show the same behaviour over various changes in RH (Figure 13.36). Slight difference in dimensions of cement paste was also simulated separately (Figure 13.42). A similar procedure was followed, as in the prediction for CBPB, to develop universal formulae.

The model for the fractional change in mass and dimensions of dissected chip and laboratory cement paste is:

$$E_{kj} = A_{14} + B_{14}t - A_{14}\exp(C_{14}t) \quad 13.27$$

Here k means the w or p; and j means m₃, m₉, d₃, d₉ or d depending on the representative of E_{kj}. The corresponding coefficients and correlations for various measurements are tabulated in Table 13.4.

A comparison of the experimentally determined data and the simulations was made to verify the suitability of the models developed. The curves are plotted in Figures 13.35, 13.37, 13.41 and 13.42.

Thus, changes in mass and dimensions of dissected chips and cement paste can be calculated by using the Equation:

$$Y_{kj} = 100\left(\frac{Y_{kjf}}{Y_{kji}} - 1\right)E_{kj} \quad 13.28$$

Using initial and final changes of dissected chips and laboratory cement paste (Table 13.4), the experimentally determined and simulated changes are presented in Figures 13.38 - 13.40 for the behaviour of dissected chips, and Figures 13.43 and 13.44 for mass and dimensional change of laboratory cement paste. An excellent correlation was obtained.

The results confirmed the suitability of the models developed. These formulae are suitable for modelling CBPB as a composite (see later chapter).

13.6 Interim Conclusions 9

1) Based on the structure of CBPB, which consists of two hygroscopic materials, wood chips and cement paste, models for the mass and dimensional changes of CBPB and its components have been developed. The models contain both Fickian and non - Fickian components (it should be noted here that although Fick's law was derived from mass transfer, it is quoted in dimensional changes in terms of the proportional relationship between the mass and dimensional change). The former was mainly effected with moisture sorption and the latter was mainly effected with the

carbonation or moisture condensation of CBPB. The fractional change was summed up as:

$$E_x = A + Bt - A \exp(-Ct)$$

Then the change of CBPB was concluded as:

$$\Delta Y_x = 100 \left(\frac{Y_{xf}}{Y_{xi}} - 1 \right) E_x$$

The method of evaluating mass and dimensional changes of CBPB has been tested, leading to the following conclusions:

- A) The changes in both mass and dimensions were essentially Fickian and non-Fickian, but coefficients were influenced by the degree of disturbance.
- B) Fractional changes in length and thickness were very close (most likely the same). They were also independent of the level of RH and history of sorption. However, condensation at high RH had a significant influence on the fractional change in mass.
- C) The model is highly flexible. It can realistically predict the changes both in mass and dimensions, not only under single change RH but also under cyclic RH.

2) A model for the accumulated change of CBPB on exposure (by virtue of carbonation of CBPB) was also developed. It was concluded that

- A) the accumulated change of CBPB was dominantly characterized by that of cement paste in it;
- B) the mechanisms of this change were the same for CBPB under both constant and cyclic RH;
- C) the coefficients of the model were affected by the level of RH due to a change in the degree of carbonation.

3) Theoretical models for the relationship between mass and dimensional change of CBPB were identified with those derived from the universal models of dimensions and mass. Numerical and experimental verification were again carried out. The concluding remarks of this section are:

- A) In general, numerical tests demonstrated the excellent agreement of the

predictions of the theory with experimental data.

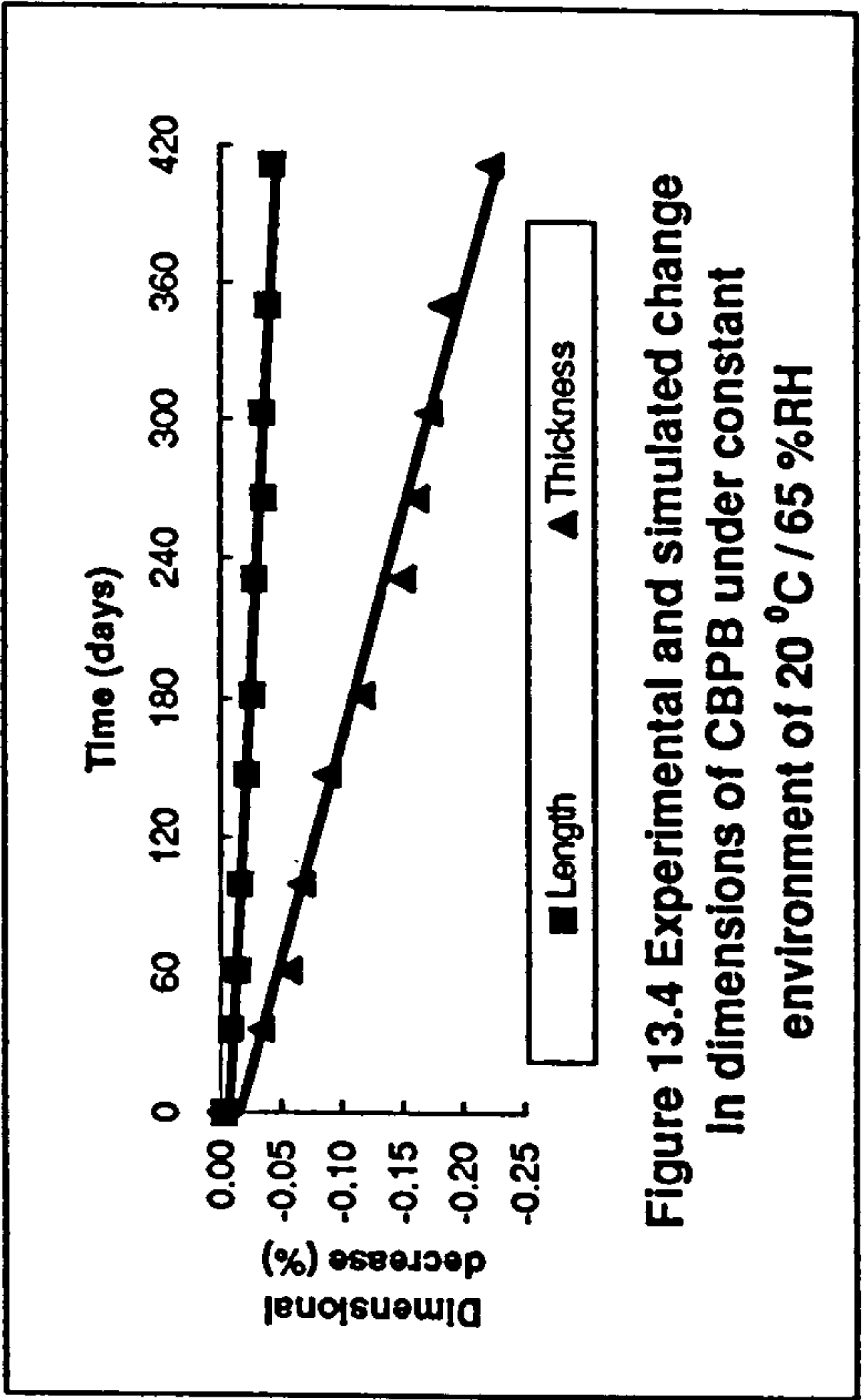
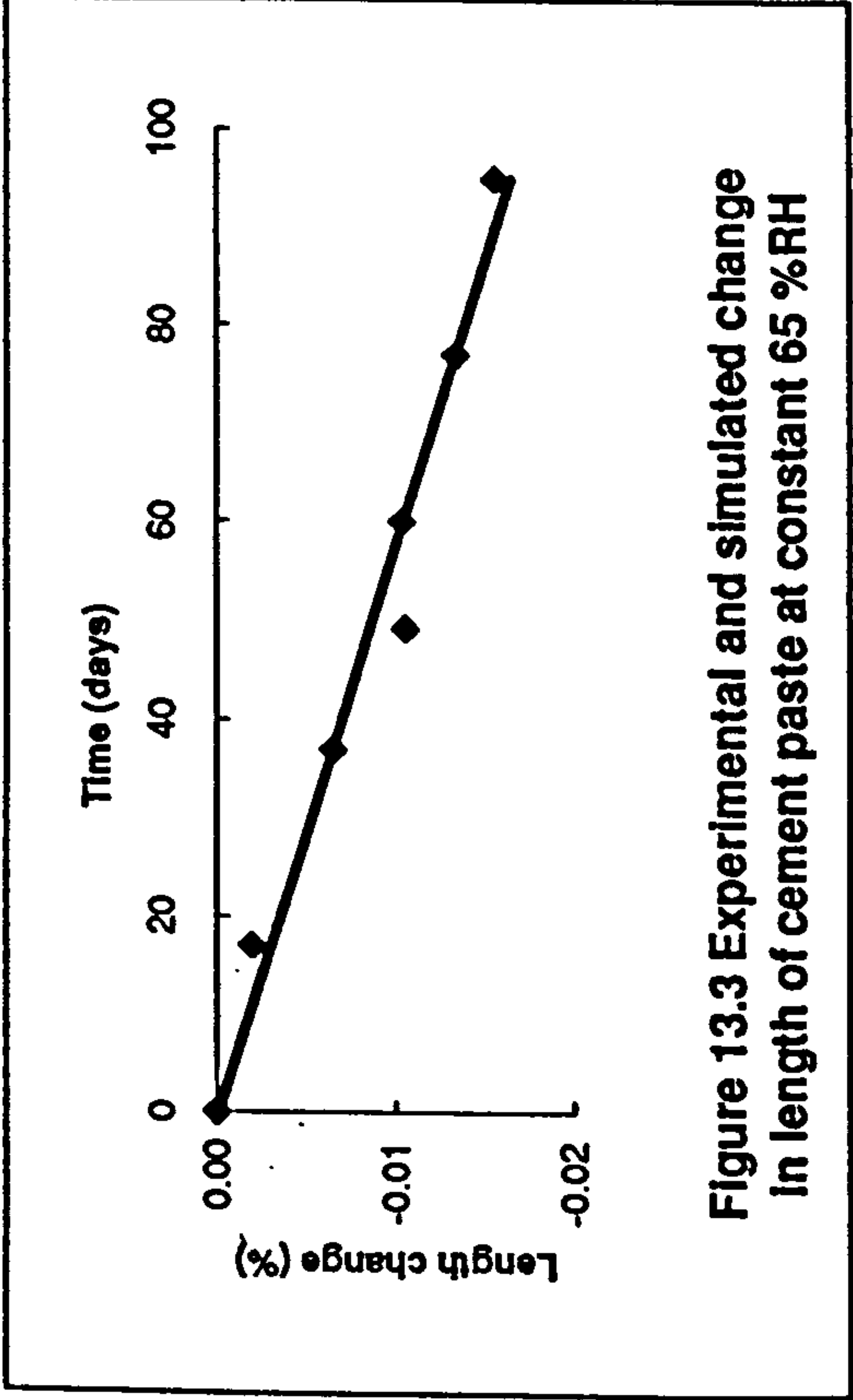
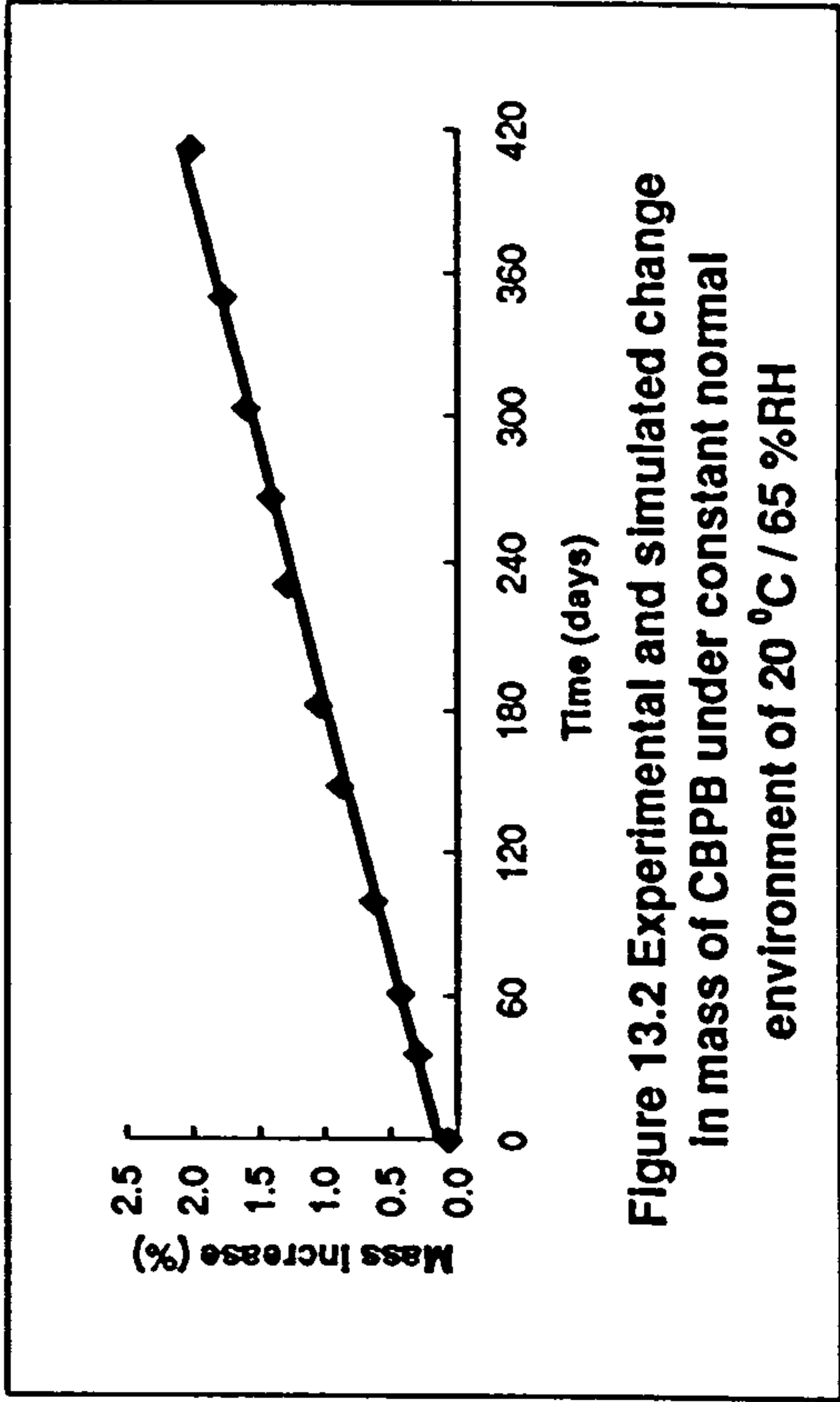
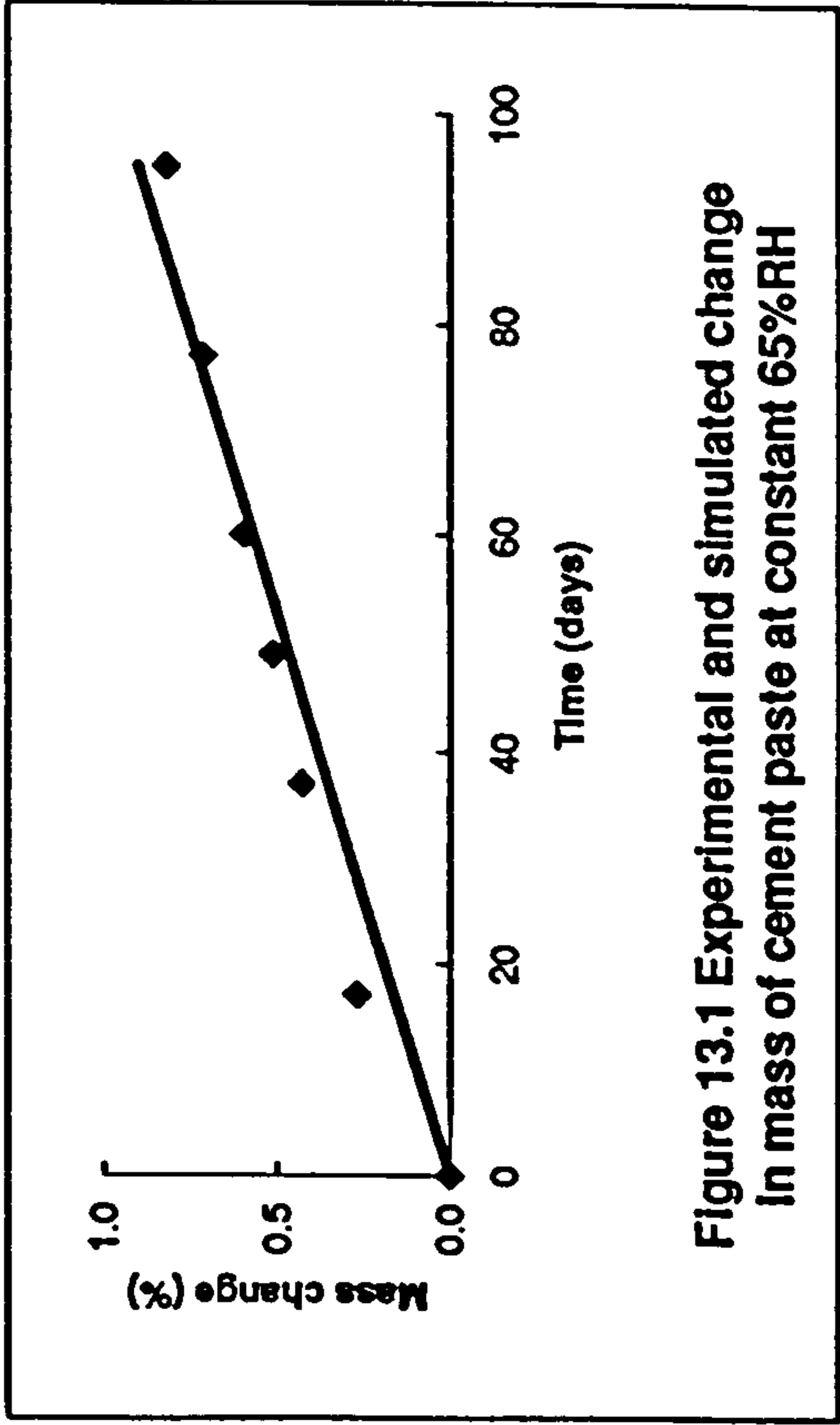
B) The relationship between dimensional and mass change of CBPB at constant 65 %RH was linear.

C) The relationship under change of RH was divided into two groups, one for those with significant influence of moisture condensation and another for those without. The relationship between dimensional and mass change for the former group was exponential, whilst that for the latter group was linear. However, there was an abrupt change in the slope of the linear lines, dividing differently dominant effects (mechanisms) in the early and late stages of exposure.

D) The relationship under cyclic RH followed the features as those under single change RH.

4) The flexibility of the model was also found in predictions for different types of CBPB (12 mm and 18 mm in this study). The thickness of CBPB had only an influence on the coefficients of the Equations.

5) The trend of changes of dissected chips and cement paste was similar to that of CBPB. A similar procedure was followed to numerically predict the changes of both components. The models were verified as a result of good agreement.



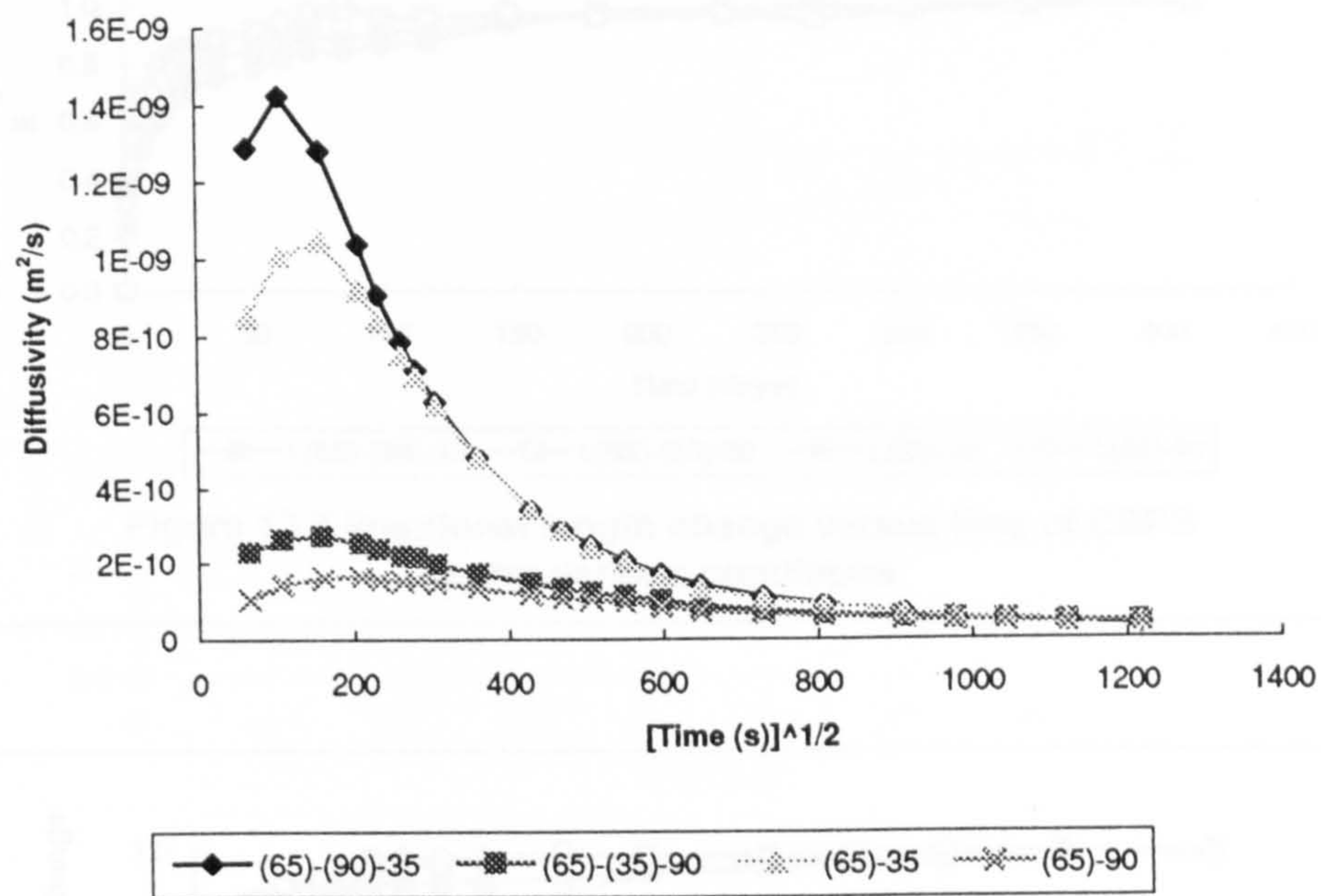


Figure 13.5 Diffusivity of CBPB under a single change in RH

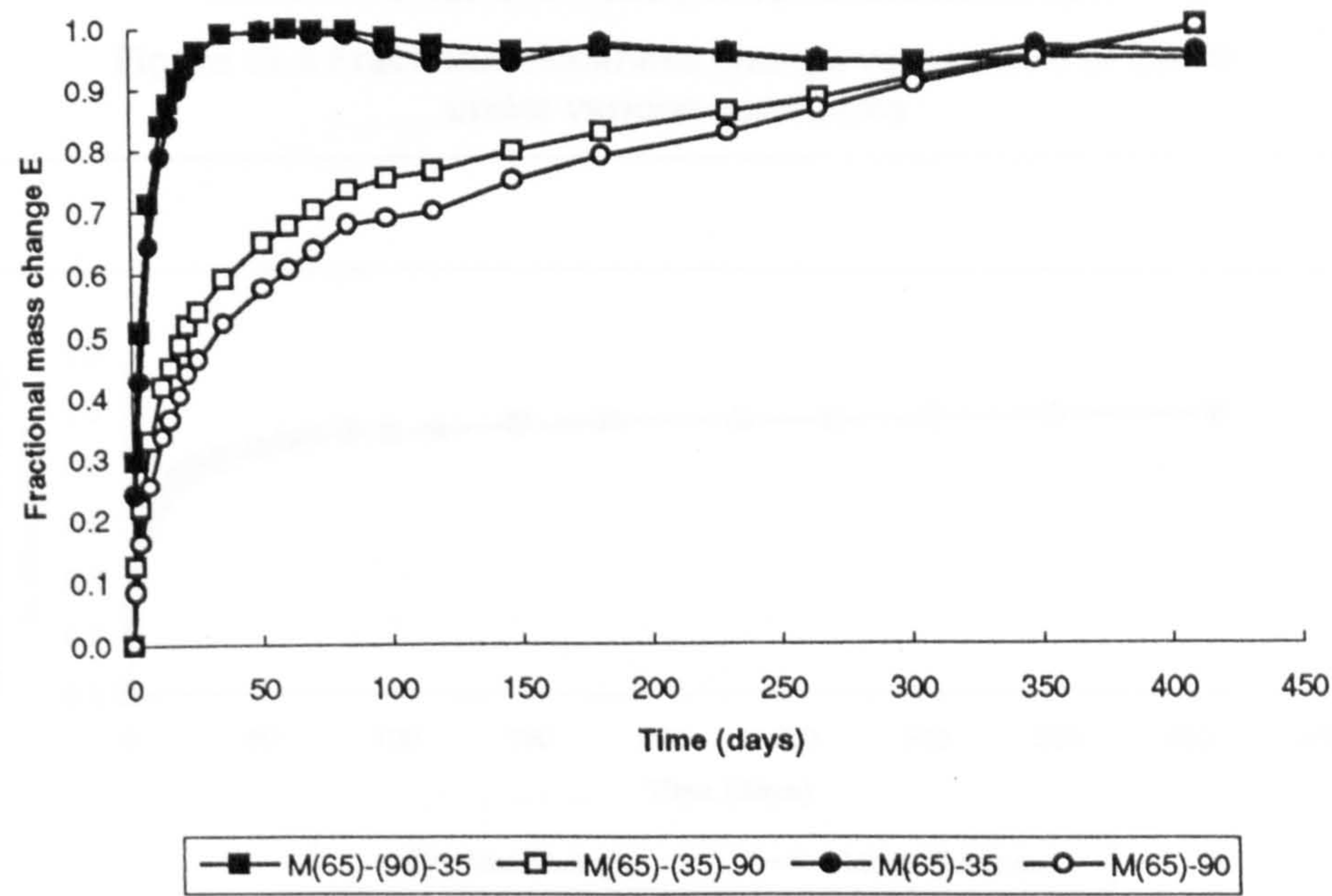
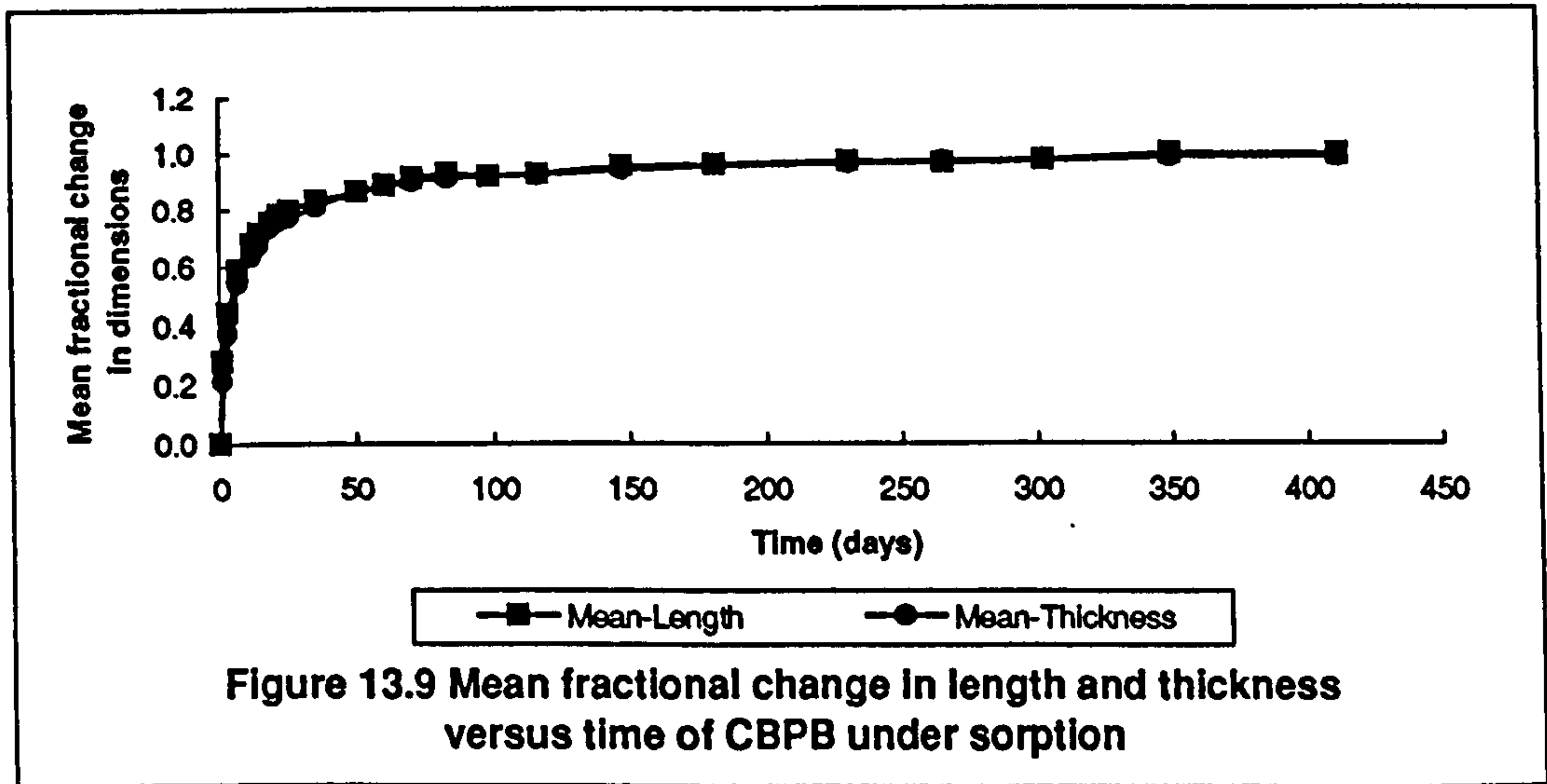
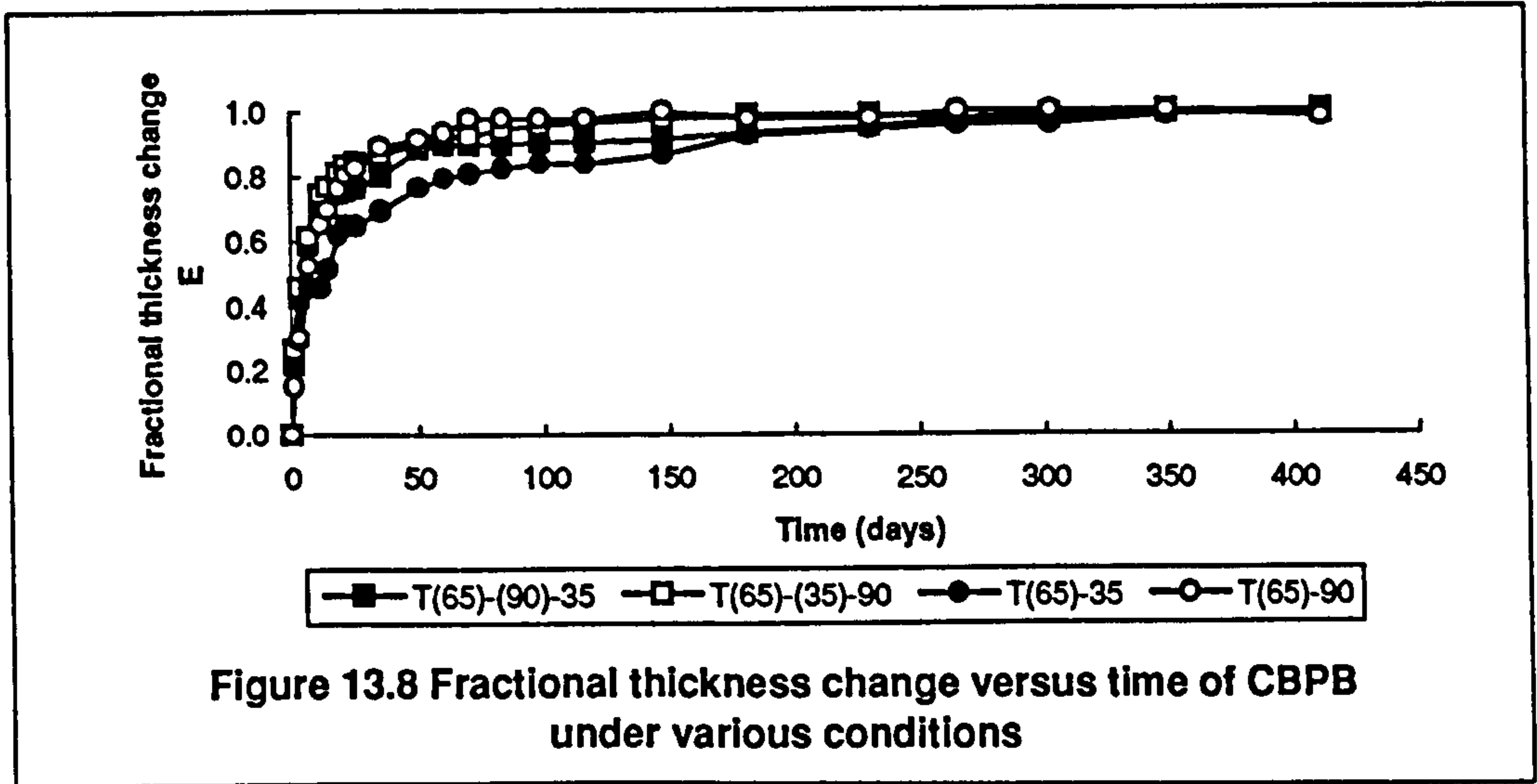
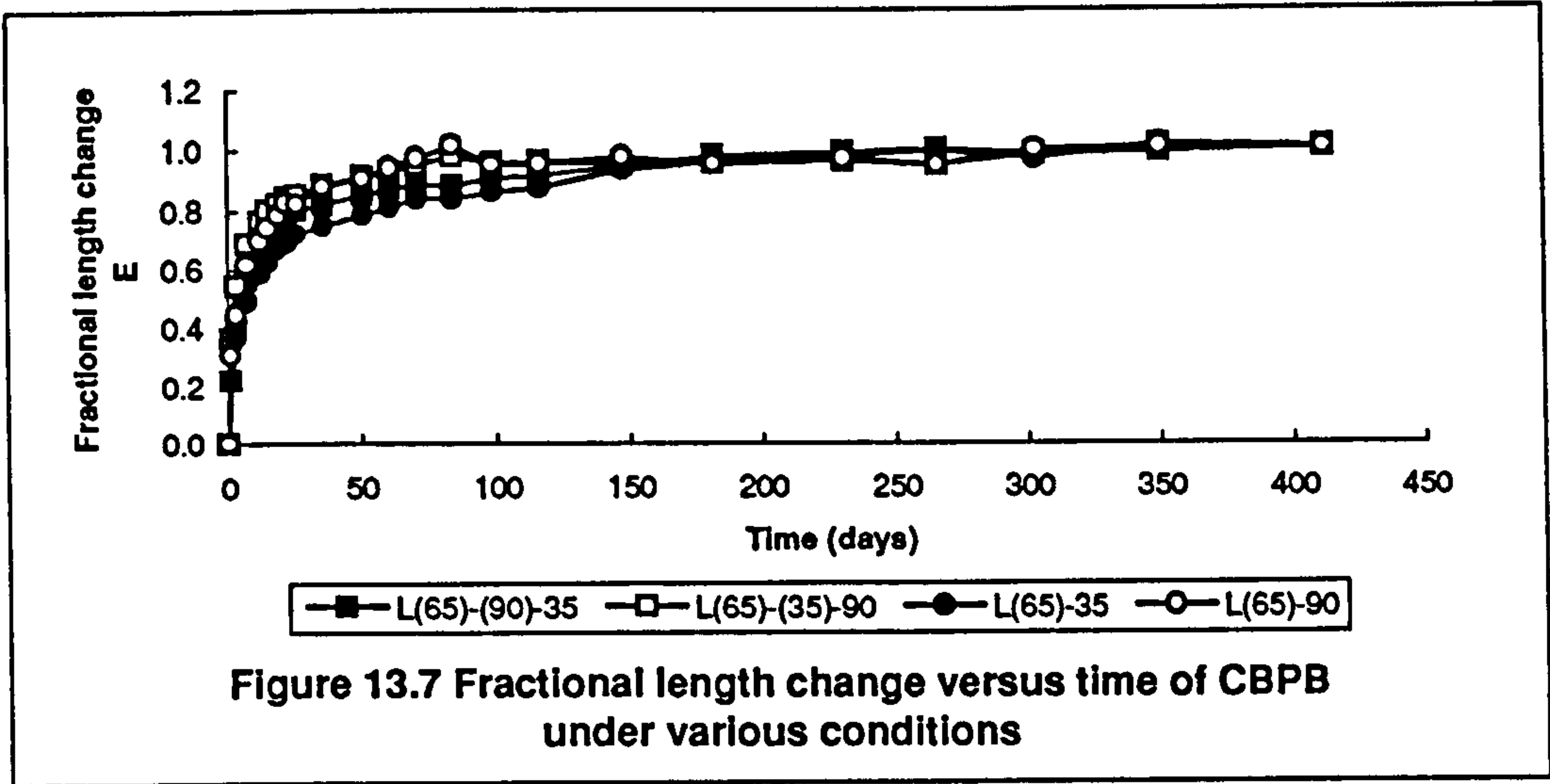


Figure 13.6 Fractional mass change versus time of CBPB under various conditions



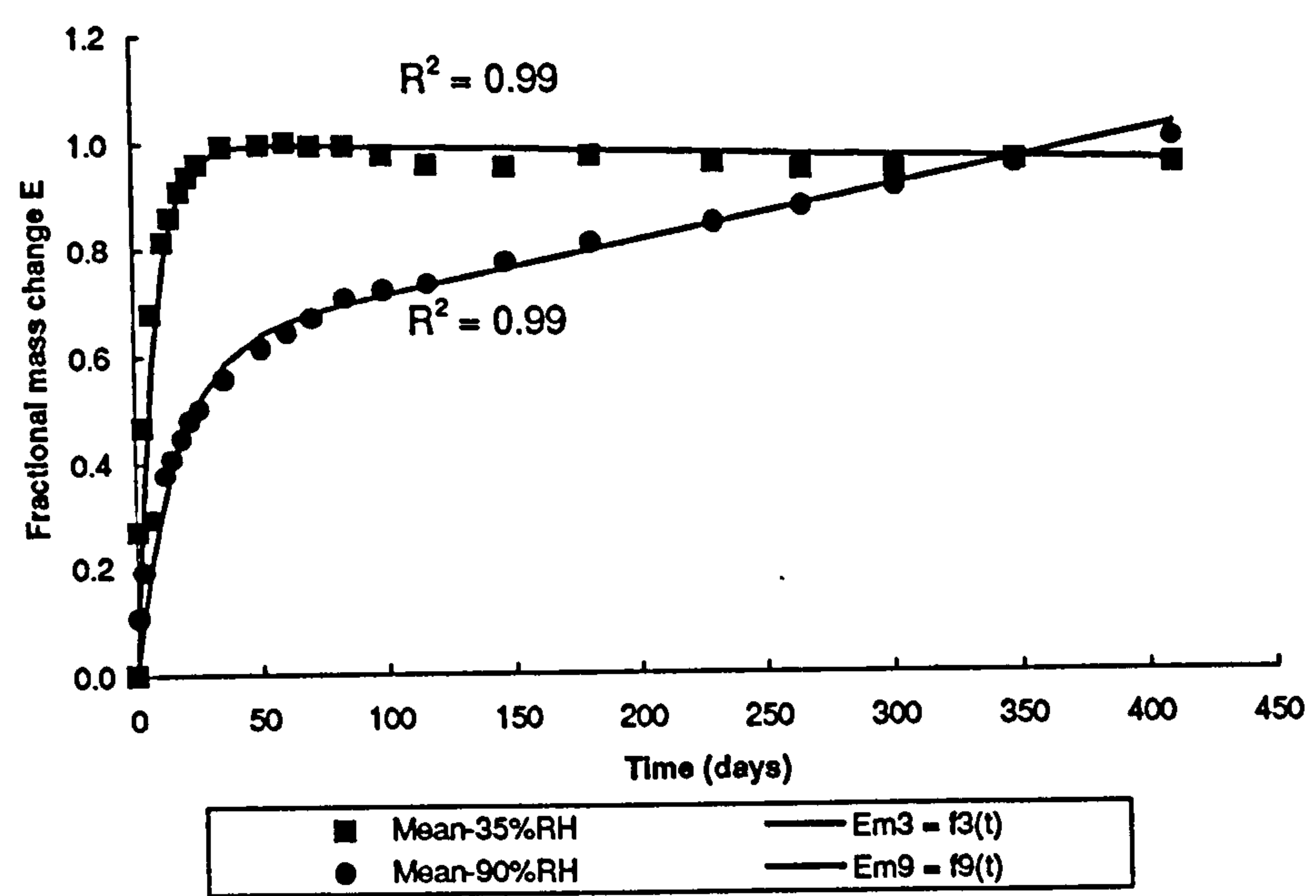


Figure 13.10 Mean fractional mass change (data points) and simulated curves (lines)

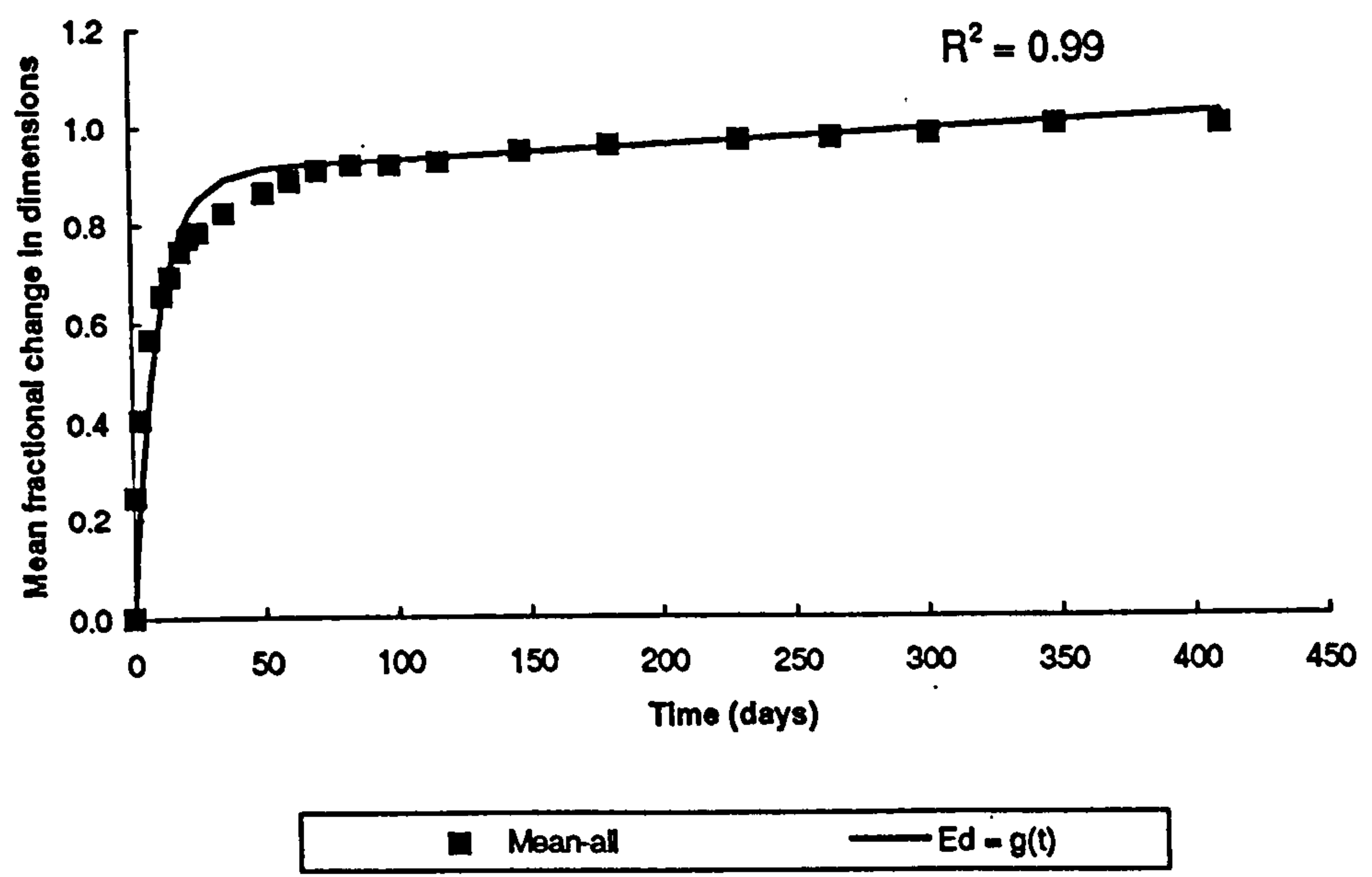


Figure 13.11 Mean fractional change in dimension (data points) and simulated curve (line) for CBPB under sorption

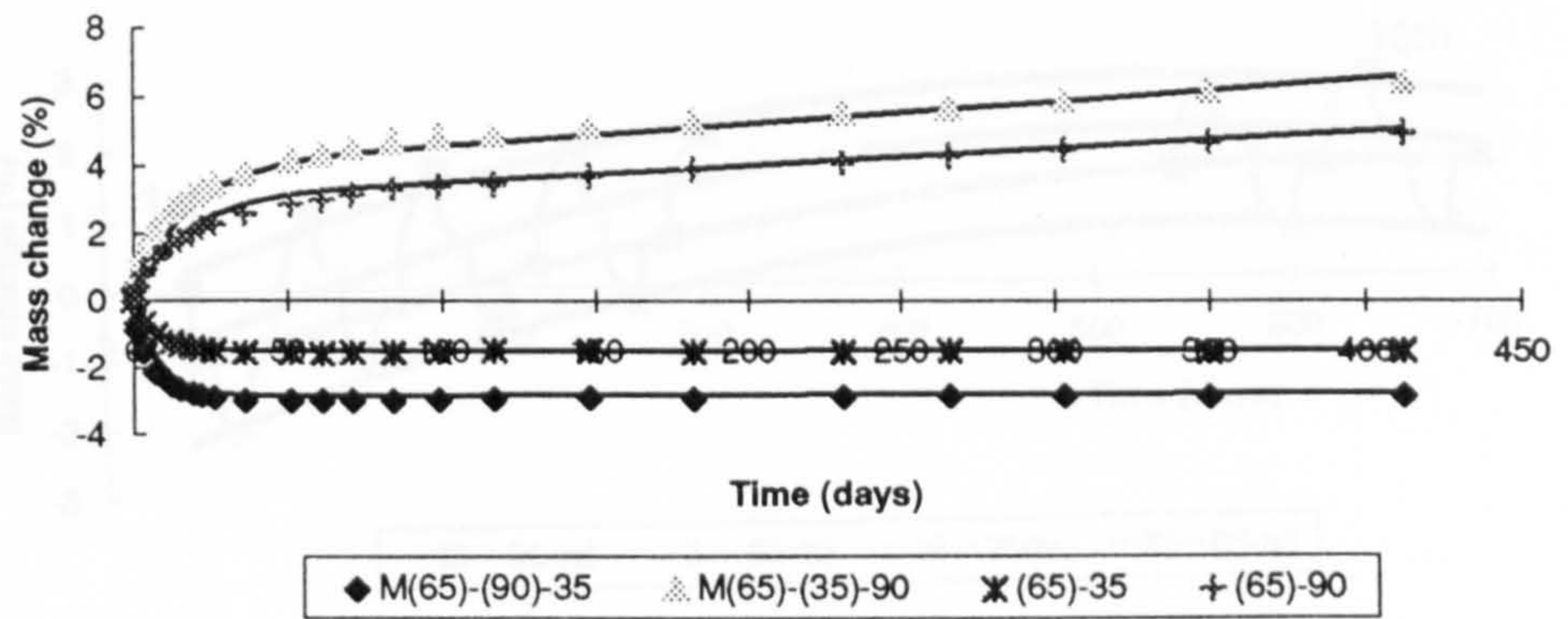


Figure 13.12 Mass change versus time of CBPB: measured curves (data points) and simulated curves (lines)

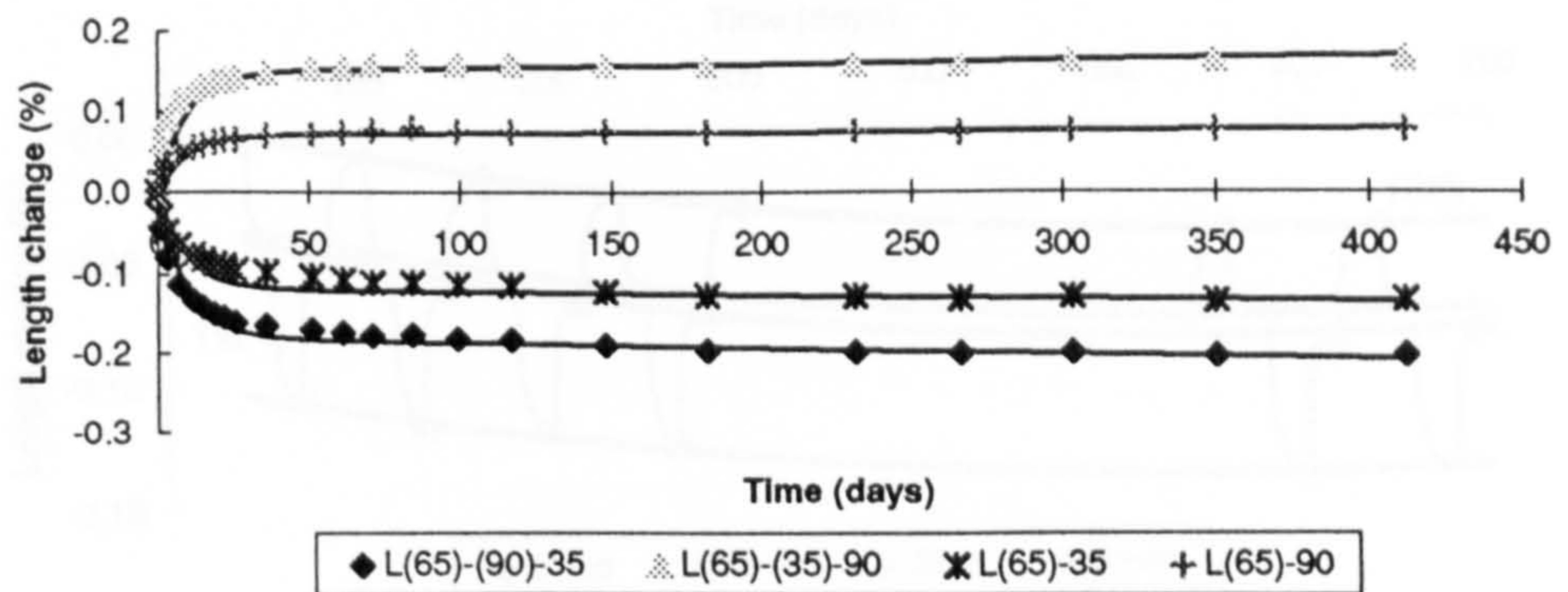


Figure 13.13 Length change versus time of CBPB: measured curves (data points) and simulated curves (lines)

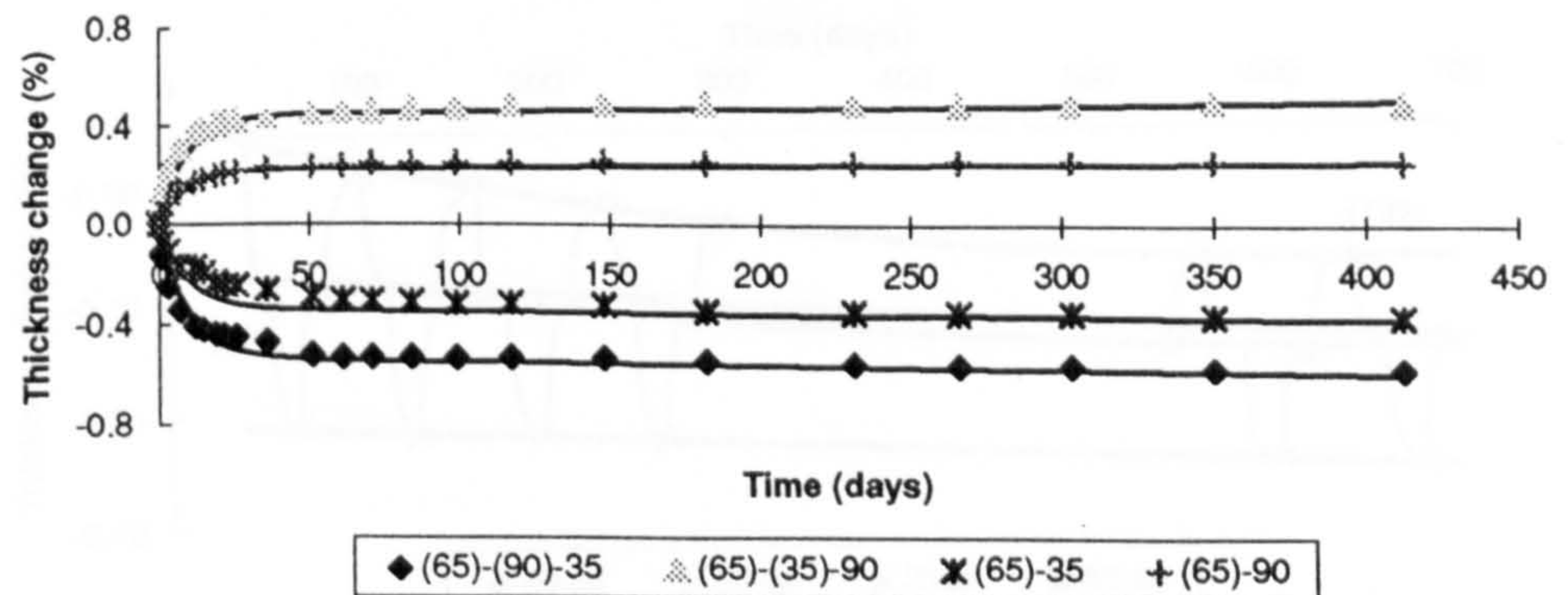


Figure 13.14 Thickness change versus time of CBPB: measured curves (data points) and simulated curves (lines)

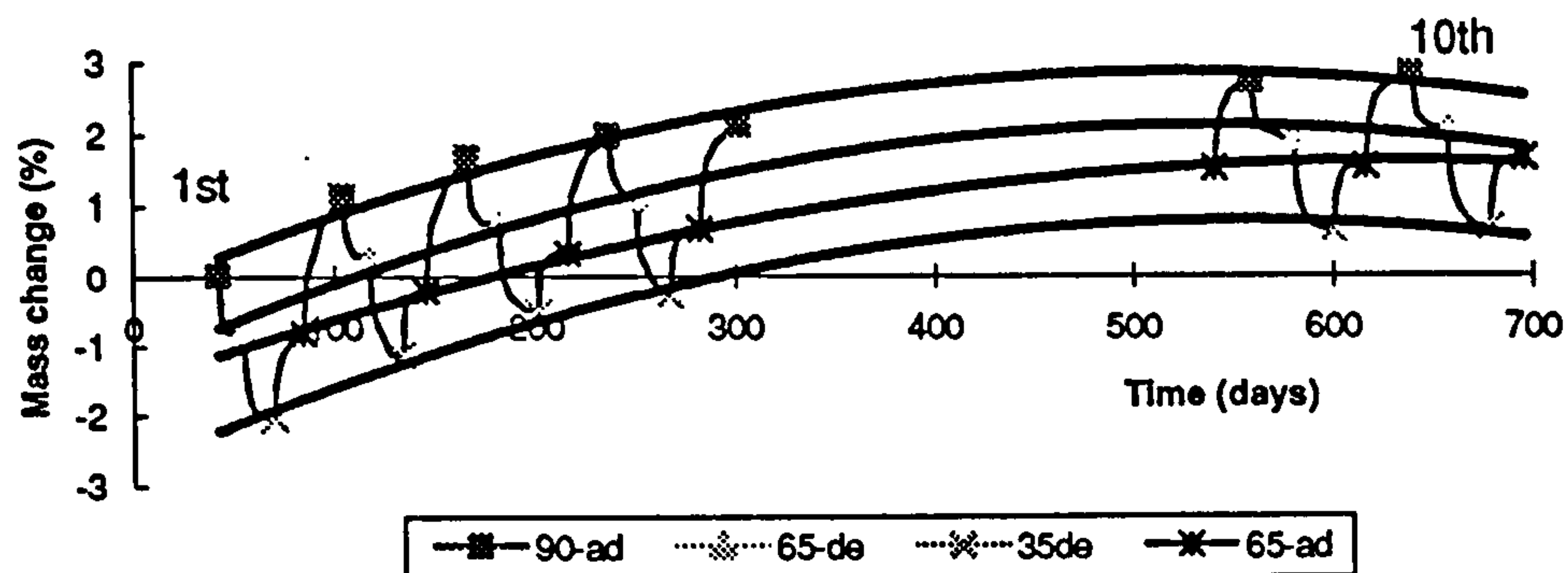


Figure 13.15 Prediction of change in mass of 12 mm CBPB against time after a series of cycles (10 cycles in 90%-65%-35%-65%-90%RH)

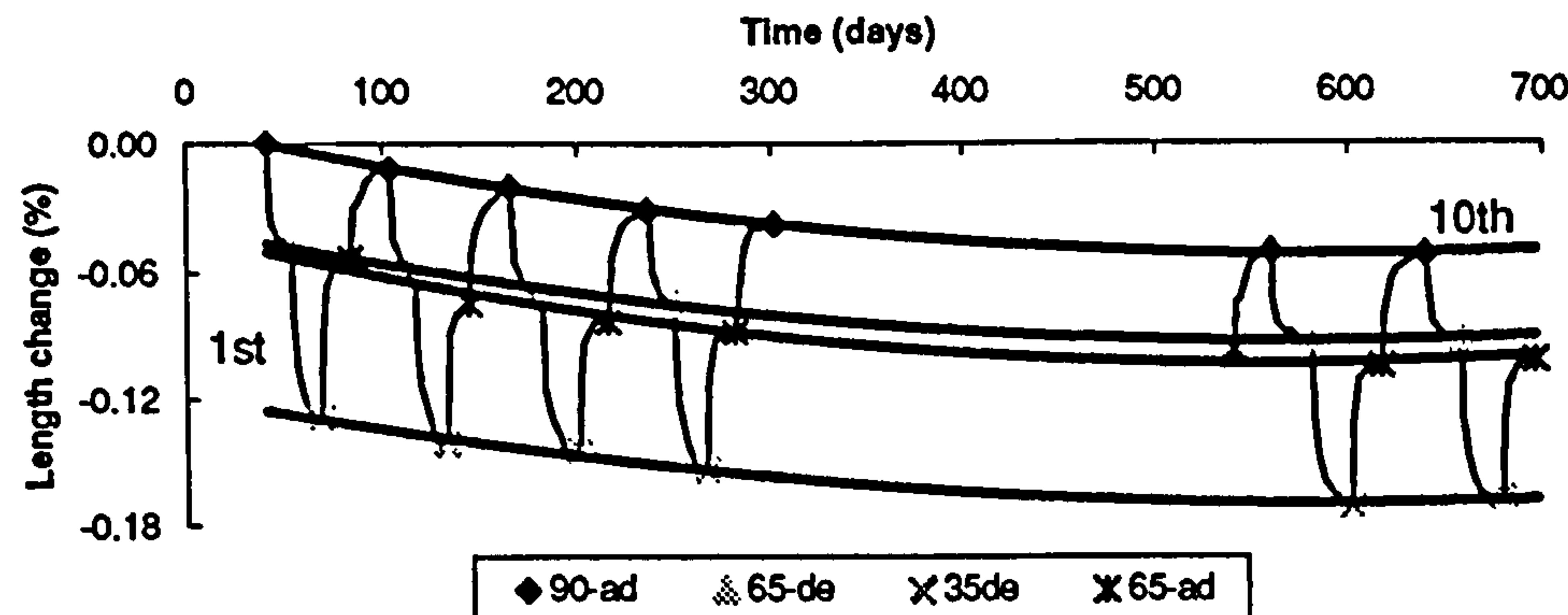


Figure 13.16 Prediction of change in length of 12 mm CBPB against time after a series of cycles (ten cycles in 90%-65%-35%-65%-90%RH)

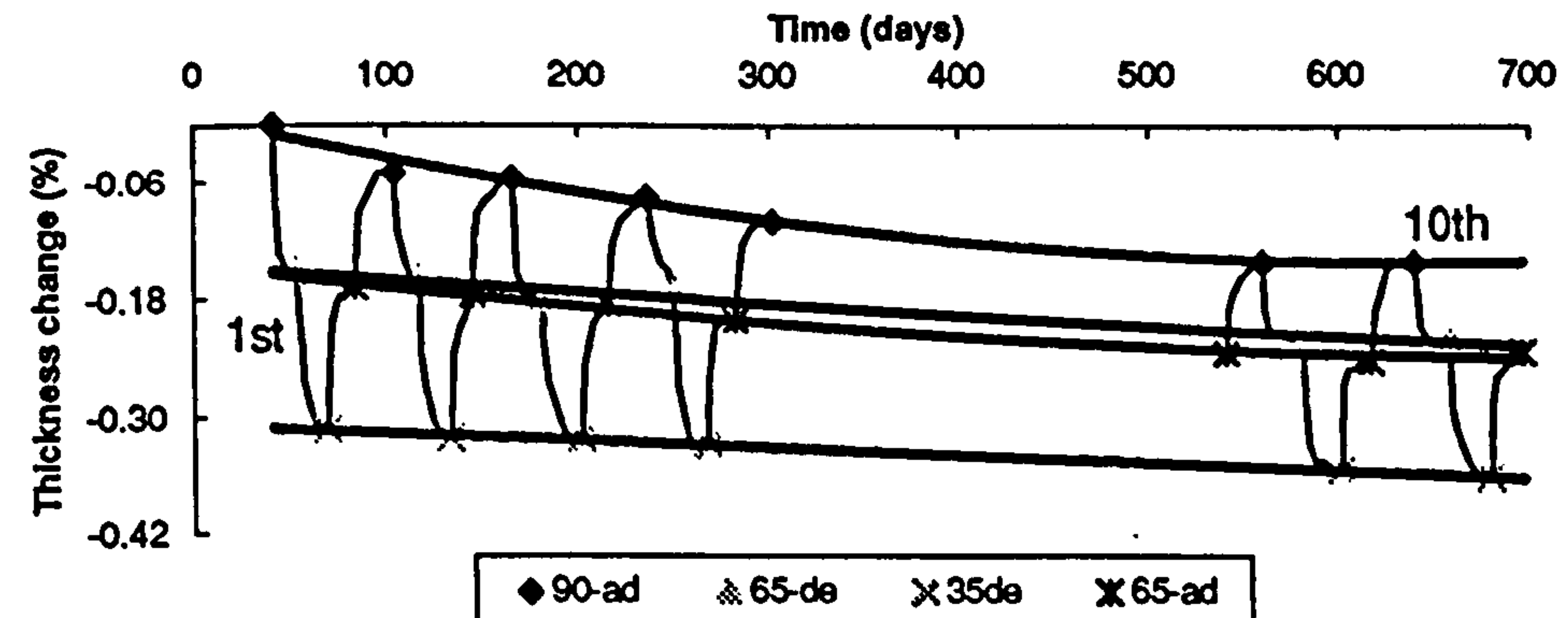
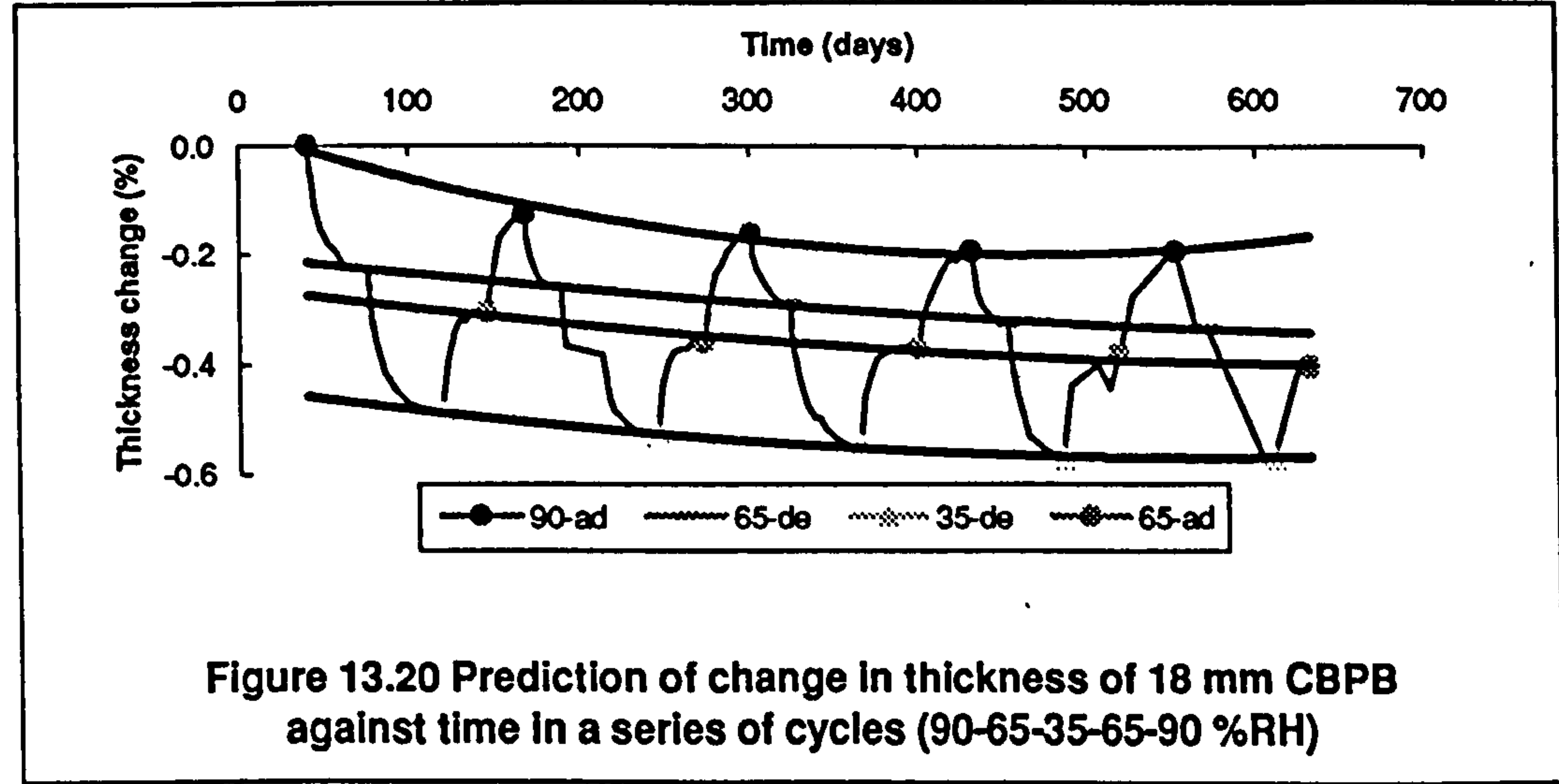
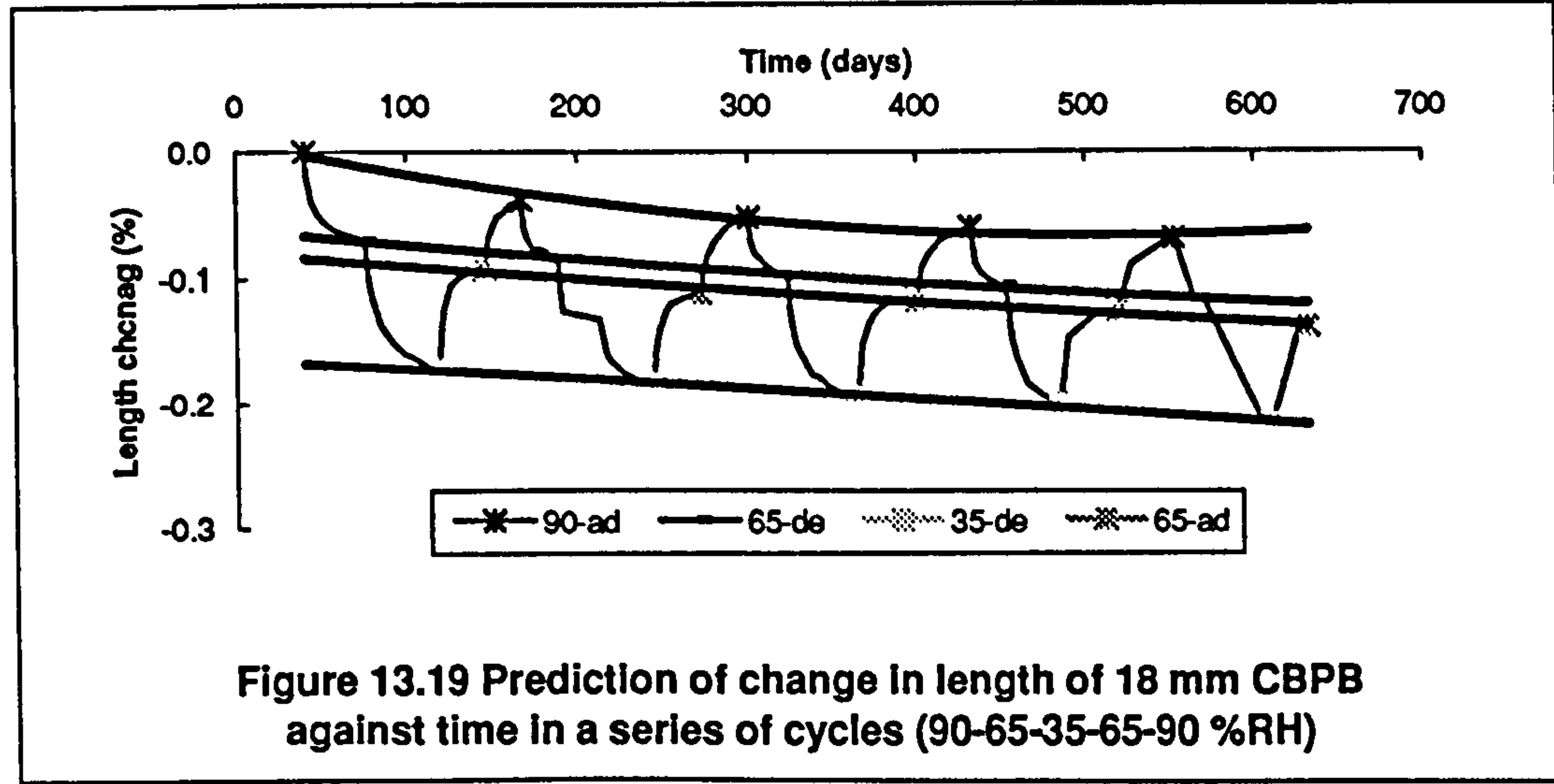
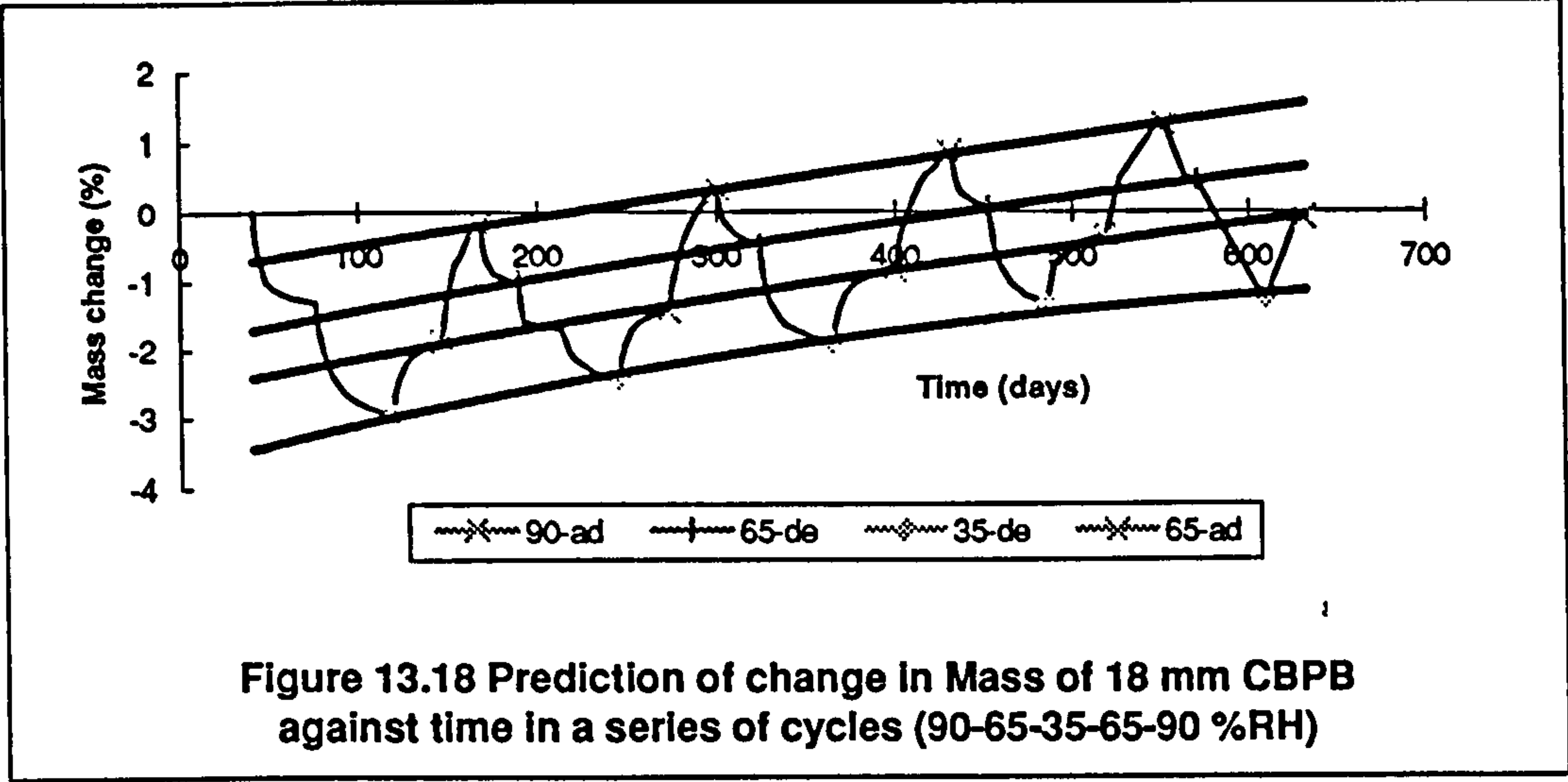


Figure 13.17 Prediction of change in thickness of 12 mm CBPB against time after a series of cycles (10 cycles in 90%-65%-35%-65%-90%RH)



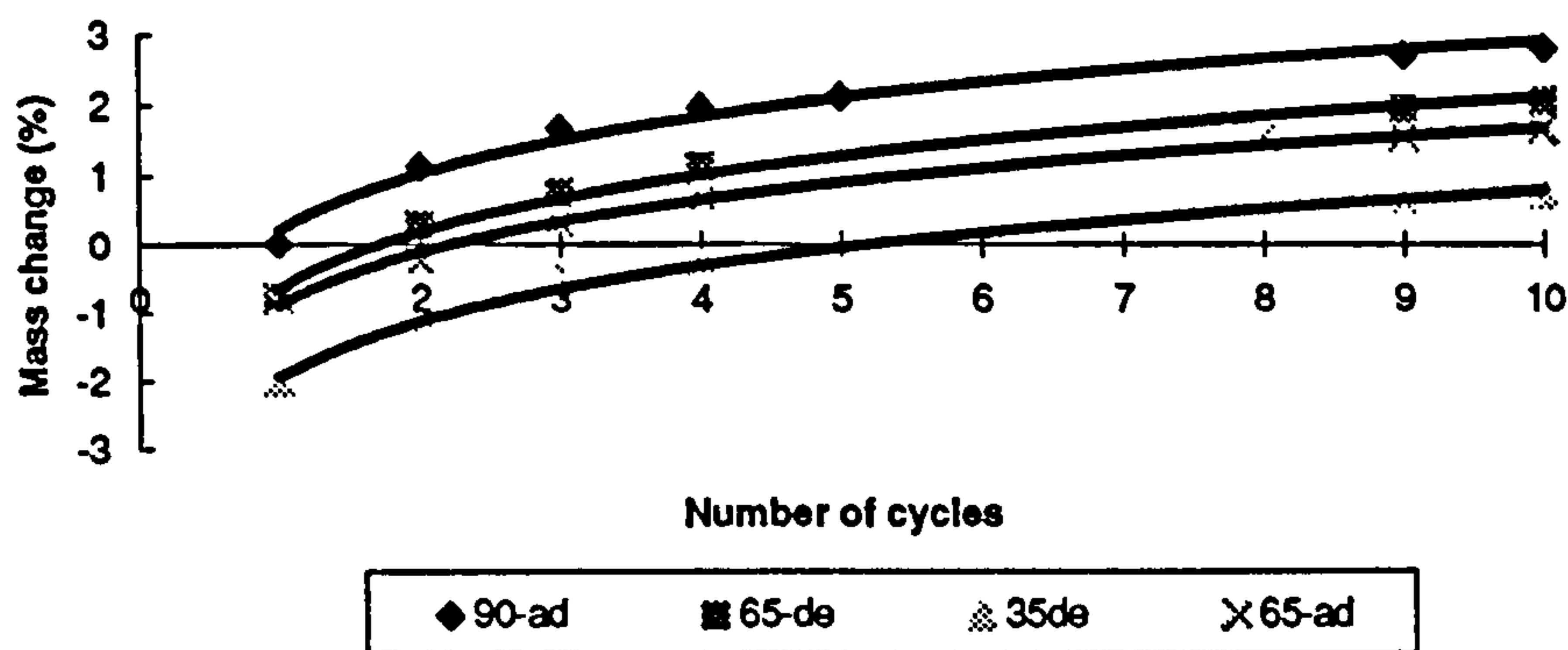


Figure 13.21 Prediction and individual fits of change in mass of 12 mm CBPB against number of cycle (cycle: 90-65-35-65-90 %RH)

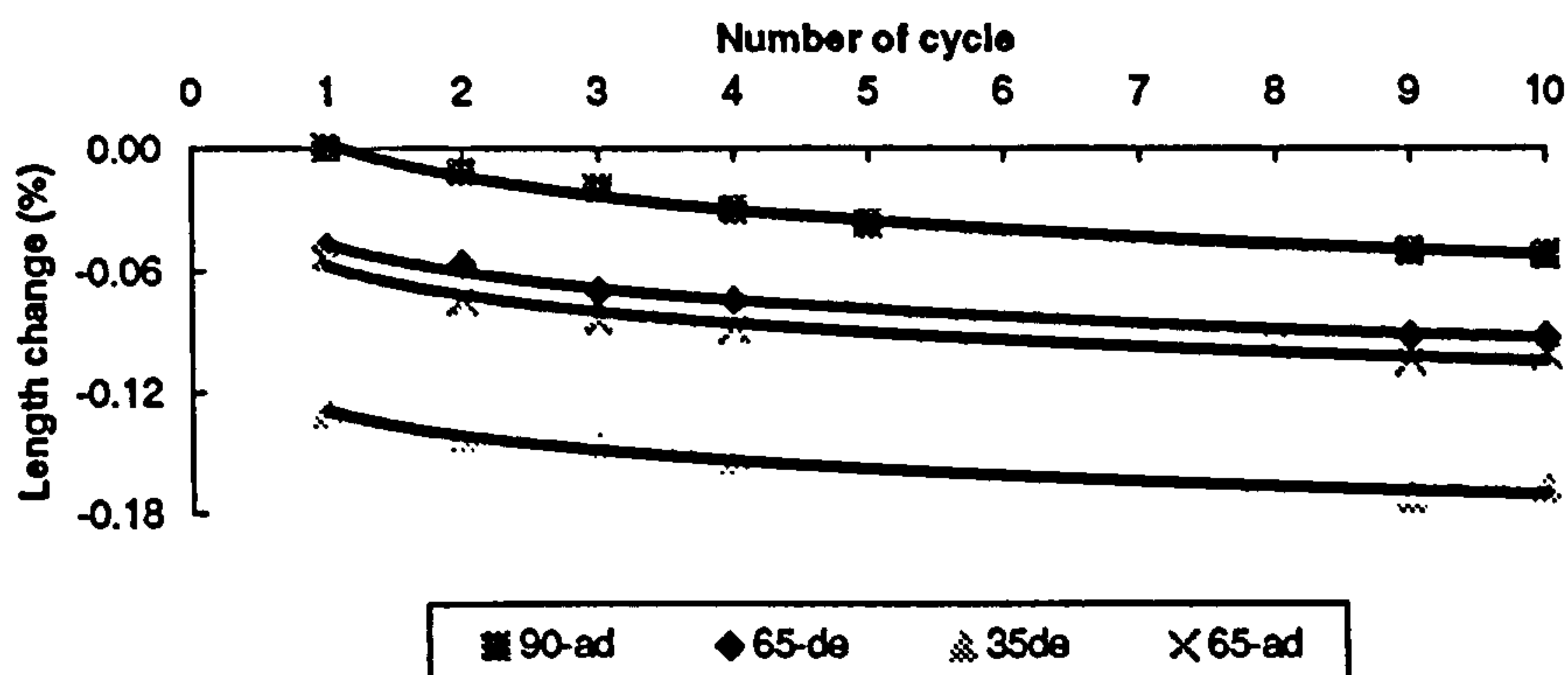


Figure 13.22 Prediction and individual fits of change in length of 12 mm CBPB against number of cycle (cycle: 90-65-35-65-90%RH)

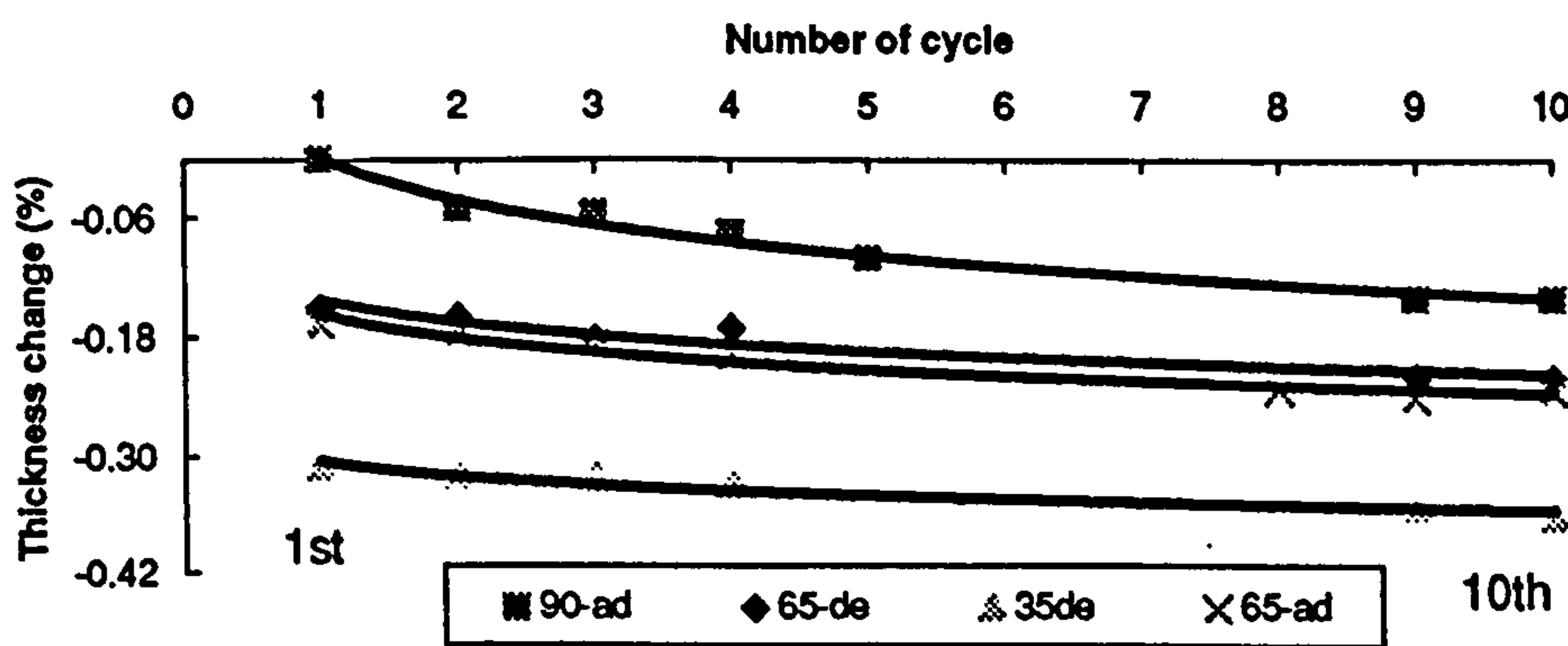
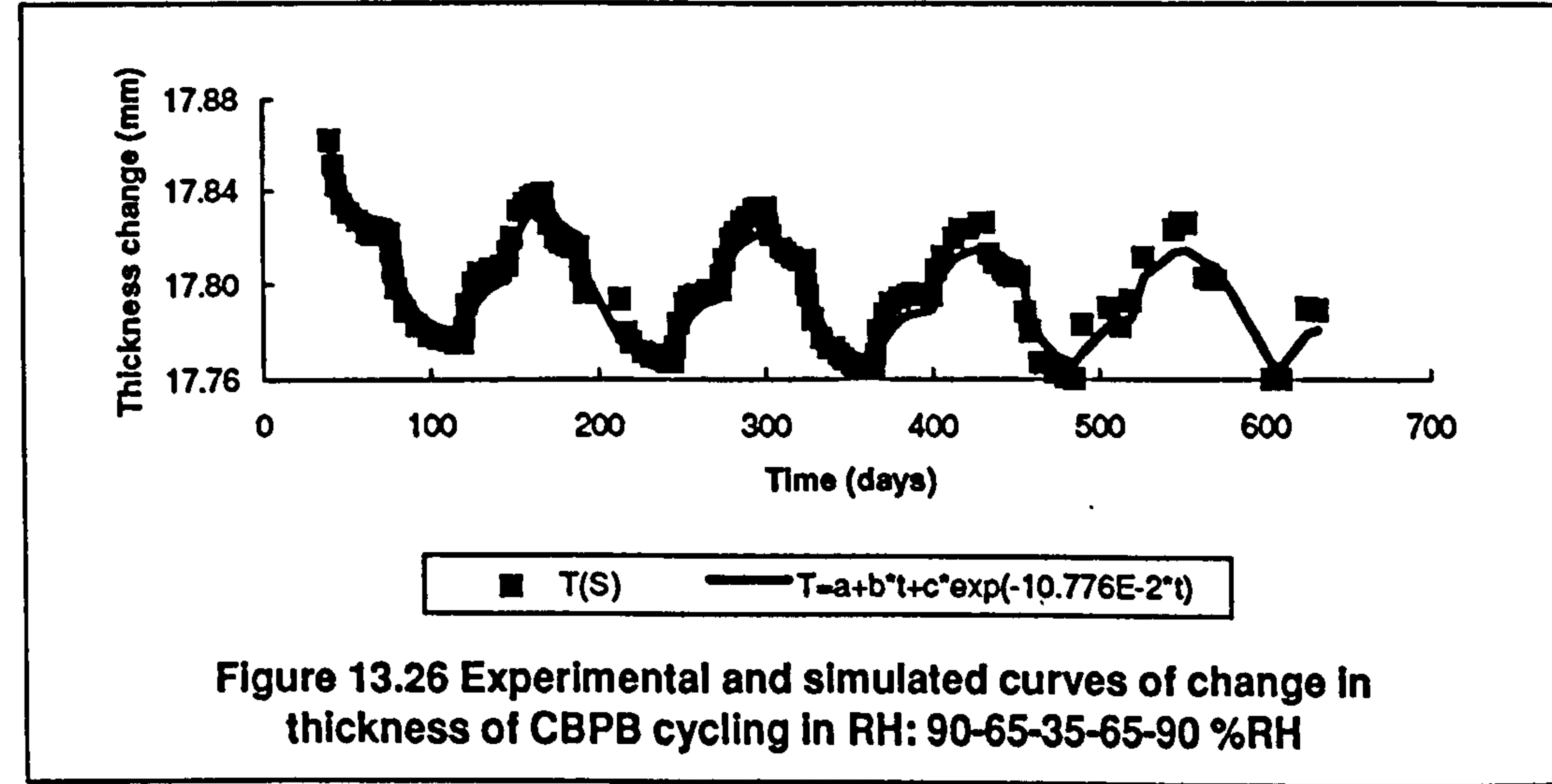
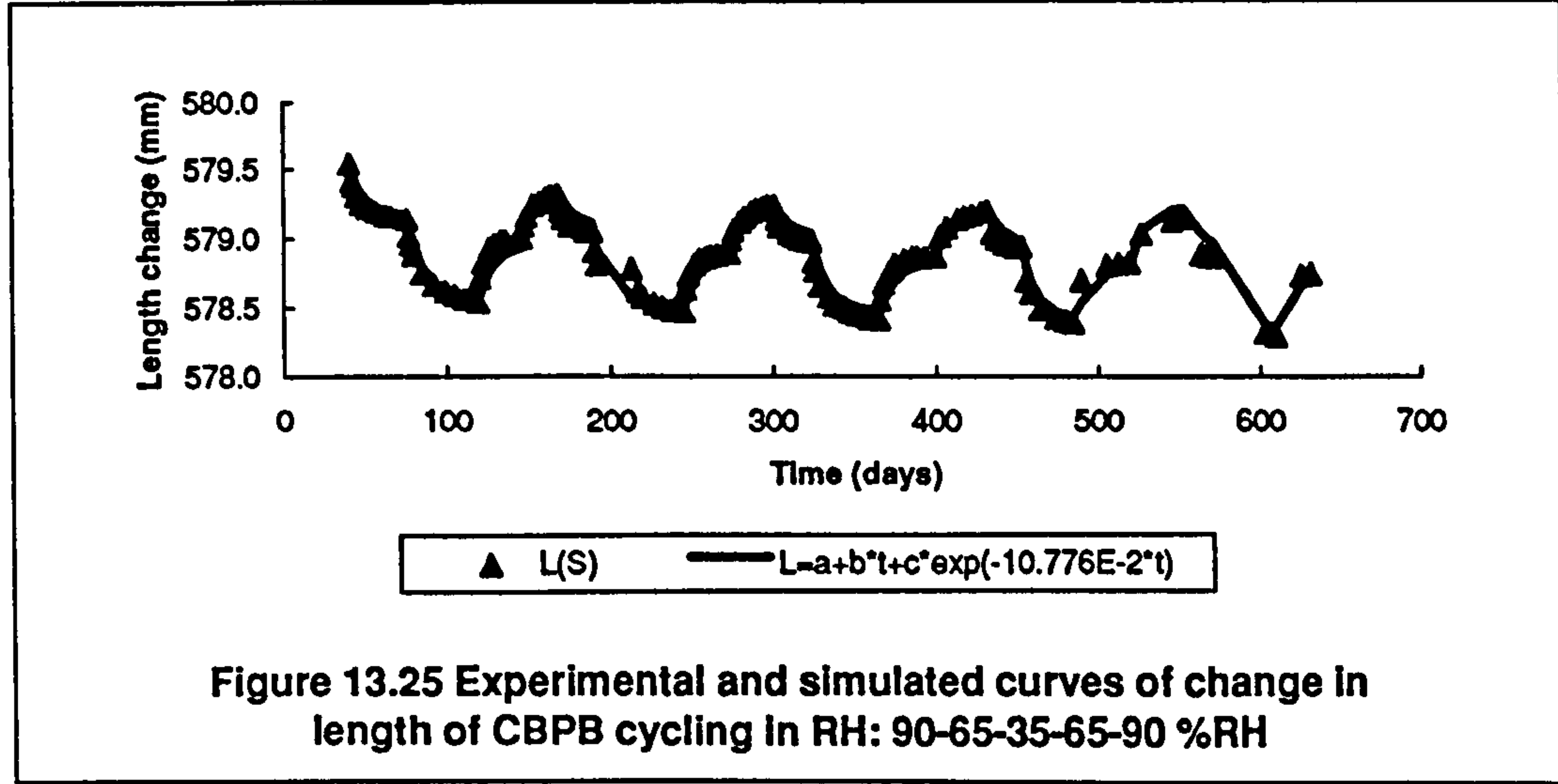
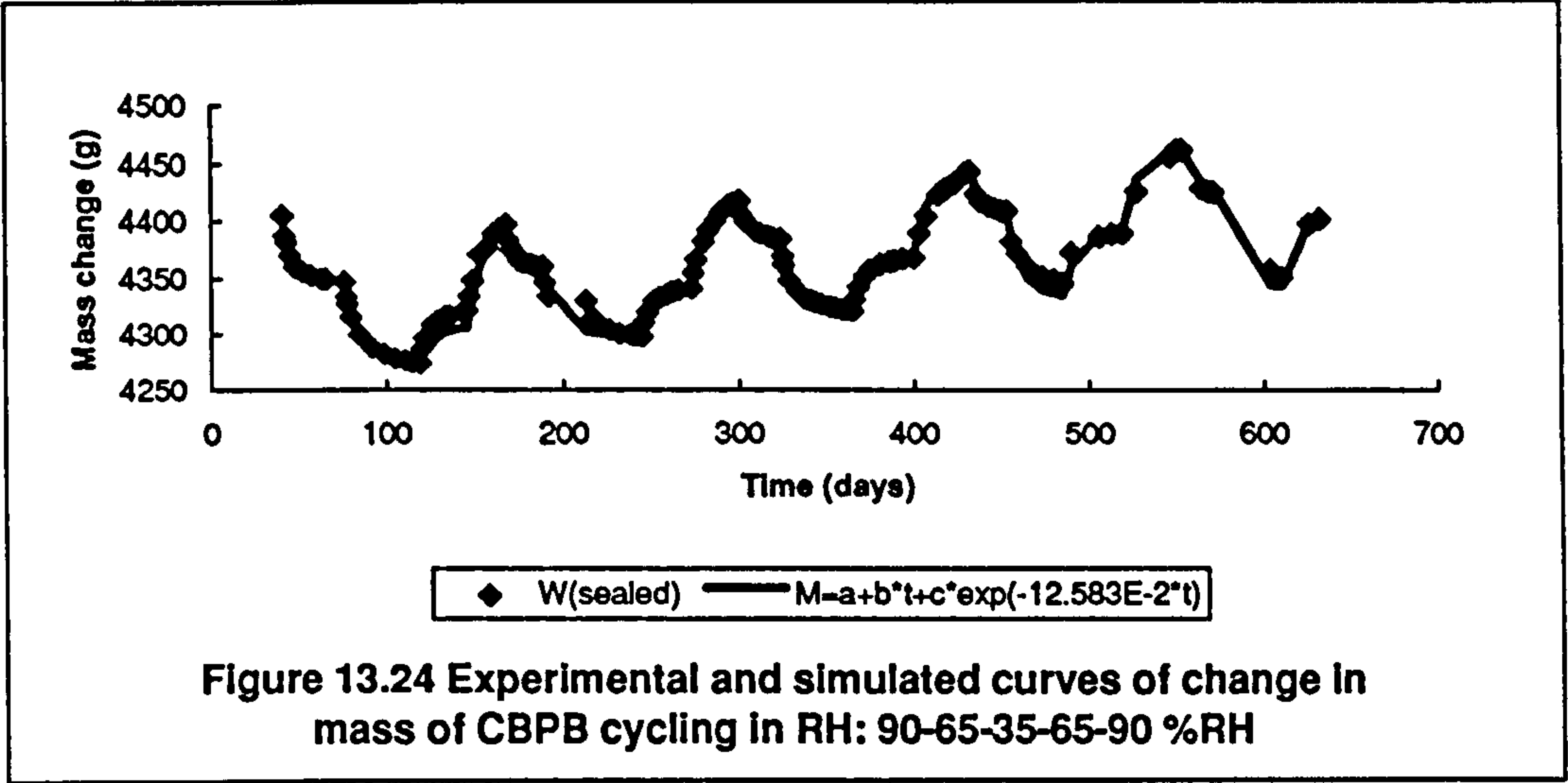
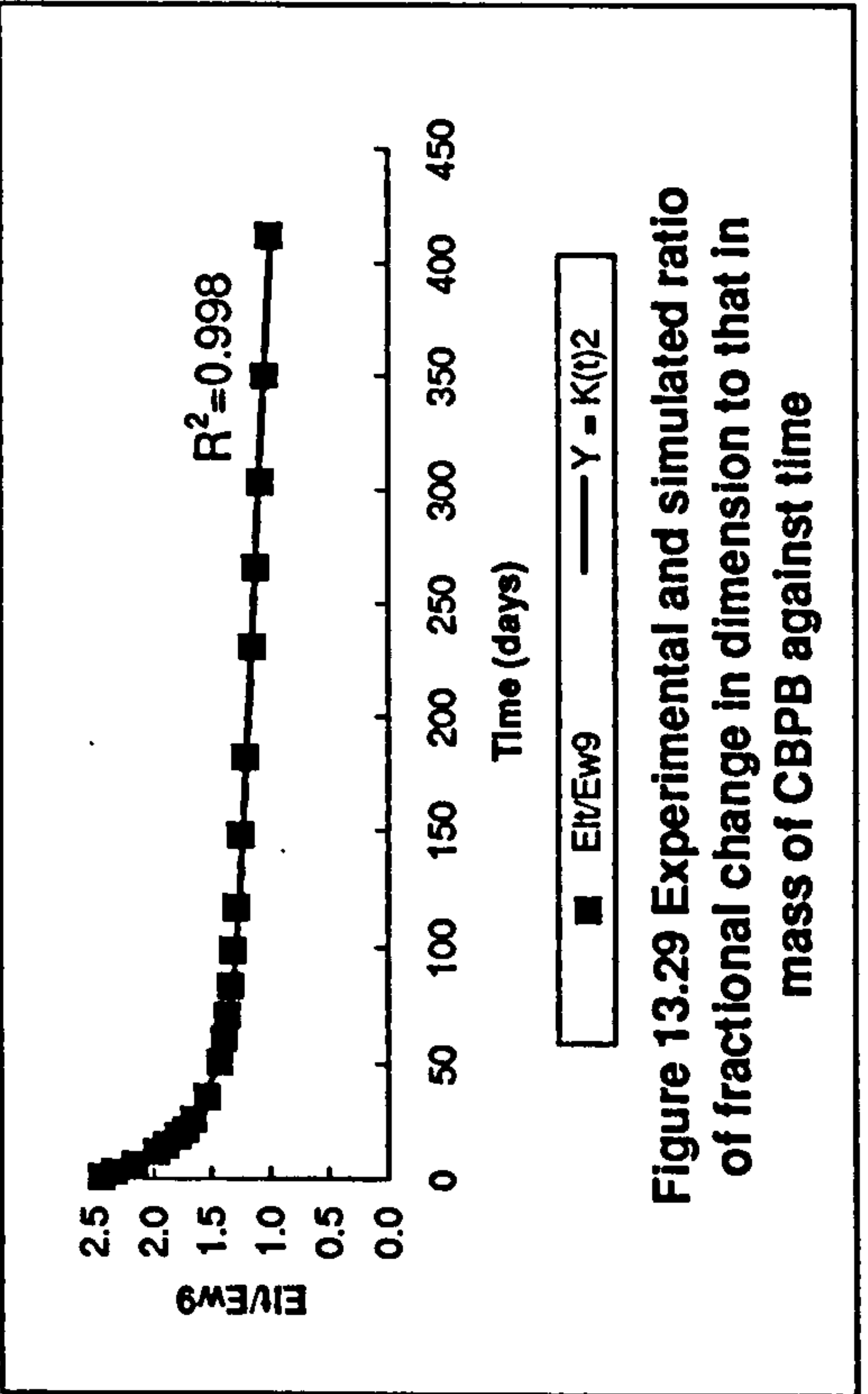
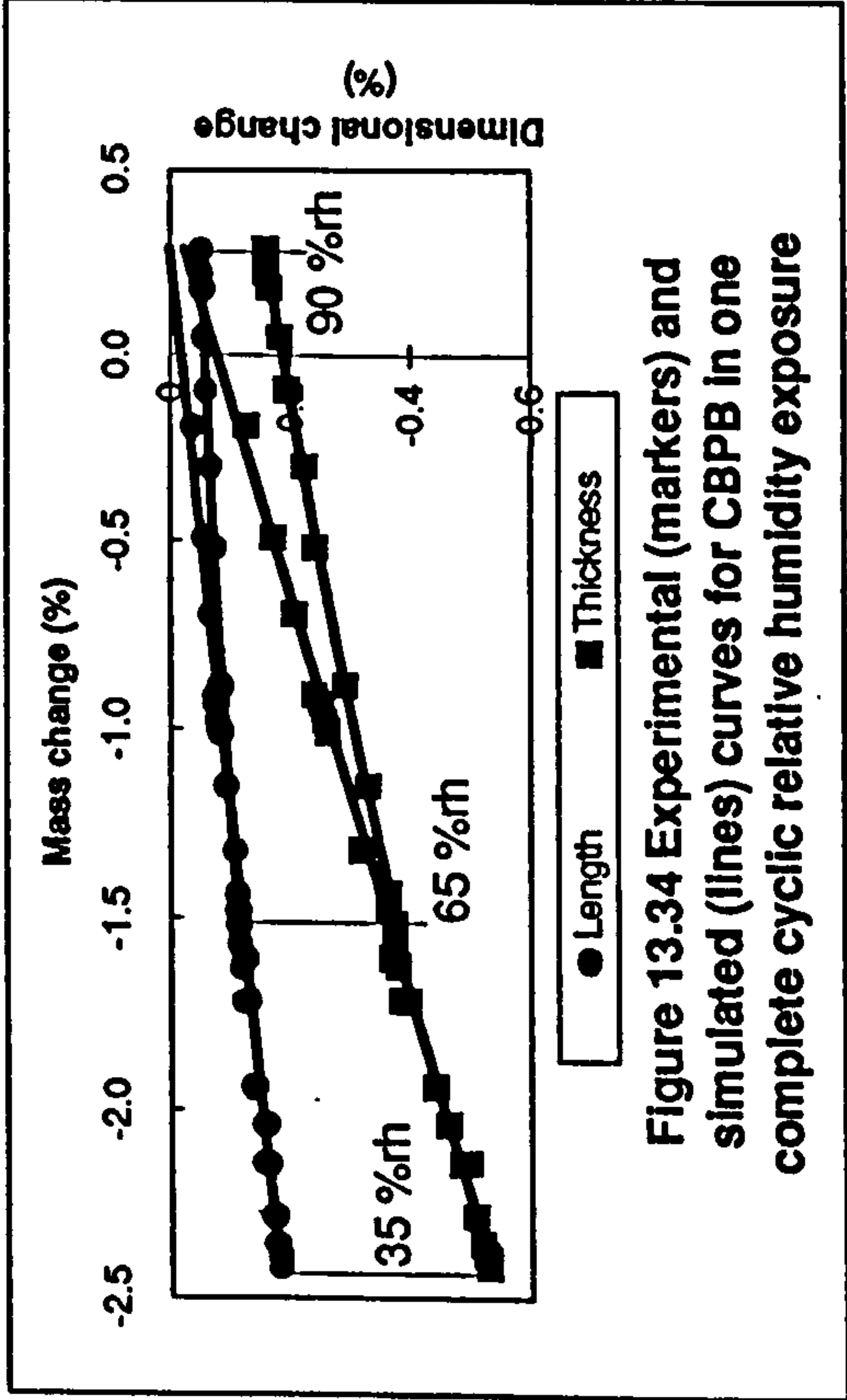
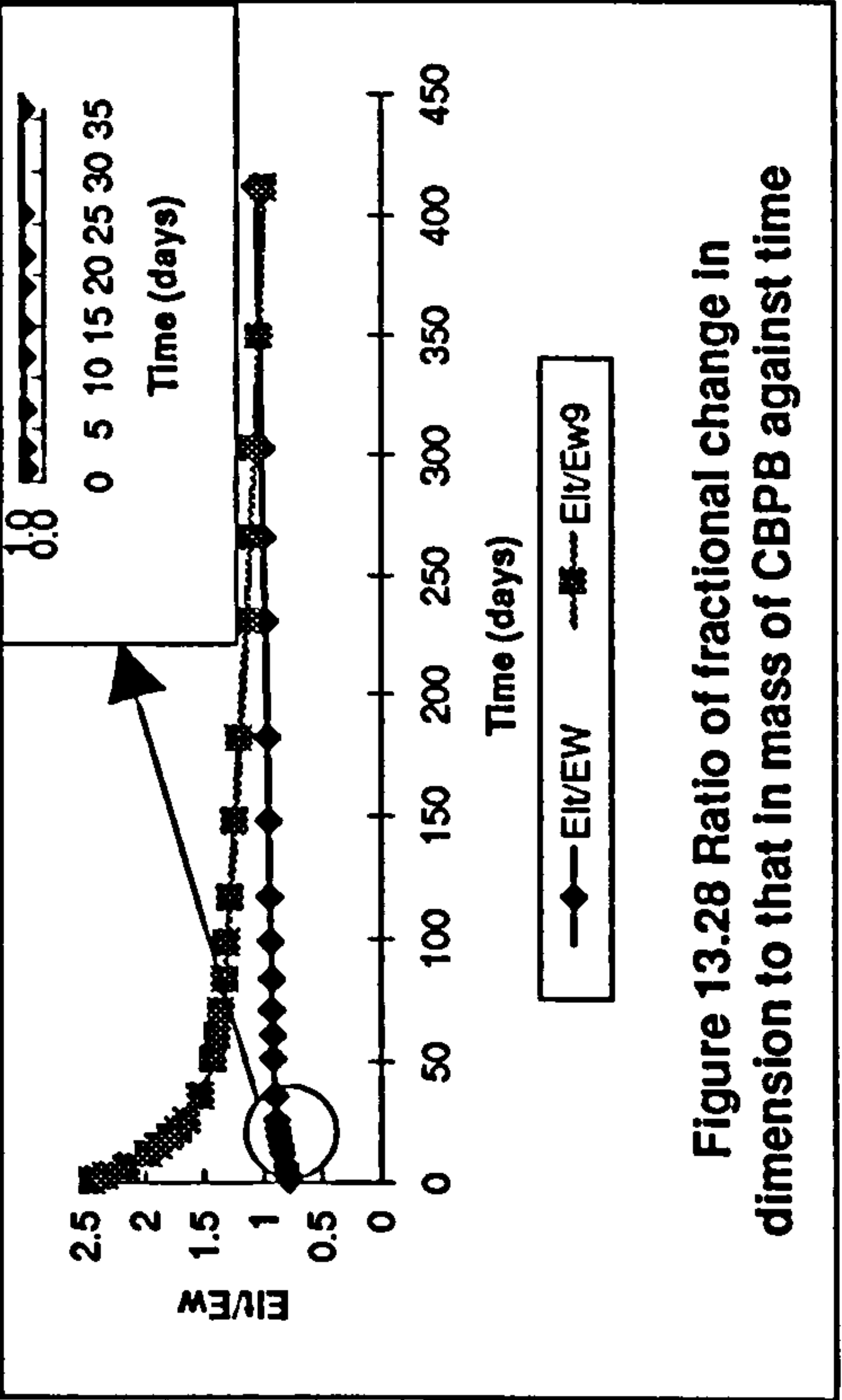
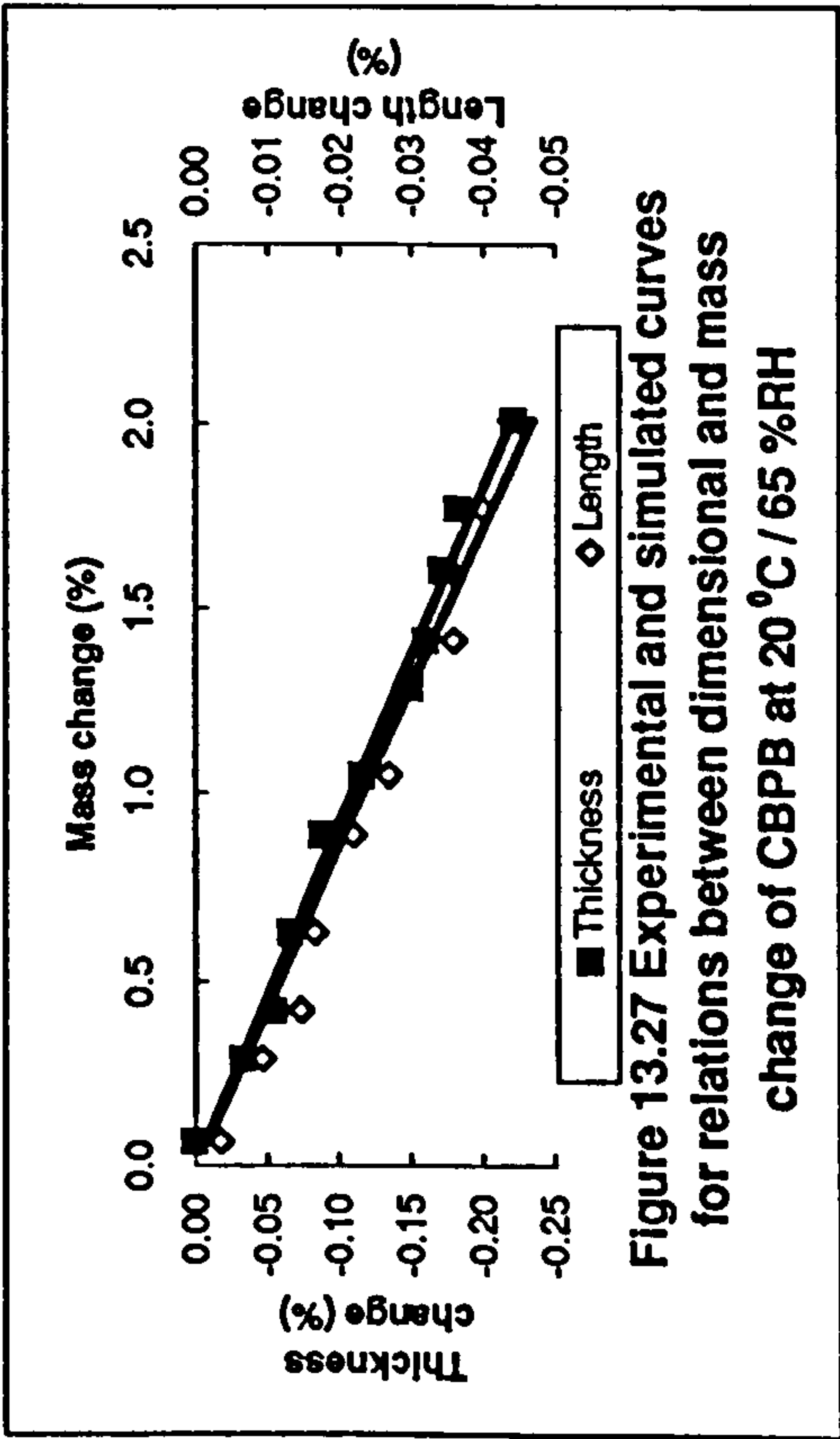
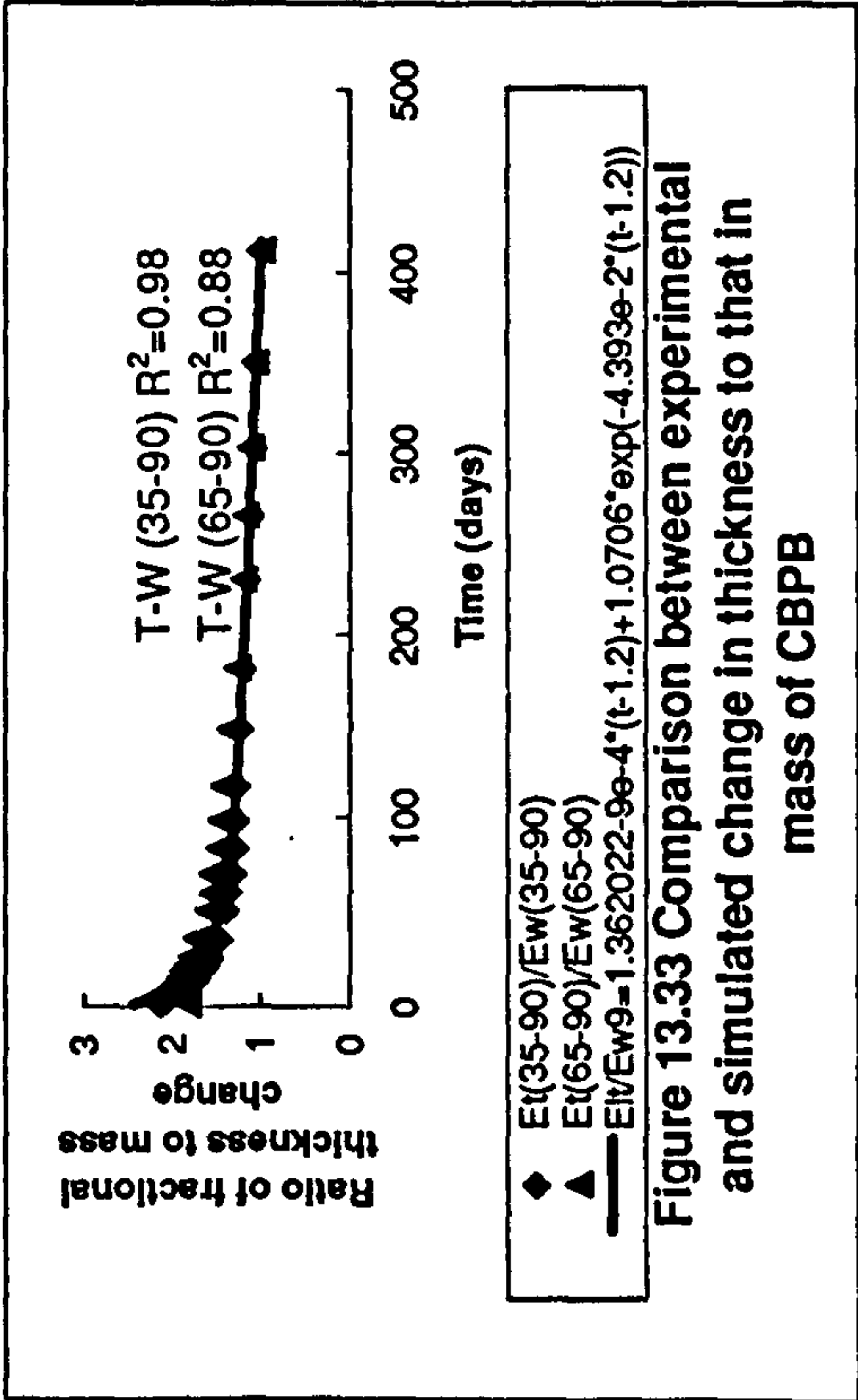
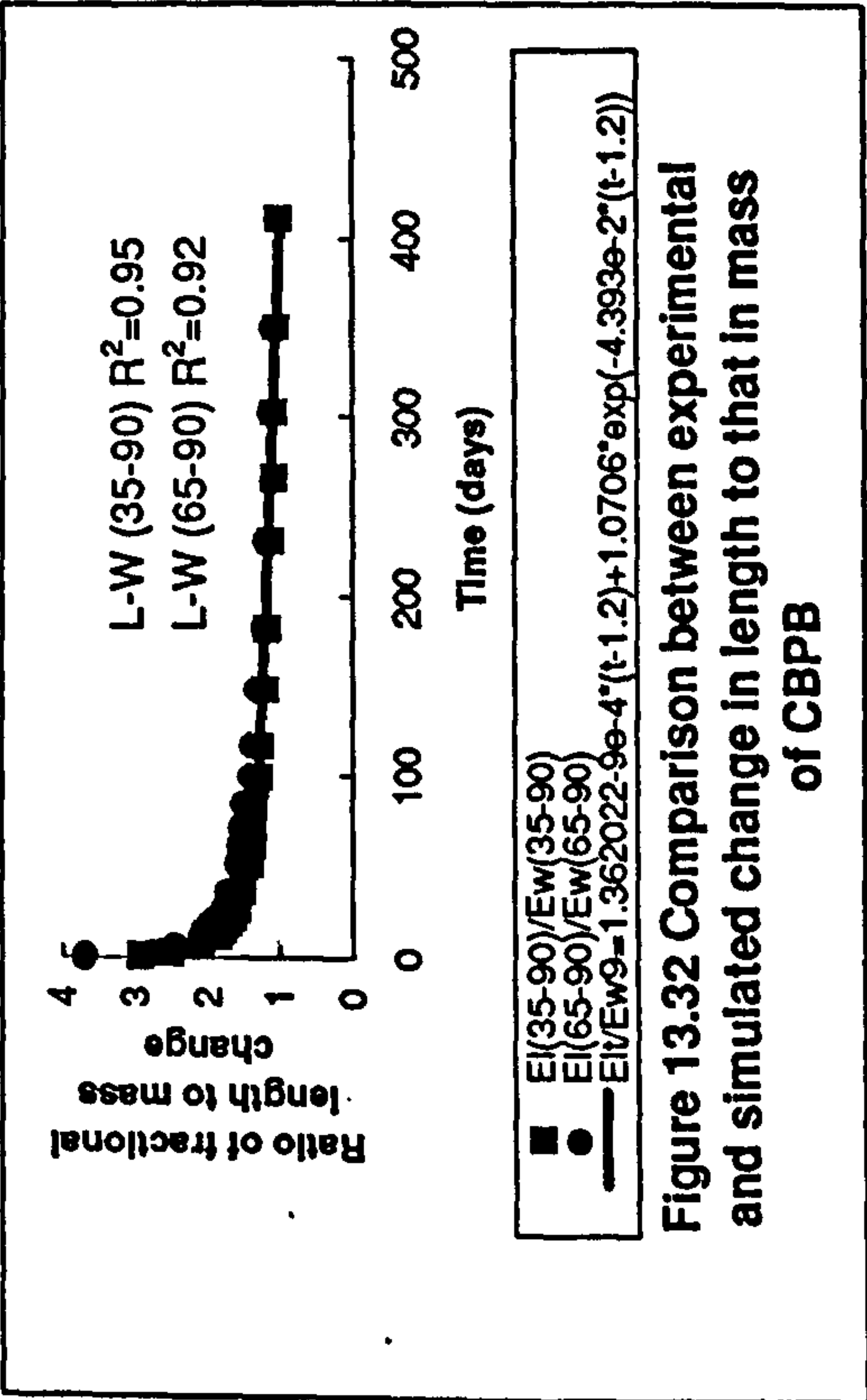
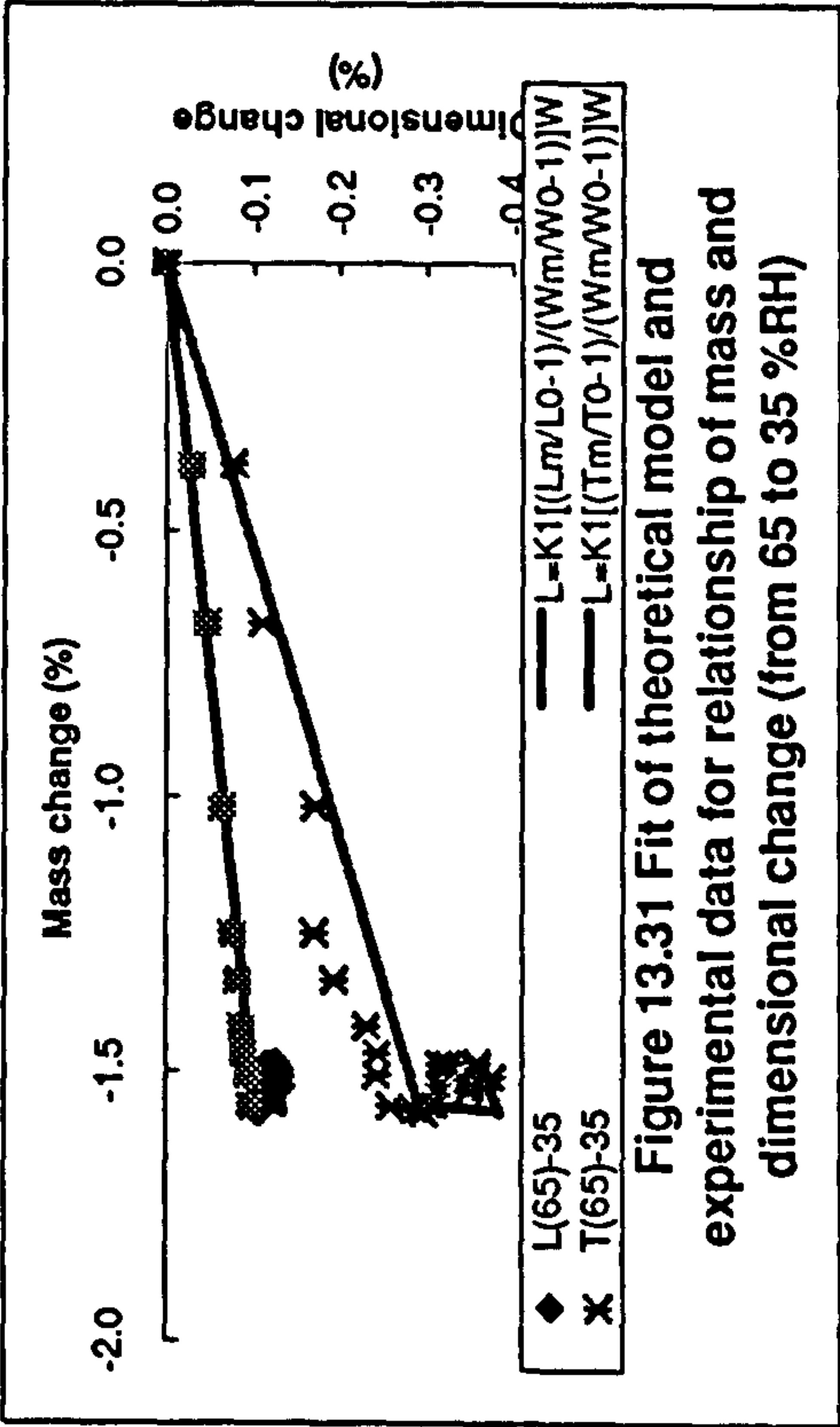
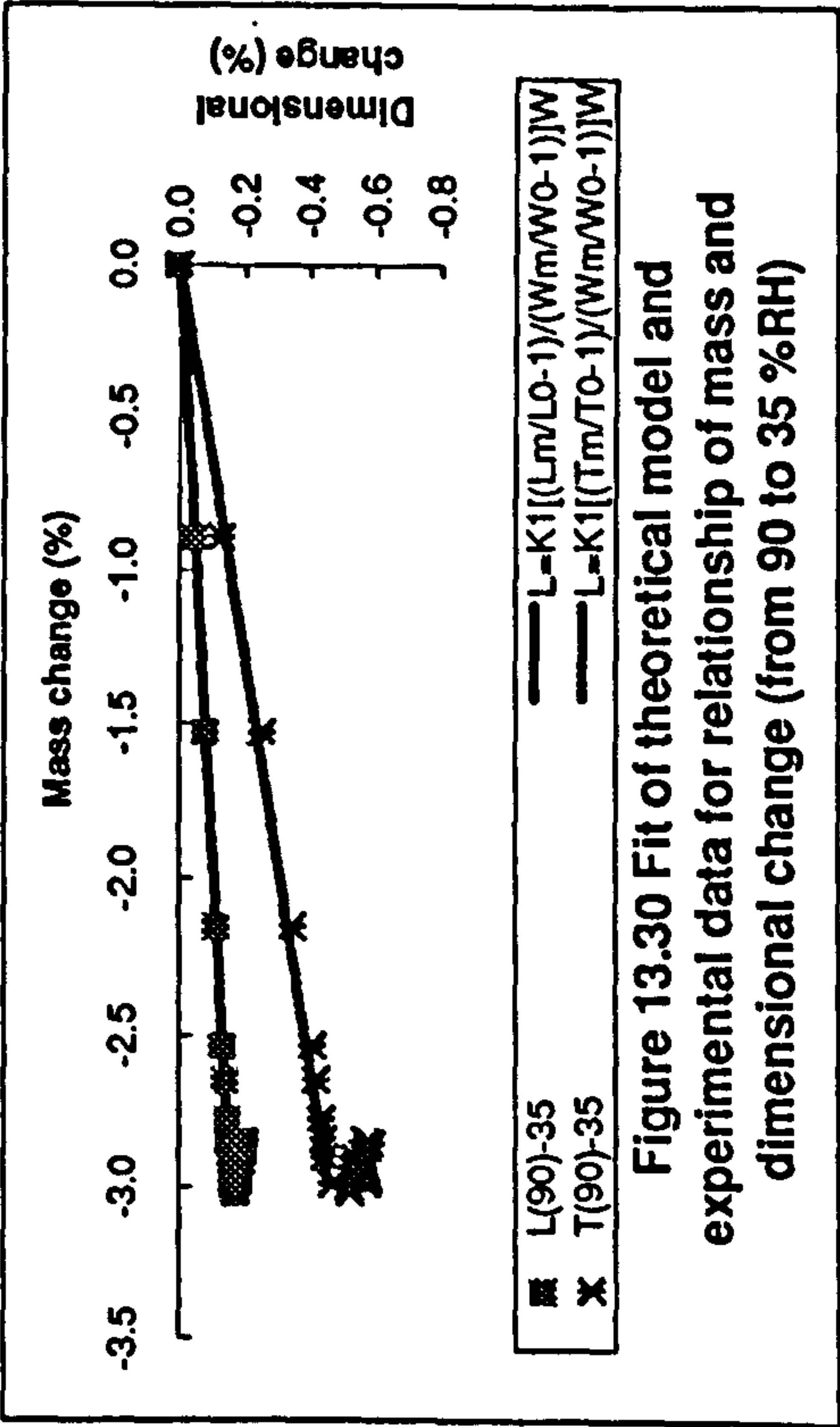
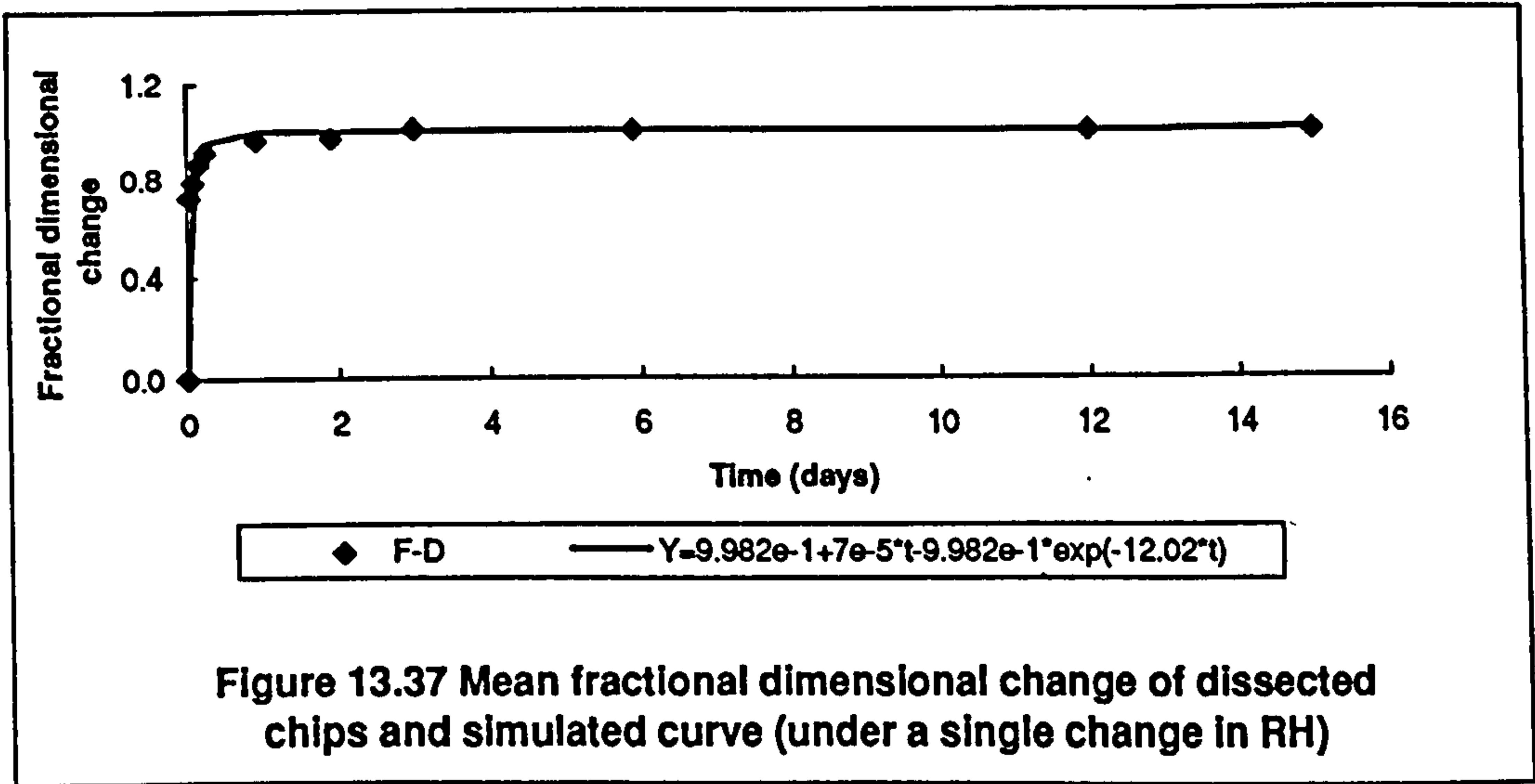
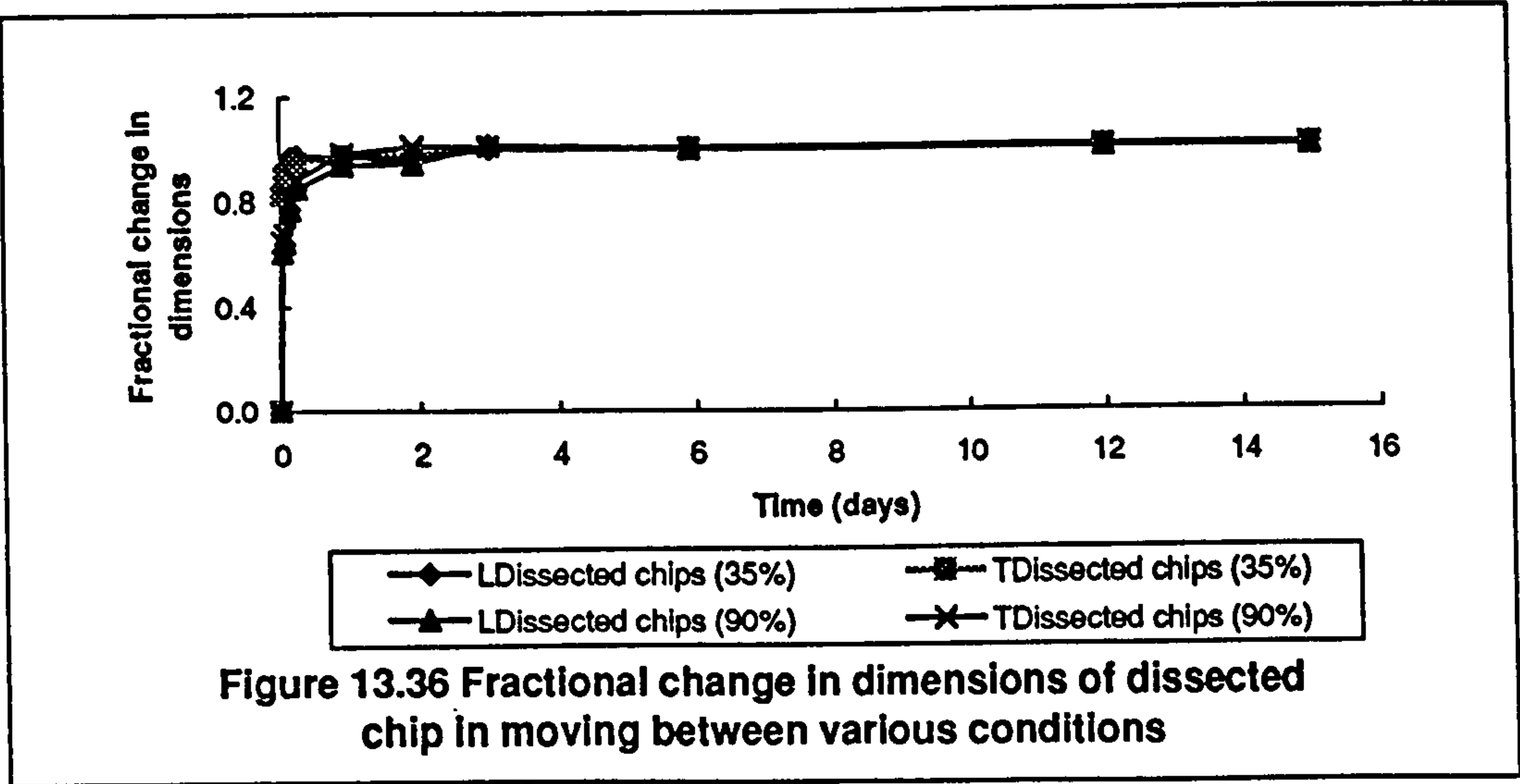
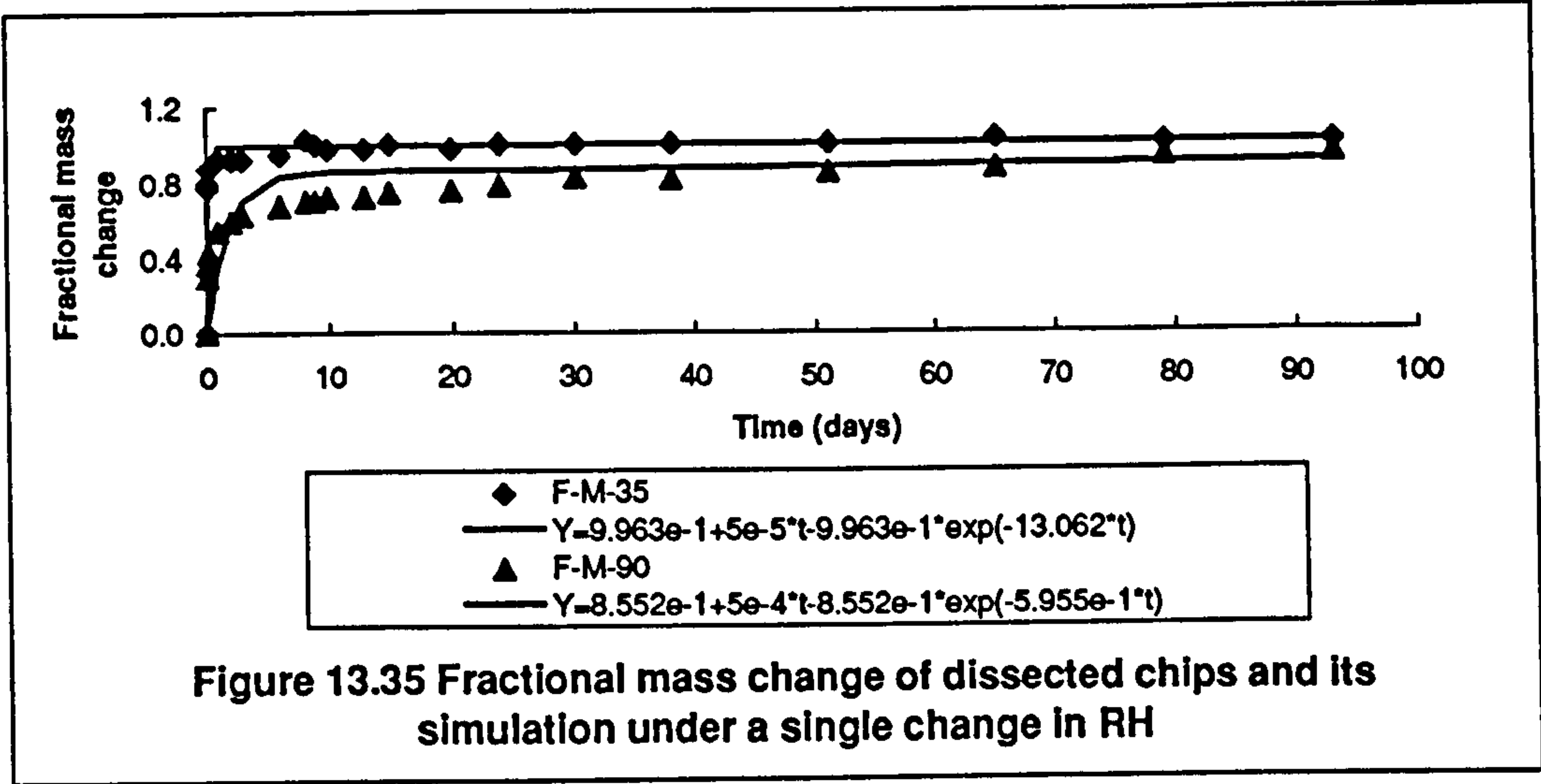


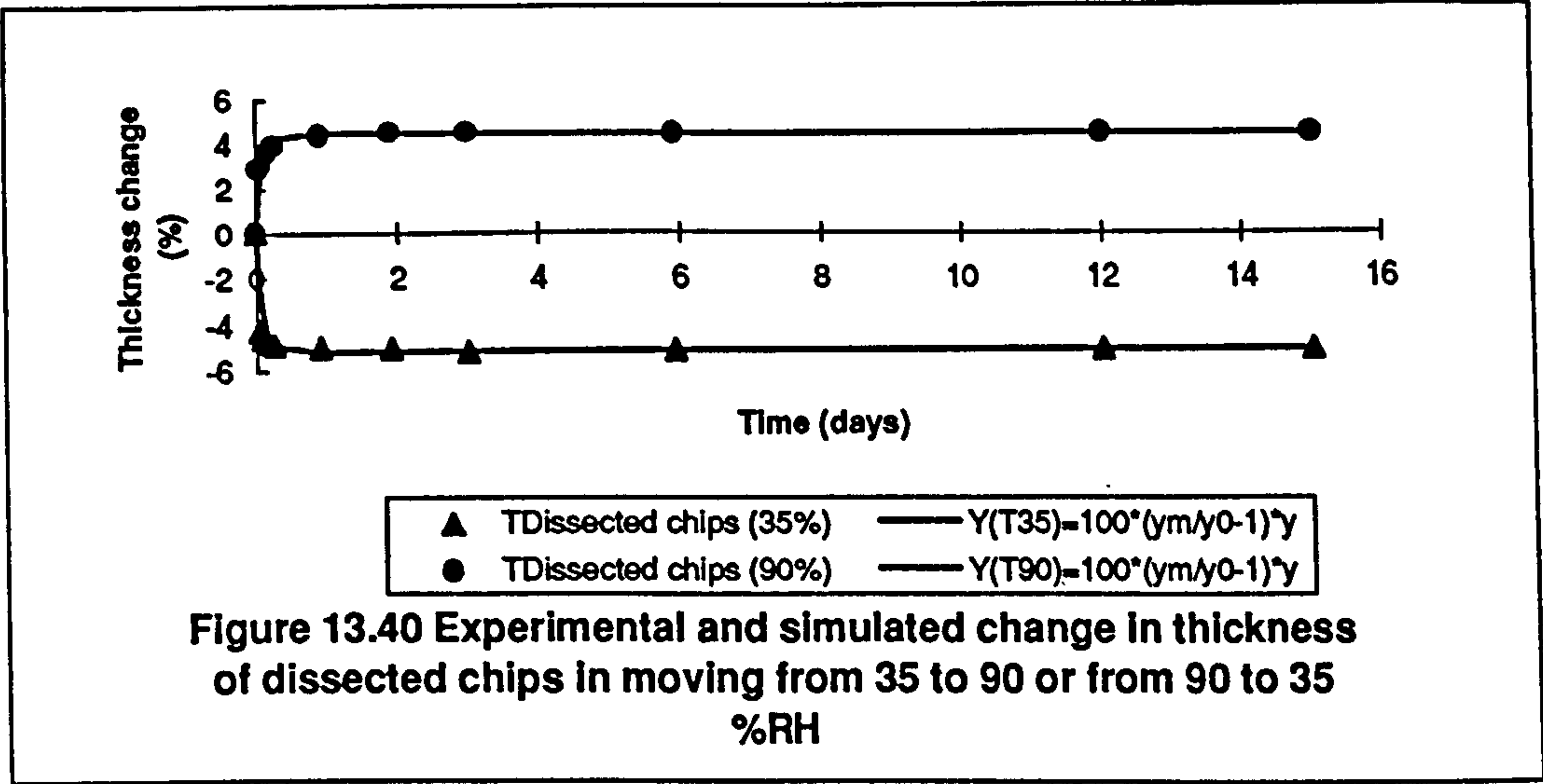
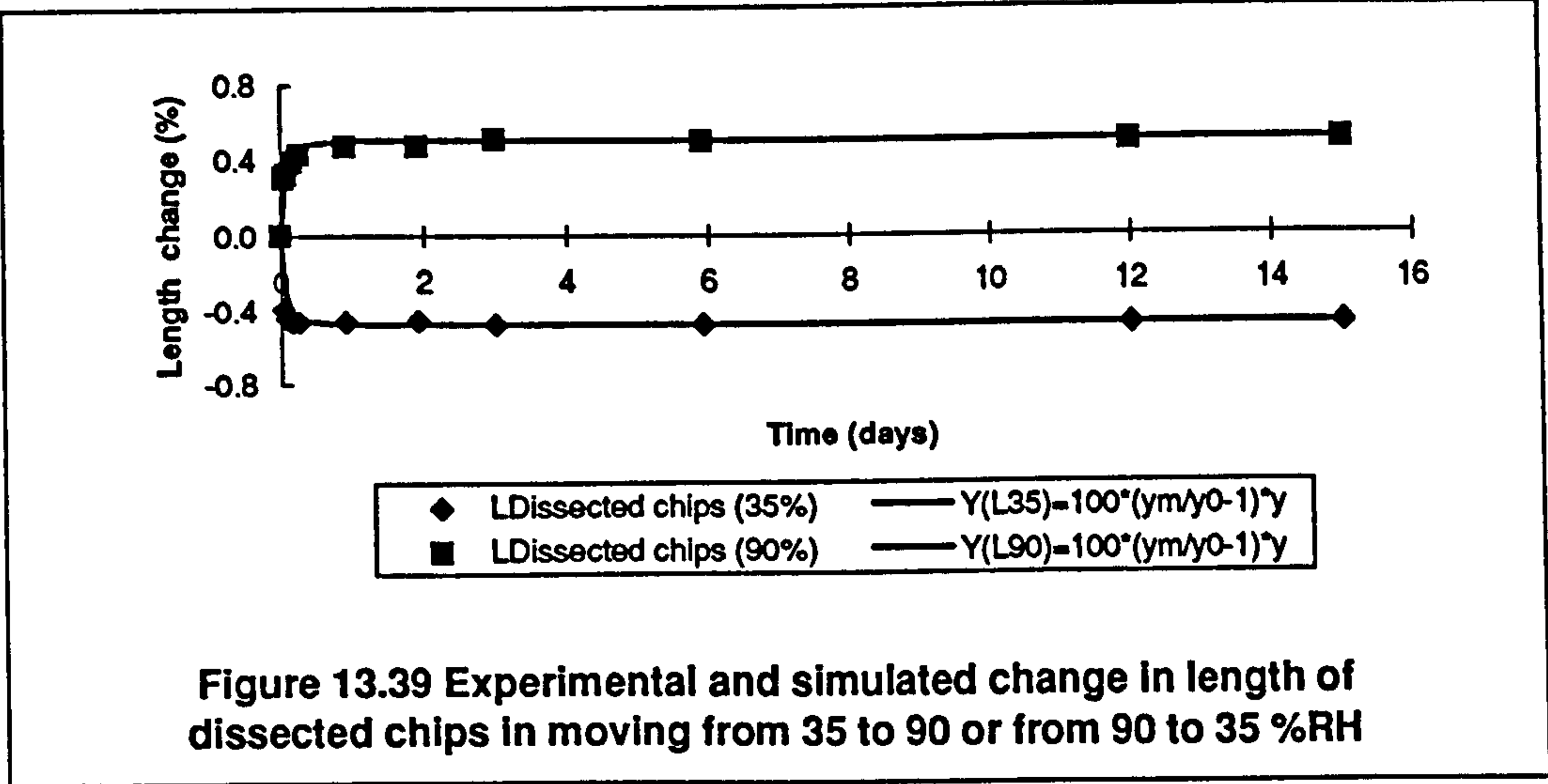
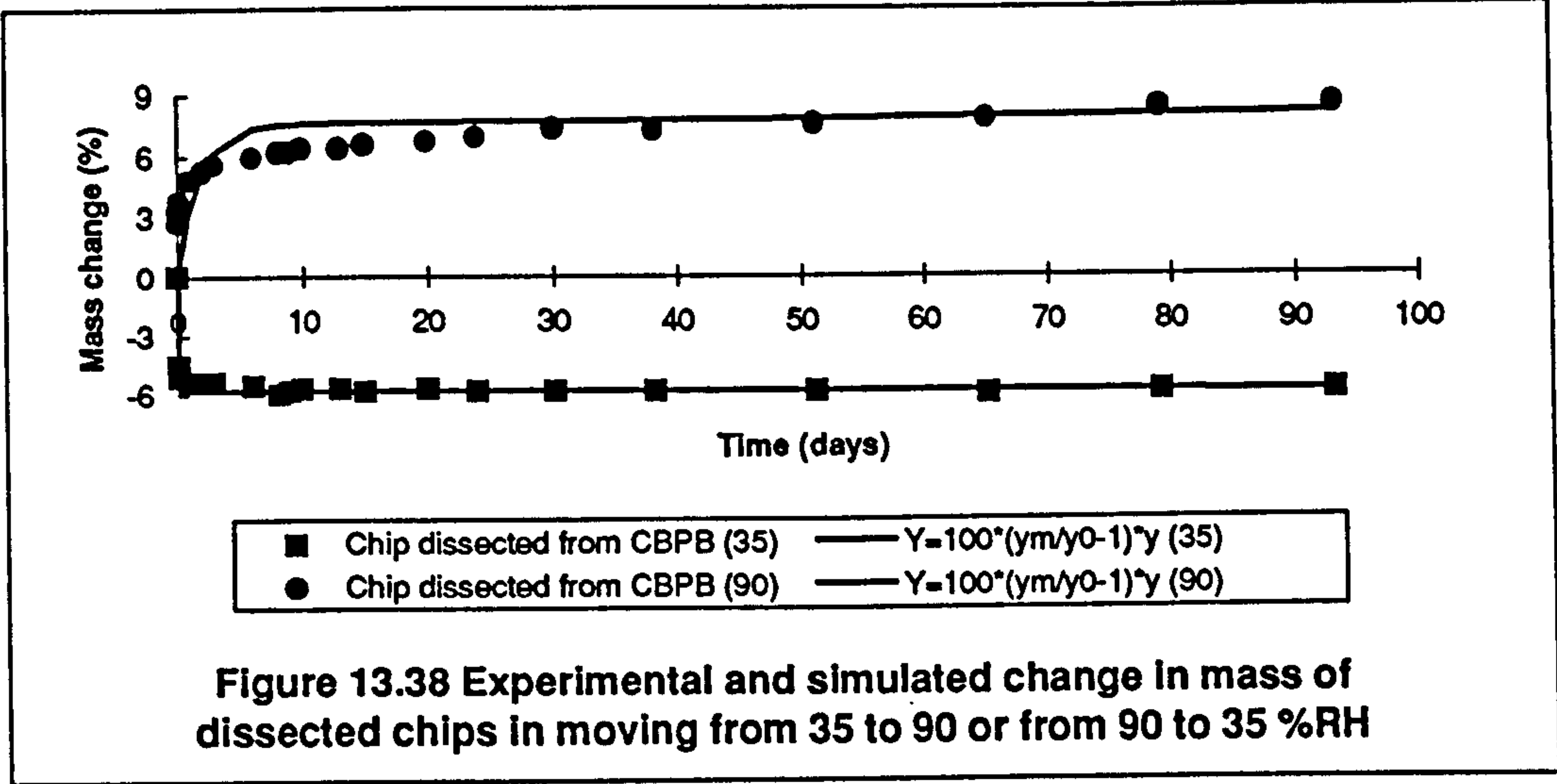
Figure 13.23 Prediction and individual fits of change in thickness of 12 mm CBPB against number of cycle (cycle: 90-65-35-65-90%RH)











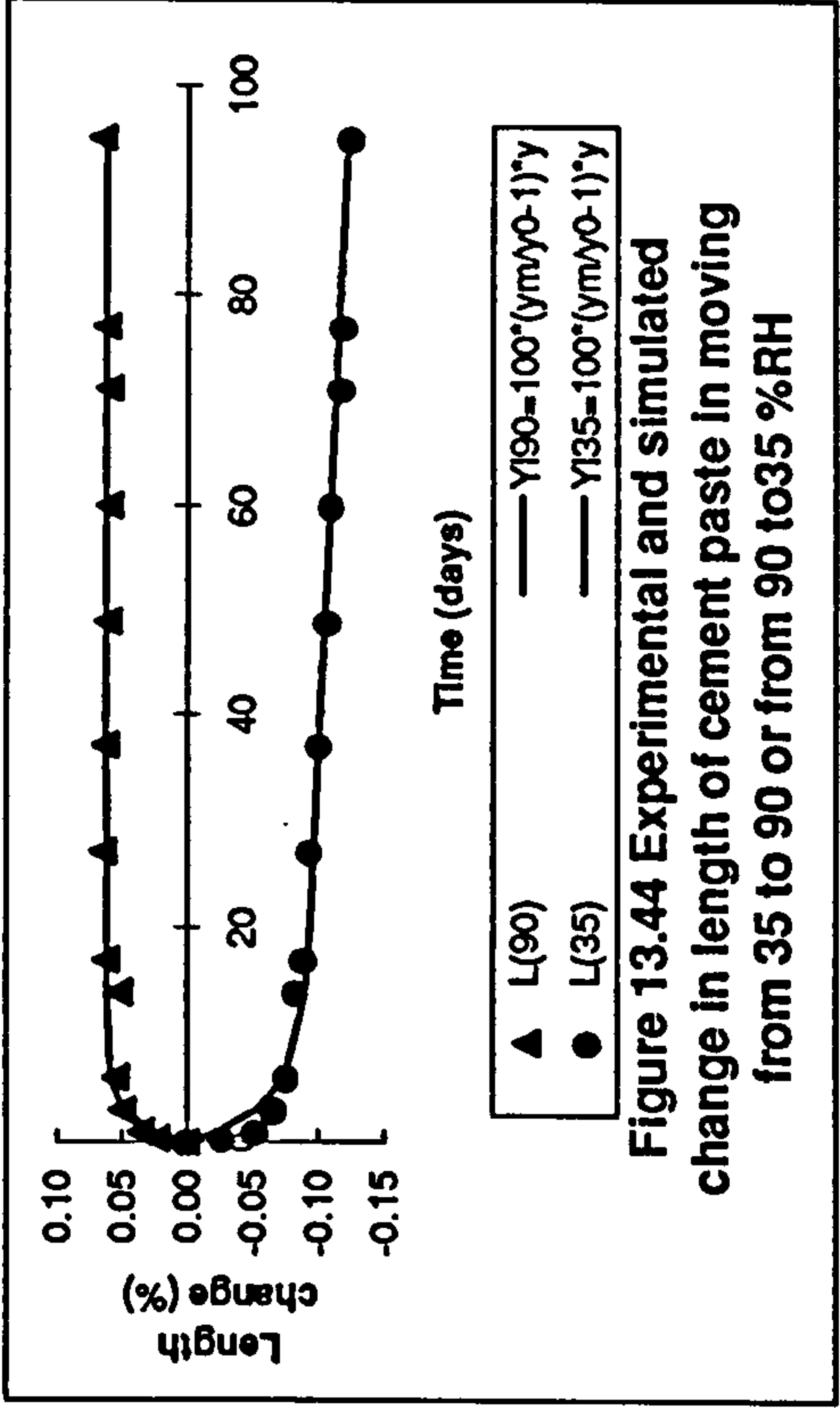
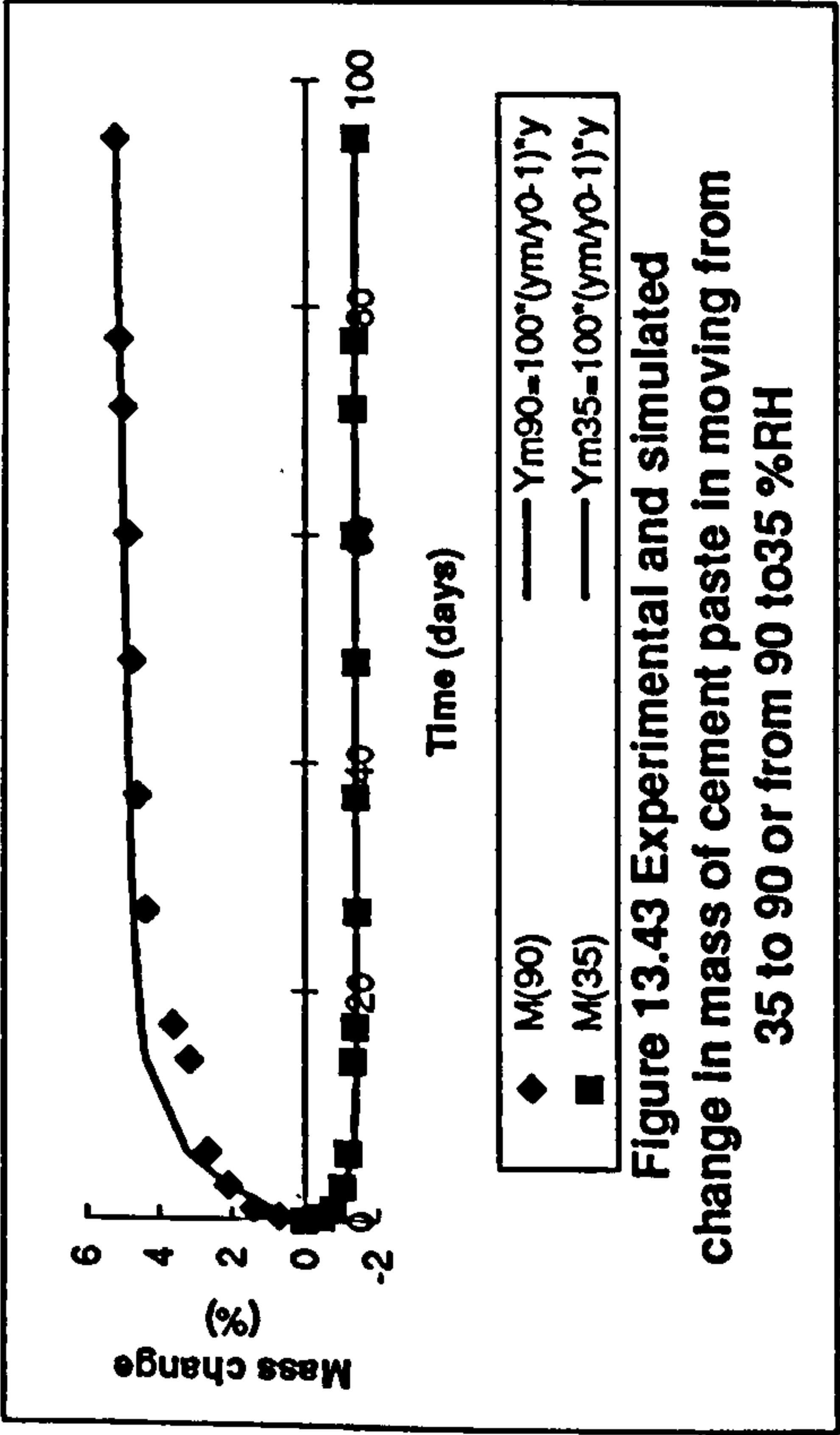
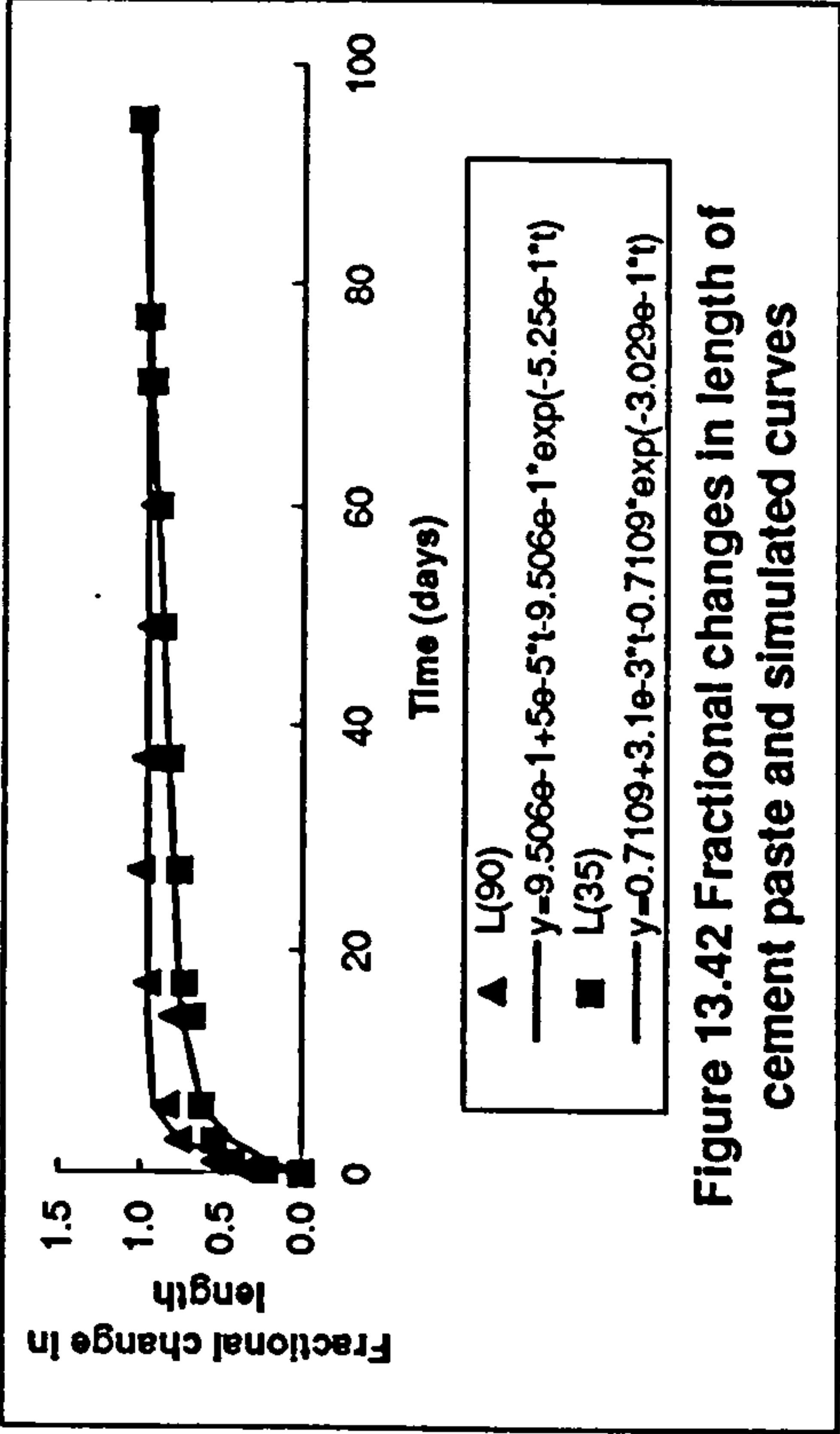
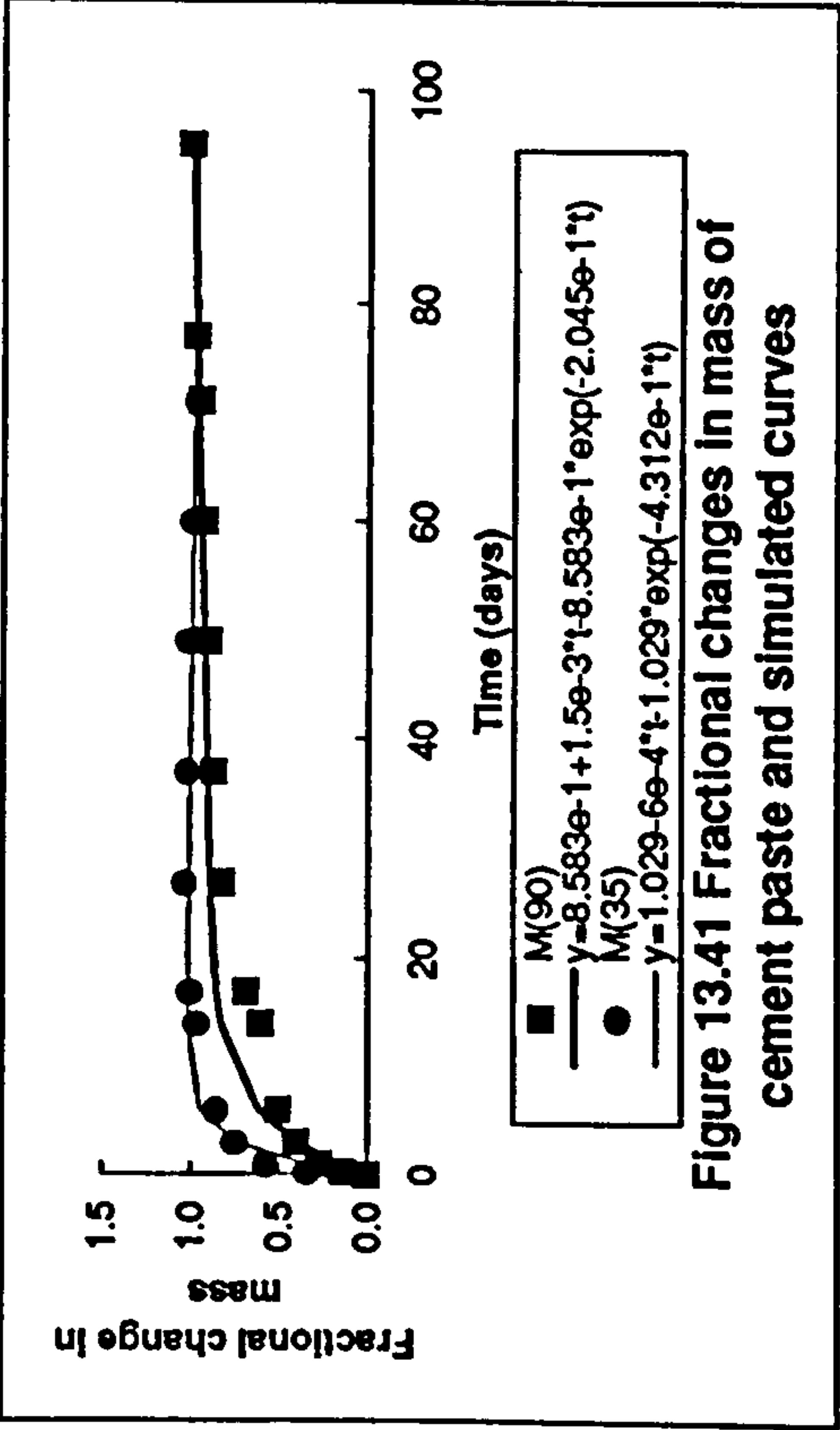


Table 13.1 R² and coefficients of model for change at constant 65 %RH

Model	y = ax + b			Y = AX ² + BX + C			
Change in	a	b	R ²	a	b	c	R ²
Laboratory cement paste							
Mass	0.0083	0.0794	0.97	-4.00E-05	0.0122	0.0256	0.99
Length	-0.0002	-0.0001	0.97	6.00E-07	-0.0002	0.0006	0.98
CBPB							
Mass	0.0047	0.1424	0.99	-3.00E-06	0.0058	0.0771	1.00
Length	-0.0001	-0.0070	0.97	1.00E-07	-0.0001	-0.0045	0.99
Thickness	-0.0005	-0.0157	0.98	4.00E-07	-0.0007	-0.0061	0.99

Table 13.2 Final / initial change values and R² (model fitting in single change humidity)

Regime	M _f / M _i	R ²	L _f / L _i	R ²	T _f / T _i	R ²
	Mass		Length		Thickness	
90-35	0.971454	0.97	0.997995	0.97	0.994132	0.97
35-90	1.063766	0.99	1.001657	0.94	1.004969	0.97
65-35	0.984895	0.99	0.998681	0.94	0.996243	0.94
65-90	1.049008	0.99	1.000777	0.96	1.002522	0.99

Note: Y (%) = 100(Y_f / Y_i - 1) E

$E_{w3} = 1.0016 - 1 \times 10^{-4}t - 1.0016 \exp(-1.258 \times 10^{-1}t)$

$E_{w9} = 6.157 \times 10^{-1} + 1 \times 10^{-3}t - 6.157 \times 10^{-1} \exp(-6.196 \times 10^{-2}t)$

$E_d = 9.005 \times 10^{-1} + 3 \times 10^{-4}t - 9.005 \times 10^{-1} \exp(-1.078 \times 10^{-1}t)$

Table 13.3 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 humidity to that; d desorption from higher humidity to that.

Table 13.4 R² and coefficients of fractional change of dissected chip and cement paste, and ratio of final to initial change values

Model		E = A + Bt - Aexp(Ct)			
Change in	RH	A	B	C	R ²
Laboratory cement paste					
Mass	35 - 90	0.8583	1.50E-03	-0.2045	0.90
Mass	90 - 35	1.0290	-6.00E-04	-0.4312	0.92
Length	35 - 90	0.9506	-5.00E-05	-0.5250	0.95
Length	90 - 35	0.7109	3.10E-03	-0.3029	0.96
Dissected wood chips					
Mass	35 - 90	0.8552	5.00E-04	0.5955	0.86
Mass	90 - 35	0.9963	5.00E-05	-13.0620	0.92
Dimension		0.9982	7.00E-05	-12.0200	0.96
Ratio of final to initial change values					
Regime	M _f / M _i	L _f / L _i	T _f / T _i		
Dissected chip					
90-35	0.927954	0.995227	0.948195		
35-90	1.088477	1.005002	1.044710		
Laboratory cement paste					
90-35	0.986004	0.99879			
35-90	1.052764	1.000651			

Chapter 14

SEM AND IMAGE ANALYSIS

14.1 Introduction

The properties of CBPB are dependent on the network of wood chips, cement paste and void spaces which are created by the interaction of the raw materials and mat formation parameters. The forms of the voids, cement paste and wood chips in the mat will significantly affect mass transfer and consequentially result in different movement of CBPB in different directions in response to external forces. It is believed that such features will have an influence on the validity of the application of the theory of mixtures to CBPB.

Very little work has been done on wood composites to characterise the network structure of the mat. Only a related topic, the density distribution within the composite has been the subject of significant inquiry. Suchsland (1959, 1962) was perhaps the first to investigate the horizontal density distribution in wood composite and determined that flake geometry would affect the structure of a mat. This investigation was continued to develop a model for the simulation of the horizontal density distribution in flake board (Suchsland and Xu, 1989 and 1991) and examined its relationship with properties of products. Both internal bond and thickness swelling of flakeboard were found to be directly affected by the horizontal density distribution. More recently a probability - based model was developed to describe a randomly packed, short fibre type wood composite (Dai and Steiner, 1994). It was concluded that the expected structural properties of a random flake layer can be adequately modeled from average flake length and width, total flake number and total layer area. Most recently the feature of voids in flakeboard has been investigated by Lenth and Kamke (1996) who examined the relationship between the occurrence of voids and the method of mat formation and the direction of flake orientation.

The purpose of this research is to characterize the structure of the CBPB mat with the objective of modelling the dimensional changes using the theory of

mixtures. A method for observing the gross structure of CBPB mat was developed using computer image analysis techniques to quantify the parameters necessary to define the structure. The result of this research will be used specifically to support information when modelling the stress - strain behaviour of CBPB, one of which is internal stresses. This will be discussed in the subsequent chapter on "Modelling CBPB as a composite" by using the theory of mixtures. However, the information provided should have very valuable implications for other areas of wood - based composite research.

14.2 Image Processing and Measurement

Samples of CBPB were vacuum impregnated with resin to provide strength and to fill any air pores with an electron - opaque medium so that they could be polished.

Backscattered electron images were made at the minimum magnification (x9) with the sample normal to the electron beam (i.e. there is no distortion due to foreshortening). The images were processed by smoothing with a 4 : 2 : 1 filter. This was done in order to remove any spurious high and low brightness pixels that would otherwise make image stretching inconsistent. After this the images were "stretched" so that the lowest grey level corresponded to a pixel brightness of 0 and the highest grey level corresponded to 255. This ensures that as far as possible all the images are rendered to a standard contrast range. These processed images were then analyzed in terms of their greyscale.

Two grey levels were used in this analysis. The lowest grey level, g_1 , corresponds to regions that contain only the encapsulating resin used in the preparation of the thin samples; the upper grey level, g_2 , corresponds to the wood particles. Since the wood particles can absorb varying amounts of the resin and the resin density and thickness can vary, g_1 and g_2 each span a range of grey levels. The picture is further complicated by the fact that the wood particles can be so heavily impregnated with resin that they are imaged at the same grey scale as true pores. So that these regions are not incorrectly identified by the software as air pores, regions are only labelled as air pores if they contain less than one region with a grey level greater than g_1 . These criteria (grey level, pore numbers) were arrived at by using

two independent assessors examining a number of images.

The classification used is thus:

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

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

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

These regions are further classified according to their sizes (area): size 0 being an area of wood chips from 0 to 1 mm², size 1 being from 1 to 2 mm² and so on, up to size 10 which are those having an area greater than 10 mm². For each object in each image the following parameters of interest were logged to a data file for each of the objects measured: Feature number, Area, Position using (x and y coordinates), Threshold number, Number of pixels/pix, Feature length, Feature breadth, Orientation, Perimeter, Area (no holes), Number of holes, Ellipse minor, Elongation 1, Elongation 2, Aspect ratio, Convex circularity, Circularity, Form factor, Hole area, Convexity, Field area, Number detected, Number of interest, Field number and Class name. According to the feature of interest on the image analysis, the specific parameters measured were further processed. These included: Area, Feature length, Feature breadth, Orientation, Perimeter, Ellipse minor, Aspect ratio, Form factor, Convexity, Field area and Class name.

The results are the sum of the examinations of five fields of view for each sample, with each view having an area of 82.64 mm², i.e. 5 x 82.64 mm².

An example of original image data for a vertical and a horizontal surface layers was included in Appendix III.

14.3 Percent Mat Area Occupied by Components

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

horizontal surfaces were examined. The results (mean values) are presented in Table 14.1.

Vertical surface

In a total area of 413.2 mm² (five views each having an image field of 82.64 mm²) on average about 42 % of side faces is occupied by wood chips and 58 % is occupied by cement paste. The detectable voids, due to air embedded during manufacture, is less than 1 %.

In Table 14.1 it appears that the total area occupied by the three components (wood chips, voids and cement paste) are similar between three samples. The one way ANOVA procedure determined that no significant difference existed between the three side faces for all the items evaluated. This fact (which actually covers all parameters measured) also verifies the accuracy of sampling and view selection for image processing.

Horizontal surface

Regarding the horizontal surface, the features of wood chips are different between layers, and this will be discussed in a following section. This section focuses on the mean / total values related to the three components. It was calculated that about 62 % area of the horizontal surface is occupied by cement paste and about 38 % occupied by wood chips. As for the vertical surface, less than 1 % area is occupied by pores.

The total percent area occupied by the three components is different between the layers. The area occupied by pore is largest in horizontal layer L3 (see section 3.6 for symbol representation). Lower values were detected in the layers near surface and at the core of CBPB. In Layer L1, detectable pore was not found in all five views. This suggests that certain sizes of wood chips, together with a certain ratio of wood chips to cement paste, may produce a most compacted CBPB.

The area occupied by wood chips increased from the surface layer to the core layer, with an exception of layer L2. About 34 % of the area is occupied by wood

chips in layer L0 compared to about 49 % in layer L5. This result is in agreement with the mechanism of mat forming used in the manufacture of CBPB.

A comparison of values between the vertical and horizontal surfaces shows that the mean percent area of wood chips is higher in the vertical than in the horizontal, while the mean percent area of cement paste is lower in the vertical than in the horizontal surface. However, a scrutiny of data indicates that the horizontal surfaces near the core contain a higher percent area of wood chips.

The higher value of the mean percent area occupied by wood chips in the vertical surface may be partly responsible for the greater change in thickness effect of CBPB.

From the mean percent areas in both the vertical and horizontal surfaces it appears that only about 40 % of the surface area is occupied by wood chips. This greatly deviates from the value fraction of raw materials used in the manufacture of CBPB (which is about 75 % by volume of wood chips and 25 % of cement paste). The result may be attributable to the significant difference in the stiffness of cement paste and wood chips, resulting in a compression in wood chips in CBPB. The fact that the compression of wood chips occurs in CBPB can also be verified by analysing the commercial CBPB products. For example, with the sample of 4258.7 g, the dimensions are 579.2 x 290.6 x 17.86 mm and the calculated volumes are about 2.99×10^{-3} , 3.81×10^{-3} and $1.42 \times 10^{-3} \text{ mm}^3$ for CBPB, wood chips and cement paste respectively. The total value $5.23 \times 10^{-3} \text{ mm}^3$ of the wood chips and cement paste is obviously much higher than the value of CBPB (2.99×10^{-3}).

This result indicates that the much higher change in the length of dissected chips was due to stress relief (chapter 9).

14.4 Orientation of Components and Voids

Due to anisotropy the orientation of wood chips is thought to be a vital factor affecting the dimensional change of CBPB. This investigation enables the examination of whether the change of CBPB length and width is identical, and whether changes between thickness and width are significantly different. Also the results are used in the evaluation of changes by applying the rule of mixtures (see following chapter).

Vertical surface

The same results were obtained for all 3 side faces of CBPB (Figure 14.1). As expected almost all chips lie flat in CBPB (Table 14.2). An area of 36 - 45 % of the total wood chips lie at an angle of 0 - 10 ° and 20 - 22 % at an angle of 171 - 180 °.

In considering the effect of the orientation of wood chips on the thickness and length changes, chips with the same effect were summed. It was found that about 90 % of wood chips lie with an angle 0 - 20°. Very few wood chips are placed with an angle of 41 - 90 ° (only about 2 %).

The mean angle was calculated based on the occupied area of wood chip. This was 11.51°, 11.27° and 10.53 ° respectively for samples T1, T2 and T3. Therefore the mean angle for the three samples is about 11.1 °.

Horizontal surface

Unlike the orientation on the side faces, the wood chips are distributed randomly on the horizontal surfaces (Figures 14.2 and 14.3, Table 14.2), whether in total area or frequency. The mean angles (based on the fractional area for each chip) were calculated, Table 14.3.

Table 14.3 Mean and effective angles of wood chips on the horizontal surfaces (°)

Layer	Mean angle	Effective angle
L0	86.53	44.46
L1	90.42	48.91
L2	86.07	38.93
L3	76.62	42.92
L4	92.64	47.31
L5	78.94	46.00

From Table 14.3, the mean angle is seen to range from about 77° to 93° . However the effective angle is about 45° (excepting for layer L1). This indicates that the effect of orientation of wood chip in the length and width directions is theoretically the same. This coincides with the design of manufacture of CBPB.

14.5 The Size and Shape of Components in CBPB

The structure of CBPB principally depends on the components (including voids) and the size of each component including the length, width, perimeter and shape. The total area occupied by each component and the orientation of the wood chips has been discussed in previous sections. Further evaluation was carried out in order to obtain a better concept of the structure of commercial CBPB. The summaries of statistics for the dimensions and area of individual components are presented in Tables 14.4 - 14.7, Figures 14.4 and 14.5. The summaries of statistics for shape factors are shown in Tables 14.5 and 14.8, and Figure 14.6.

14.5.1 Size of Components

Pore

Table 14.3 shows extreme variability in the length, width, perimeter or area of pore, with the most significant variability being for the area of pore. However, the degree of variabilities for the parameters are very similar for various layers.

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

A comparison of the mean values in the horizontal face with that in the vertical surface shows that the mean values of all parameters measured in the vertical surface

were similar to those in the horizontal surfaces, Tables 14.4 and 14.5.

Dark wood and wood chips

"Dark wood" is designed as the pores in wood chips. The total area of wood chips should include both the measured areas of dark wood and wood chips. The measurement (Table 14.7) shows very low values for the area detected as the dark wood (except for L3), thus the discussion concentrates on the wood chips.

As for the size of pores, the variability in the size of wood chips is significant, especially for the wood chips with areas ranging between 0 - 1 mm². Hence, for the same size class of wood chips, the mean values were different within the six layers. There was a tendency for the lower mean values to be in the surface and core layers. For the same class of wood chips, a one way ANOVA model determined that significant differences in the perimeter of wood chips existed only in those with an area of 0 - 1 mm², 1 - 2 mm² and 3 - 4 mm². There was no significant between all other parameters measured among layers.

In addition to the different sizes within various layers, the percent area represented by the various size classes of wood chips changes with layers (Tables 14.5 and 14.6). It should be noted that the results for the three vertical surfaces are very close, the ANOVA test confirming no significant differences.

A typical histogram has been reproduced to show the distribution of the area of wood chip with different layers (Figure 14.4). This illustrates the percent of total observed horizontal area occupied by wood chips as a function of wood size for the six layers examined, and a comparison of the values for the horizontal and vertical surfaces. It appears that the percent area is fairly evenly distributed for the size class 0 - 4 mm² among layers, with an exception of layers L3, which may be due to the wood being detected as "dark wood", resulting in a high percent value of the area occupied by the dark wood. For the largest (≥ 5 mm²) and smallest (0 - 1 mm²) size of wood chips there were very marked differences of percent area occupied between the layers. This visually confirms the general concept that wood chip size gradually increases from the surface to core layer in graduated particleboard. The size class of 0 - 1 mm² comprised about 45 % of the total area of 34 % of wood chips in the

horizontal surface for layer L0 compared to 35 % of the total area of 49 % of wood chips for the layer L5, while the size class of $\geq 5 \text{ mm}^2$ only occupied 14 % for L0 compared to 32 % for L5.

A comparison of values in Table 14.4 with those in Table 14.5 shows a difference in size between horizontal and vertical surfaces. The mean values calculated from both horizontal and vertical surfaces are illustrated in Figure 14.5. It is interesting that the mean length was very similar for the wood chips in the horizontal and vertical surfaces. However, the breadth, perimeter and area were greater for chips in the horizontal surfaces than in vertical surfaces. These results agree with the general concept of the structure of particleboard and the dimensions of wood chips.

14.5.2 Shape of Components

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

$$\text{Form factor} = \frac{4 \cdot \pi \cdot \text{area}}{\text{perimeter}^2}$$

Another important factor is the aspect ratio:

$$\text{Aspect ratio} = \frac{\text{length}}{\text{breadth}}$$

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

An axis of minor ellipse is:

$$\frac{4.area}{\pi.length}$$

and circularity is:

$$\frac{perimeter}{2.\sqrt{\pi.area}}$$

Circularity = 1 for a disk.

In Table 14.8, the one way ANOVA was carried out to compare the average shape factors for the six layers. The results show that there were significant differences in the average shape factors of pores among horizontal surfaces.

For wood chips, the degree of significance varied with the size class of wood chips. After a scrutiny of a number of wood chips found in each horizontal surface, it can be concluded that there was a significant difference for the average shape factor of wood chips. The average form factors for both surface and core layers were greater than those for intermediate layer(s). For wood chips with an area of 0 - 1 mm², it was 0.32 for layers L0 and L5 compared to 0.23 and 0.24 for layer L3 and L2 respectively. Conversely for the aspect ratio, the higher values occurred in intermediate layers with lower values in the surface and core layers. The results indicate that relatively shorter and smoother edged wood chips were placed in the surface and core layers of CBPB.

A comparison of average form factors in horizontal surfaces with those of vertical surfaces shows that the form factors were similar between the two surfaces but the aspect ratios were very different (Table 14.5 and Figure 14.6). This illustrates that the shape of wood chips is long, wide and thin.

14.6 Interim Conclusions 10

1) A technique for quantifying the structure of CBPB has been presented which has proved to be efficient and effective. Images of both vertical and horizontal surfaces were obtained and the structural parameters, including the percent area occupied by void, cement paste and the various orientations of wood chips, the orientation

(distribution) of individual components, the size and shape of individual components, were quantified.

2) In the horizontal surface, there was a significant difference in the percent area occupied by voids among the six layers, with a lower percent area for surface and core layers compared to intermediate layers. However, the total values of detectable voids was less than 1 % of the total surface area (five views of each image field 82.64 mm² for each samples). A similar result was obtained for the vertical surfaces.

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

4) The percent area occupied by wood chips was different among layers: the values increased from surface to core layer (from 34 % to 49 %), excepting for the layer L2. This was in agreement with the mechanism of mat forming in the manufacture of CBPB.

5) The mean percent area occupied by cement paste was higher in the horizontal surface than in the vertical surface.

6) Overall, the mean percent area occupied by wood chips is only about 40 %, which is much lower than the volume fraction for raw materials in the manufacture of CBPB (about 75 %). This indicated that the wood chips in CBPB are highly compressed. Obviously, the much higher change in the length of CBPB discussed in chapter 9 was due to the stress relief.

7) In the vertical surface, wood chips nearly all lie flat. The distributions of orientation (separated into 18 classes) showed that an area of 36 - 45 % of wood chips lie at an angle of 0 - 10° and 20 - 22 % at an angle of 171° - 180°. The average orientation of wood chips, based on the area fraction of individual wood chips, is 11.1°.

8) In the horizontal surface, the wood chips are randomly distributed (with regard to either total area or frequency). The effective mean angle was about 45° , confirming that the effect of wood chip on the length and width change is the same.

9) The average size of pore was not significantly different among horizontal layers, being about 0.52 - 0.69 mm in length and half this for width. This shows the distribution of pore size was fairly uniform. The size of pore detected in the vertical surface was similar to that in horizontal surfaces.

10) The size of wood chips was different between the six layers, there was a tendency of change in the mean values of the same size class of wood chip between layers, being a lower value in the surface and core layers.

11) The percent area occupied by various classes of wood chips was different between different layers, increasing from surface to the core layer for the percent area occupied by larger wood chips. A very marked difference existed for the largest ($\geq 5 \text{ mm}^2$) and smallest ($0 - 1 \text{ mm}^2$) wood chips.

12) Compared to those in horizontal surface, the percent area is much higher for the smallest wood chips ($0 - 1 \text{ mm}^2$) in the vertical surface but much lower for the largest wood chips ($\geq 5 \text{ mm}^2$). The mean length of each size class of wood chips was very close, but the width, perimeter and area are lower. This illustrated the placement of wood chip in CBPB.

13) There were significant differences in the shape factors of pores between horizontal layers.

14) The shape factors for wood chips were significantly different between the horizontal layers. The average form factors for both surface and core layers were greater than those for intermediate layer(s), and the converse for the aspect ratio, indicating that relatively shorter and smoother (edged) wood chips were placed in the surface and core layer of CBPB.

15) The mean form factors were similar but aspect ratios were much higher in vertical surfaces than in horizontal surfaces, illustrating the feature of wood chips being long, wide and thin in three dimensions.

16) The findings of image analysis indicate that both sampling and view selection were representative and appropriate. The results: -

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

Table 14.1 Total / mean area occupied by components of CBPB on vertical and horizontal surfaces

Surface	T1	T2	T3	T-mean	L0	L1	L2	L3	L4	L5	L-mean
Number of View	5	5	5	5	5	5	5	5	5	5	5
Total area observed	413.2	413.2	413.2	413.2	413.2	413.2	413.2	413.2	413.2	413.2	413.2
Pore											
Number of object	51	20	55	42	6	47	44	29	31	26	
Area (mm2)	2.90	0.96	3.99	2.62	0.29	2.99	3.85	2.10	1.86	1.85	
% of total area	0.70	0.23	0.97	0.63	0.07	0.72	0.93	0.51	0.45	0.45	
COV (%)	41.47										36.03
Wood chips											
Number of object	465	548	567	527	353	335	298	349	329	424	348
Area (mm2)	163.58	183.39	170.67	172.55	141.61	144.34	122.02	162.18	168.23	203.56	156.99
% of total area	39.59	44.38	41.30	41.76	34.27	34.93	29.53	39.25	40.71	49.26	37.99
COV (%)	4.11										8.00
Cement paste											
Area (mm2)	246.72	228.85	238.54	238.04	271.30	268.86	288.19	247.17	242.87	207.78	254.36
% of total area	59.71	55.38	57.73	57.61	65.66	65.07	69.75	59.82	58.78	50.29	61.56
COV (%)	2.66										4.97

Table 14.2 Percent area occupied by wood chip under various angle classes in horizontal and vertical surfaces

Angle (°)	L0 (%)	L1 (%)	L2 (%)	L3 (%)	L4 (%)	L5 (%)	T1 (%)	T2 (%)	T3 (%)	T-mean (%)
0--10	6.40	4.99	13.05	10.18	2.85	9.68	35.80	37.34	44.68	39.27
11--20	4.46	5.83	9.80	10.08	1.84	6.03	12.32	16.97	10.55	13.28
21-30	3.19	3.06	3.72	2.95	6.33	4.25	2.26	1.79	5.52	3.19
31-40	11.19	3.82	3.28	7.25	3.91	2.52	2.60	0.93	1.61	1.72
41-50	6.75	3.44	4.34	11.28	10.32	9.93	0.19	0.76	0.16	0.37
51-60	5.36	10.75	1.53	9.06	8.13	8.58	0.18	0.52	0.20	0.30
61-70	8.36	5.87	5.15	6.39	1.90	7.79	0.00	0.21	0.05	0.08
71--80	2.77	6.88	5.04	2.02	11.12	4.05	0.00	0.36	0.13	0.16
81--90	4.76	2.07	7.97	4.42	6.49	4.81	0.18	0.11	0.00	0.10
91-100	2.68	11.83	3.35	4.31	3.63	1.58	0.09	0.00	0.02	0.04
101-110	5.89	3.81	3.32	3.39	1.06	15.95	0.14	0.02	0.03	0.07
111-120	2.30	6.88	3.66	3.49	4.38	3.95	0.15	0.15	0.05	0.12
121-130	6.60	4.74	5.20	3.19	8.79	1.38	0.08	0.13	0.11	0.10
131-140	15.33	5.50	3.42	11.71	10.02	5.13	0.82	0.55	0.81	0.73
141-150	2.05	8.74	4.27	3.44	6.02	2.72	1.65	1.76	1.50	1.63
151-160	2.78	5.38	6.84	4.04	2.50	2.83	4.21	3.21	3.04	3.49
161-170	5.91	3.28	14.72	2.09	7.44	6.88	17.68	13.65	11.02	14.11
171-180	3.23	3.13	1.36	0.71	3.26	1.94	21.65	21.56	20.54	21.25
Total	100	100	100	100	100	100	100	100	100	100

Table 14.4 Size of pores and wood chips in six horizontal layers making up the thickness of CBPB

Length (mm)				Breadth (mm)				Perimeter (mm)				Area (mm ²)				
Groups	Mean	Max.	Min.	COV (%)	Mean	Max.	Min.	COV (%)	Mean	Max.	Min.	COV (%)	Mean	Max.	Min.	COV (%)
Pore (0-1 mm ²)																
L0	0.62	0.86	0.48	24.46	0.23	0.39	0.17	37.77	2.04	2.85	1.24	27.83	0.05	0.07	0.03	35.64
L2	0.52	1.11	0.31	31.87	0.27	0.53	0.11	31.84	1.75	3.87	0.88	40.23	0.06	0.20	0.03	57.75
L3	0.69	2.25	0.36	49.61	0.27	0.61	0.14	42.68	1.99	5.49	1.09	46.91	0.09	0.37	0.03	82.35
L4	0.57	1.28	0.34	38.83	0.29	0.51	0.19	36.85	1.95	6.71	1.05	58.80	0.07	0.22	0.03	80.50
L5	0.60	1.10	0.33	32.09	0.25	0.65	0.09	46.05	1.92	3.98	1.12	36.12	0.06	0.19	0.03	63.90
p	>0.05				>0.05				>0.05				>0.05			
Dark wood (0-1 mm ²)																
L0	0.55	0.75	0.34	38.79	0.27	0.44	0.20	42.23	2.31	4.04	1.16	59.67	0.06	0.09	0.03	55.68
L2	0.90	3.41	0.31	59.65	0.40	1.00	0.17	48.77	4.03	20.68	0.95	87.02	0.18	1.05	0.04	122.49
L3	1.46	5.14	0.54	82.85	0.60	2.07	0.18	75.75	5.38	28.77	1.21	102.70	0.71	5.52	0.05	176.10
L4	0.98	2.90	0.33	57.35	0.45	1.17	0.12	55.63	4.75	26.77	0.92	105.03	0.22	1.40	0.03	127.01
L5	0.79	2.54	0.31	59.17	0.39	1.46	0.17	57.03	3.46	19.71	1.06	92.15	0.16	1.85	0.03	186.13
p	<0.01				<0.01				>0.05				<0.01			

Length (mm)			Breadth (mm)			Perimeter (mm)			Area (mm ²)							
Layer	Mean	Max.	Min.	COV (%)	Mean	Max.	Min.	COV (%)	Mean	Max.	Min.	COV (%)				
Wood (0-1 mm ²)																
L0	0.89	4.03	0.30	59.64	0.38	1.32	0.11	56.06	2.74	14.14	0.91	70.15	0.20	1.05	0.03	106.44
L1	0.85	2.94	0.27	57.17	0.40	1.34	0.12	55.09	2.59	8.71	0.85	62.08	0.21	0.98	0.03	104.60
L2	0.93	3.31	0.30	61.18	0.41	1.23	0.12	61.73	3.42	16.26	0.86	80.30	0.22	1.06	0.03	111.99
L3	0.92	3.23	0.31	55.62	0.37	1.09	0.12	55.42	3.03	10.87	0.85	59.82	0.17	1.03	0.03	110.25
L4	0.90	3.64	0.25	58.08	0.40	1.34	0.12	55.93	2.98	11.63	0.83	66.37	0.21	0.97	0.03	105.40
L5	0.87	2.68	0.29	63.05	0.39	1.25	0.13	58.52	2.79	10.43	0.81	72.47	0.20	0.95	0.03	115.07
p	>0.05			>0.05			<0.01			>0.05						

Wood (1-2 mm ²)																
L0	2.66	4.43	1.73	26.20	1.13	1.69	0.60	26.66	9.70	15.16	5.79	31.15	1.35	1.86	1.02	20.45
L1	2.63	4.94	1.59	32.01	1.02	1.58	0.57	23.59	8.19	13.91	5.26	24.91	1.35	1.97	1.01	18.92
L2	3.26	4.98	2.19	27.80	1.03	1.37	0.82	18.07	12.50	18.31	8.30	23.06	1.57	2.41	1.14	25.58
L3	3.06	4.45	1.69	33.42	0.91	1.37	0.62	30.14	9.42	12.63	5.69	29.23	1.49	2.03	1.04	25.02
L4	2.66	3.75	1.76	23.91	1.22	1.73	0.62	27.00	10.67	16.88	6.22	31.97	1.51	2.00	1.08	18.43
L5	2.76	4.89	1.85	26.20	1.08	1.58	0.68	23.47	9.10	17.64	6.26	28.46	1.46	1.94	1.02	20.40
p	>0.05			>0.05			<0.01			>0.05						

Wood (2-3 mm ²)																
L0	3.62	5.10	2.95	20.26	1.53	1.98	1.31	18.97	13.24	17.23	10.65	20.88	2.56	2.96	2.13	12.62
L1	3.92	4.76	3.20	17.92	1.46	1.79	1.24	16.84	14.52	16.06	11.29	15.46	2.37	2.87	2.10	14.87

L2	3.25	3.61	2.78	10.25	1.58	1.78	1.44	9.50	17.28	22.87	12.30	25.90	2.77	3.45	2.15	21.21
L3	3.84	5.89	2.42	32.92	1.41	1.83	0.93	28.43	14.54	24.33	9.62	39.43	2.52	2.87	2.14	11.38
L4	3.71	5.00	2.50	26.45	1.41	2.29	0.72	35.68	12.36	17.16	8.51	24.92	2.55	3.58	2.16	18.42
L5	3.74	5.40	2.32	27.91	1.52	2.50	0.96	35.61	16.85	31.82	11.16	41.77	2.59	2.94	2.05	11.95
p	>0.05				>0.05				>0.05				>0.05			
Wood (3-4 mm²)																
L0	3.66	4.72	3.05	17.13	1.96	2.66	1.53	22.43	14.89	19.05	11.24	23.36	3.62	3.94	3.25	10.89
L1	3.97	5.84	2.80	32.93	1.57	1.85	1.03	23.44	14.87	19.71	12.15	22.46	3.52	4.02	3.45	11.46
L2	5.94	6.75	5.12	19.42	1.43	1.59	1.26	16.38	25.92	27.79	24.05	10.20	4.37	4.91	3.82	17.66
L3	3.78	4.34	3.38	13.32	1.64	1.72	1.59	3.98	12.83	13.83	11.43	9.76	3.22	3.49	3.06	7.29
L4	4.26	7.15	3.27	38.36	1.78	2.43	1.18	26.75	14.78	21.36	11.73	25.57	3.67	4.43	3.29	12.45
L5	3.91	4.14	3.61	6.98	1.77	2.32	1.46	26.93	14.68	18.69	12.44	23.73	3.72	4.16	3.18	13.48
p	>0.05				>0.05				<0.01				>0.05			
Wood (>= 4 mm²)																
L0	4.80	6.48	3.67	30.91	2.37	2.78	2.08	15.41	18.70	20.45	16.77	9.87	6.73	9.50	5.34	35.58
L1	5.94	8.38	3.88	32.26	2.86	3.63	2.28	22.59	28.30	43.50	17.21	39.55	7.73	13.80	4.74	53.80
L2	5.76	6.49	5.09	12.20	2.38	2.97	1.94	22.41	28.41	36.49	21.42	26.73	6.40	8.05	5.10	23.53
L3	5.90	6.87	4.71	13.95	2.31	3.81	1.56	43.81	23.01	31.49	14.49	30.95	7.36	13.94	4.16	60.70
L4	5.67	6.58	3.83	23.92	2.12	2.24	1.87	6.02	22.53	28.99	18.85	17.37	5.98	8.44	4.24	24.62
L5	6.80	9.29	4.59	29.51	2.61	4.15	1.69	38.83	26.56	39.10	14.29	37.63	10.70	26.09	4.39	76.52
p	>0.05				>0.05				>0.05				>0.05			

Table 14.5 Mean values of size and shape of pore and wood chips in three vertical surfaces

Layer	Size of component											
	Length (mm)				Breadth (mm)				Perimeter (mm)			
	Mean	Max.	Min.	COV (%)	Mean	Max.	Min.	COV (%)	Mean	Max.	Min.	COV (%)
Pore0	0.54	1.61	0.30	35.07	0.26	0.64	0.11	38.09	1.76	5.26	0.80	47.89
									0.07	0.55	0.03	98.31
DW0	1.00	2.59	0.38	62.74	0.42	0.96	0.20	49.68	4.04	12.21	1.20	80.19
									0.19	0.94	0.03	137.54
Wood0	1.13	4.83	0.29	66.25	0.33	1.25	0.09	56.20	2.99	14.42	0.77	71.39
									0.21	1.12	0.03	103.70
Wood1	4.11	7.81	2.06	30.96	1.04	1.77	0.53	32.60	13.58	26.42	6.63	39.01
									1.49	2.27	1.04	20.08
Wood2	5.74	9.28	3.29	32.78	1.36	1.90	0.89	22.81	20.16	36.05	8.75	36.24
									2.59	3.07	2.05	12.46
Wood3	6.80	9.09	4.57	23.90	1.36	2.73	0.85	41.60	22.92	32.57	14.37	29.05
									3.42	3.97	3.02	10.04
Wood>=4	8.16	9.10	6.45	14.32	2.32	3.68	1.49	40.76	48.50	62.88	41.32	20.08
									6.35	7.20	4.84	17.52
Shape of component												
	Form factor			Aspect ratio		Axis of monor ellipse			Circularity			
	No.	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean
Pore0	126	0.28	44.10	2.29	43.41	0.14	37.84	2.03	23.32			
DW0	29	0.21	50.59	2.37	34.77	0.23	47.40	2.45	31.78			
Wood0	1444	0.31	48.09	3.59	47.82	0.19	49.69	1.99	29.19			
Wood1	78	0.13	61.89	4.41	46.46	0.47	30.43	3.22	34.44			
Wood2	16	0.11	81.56	4.41	39.17	0.60	33.89	3.63	35.36			
Wood3	9	0.10	53.13	5.75	43.03	0.64	21.55	3.57	28.00			
Wood>=4	4	0.03	29.46	4.04	43.98	0.98	29.61	5.56	15.93			

Table 14.6 Total area occupied by various classes of wood chips in six horizontal layers

		DW	Wood0	Wood1	Wood2	Wood3	Wood>=4	Total wood	Pore0	CP
L0	Area (mm ²)	0.23	63.59	21.61	17.89	18.09	20.20	141.61	0.29	271.59
	% of total wood	0.16	44.91	15.26	12.63	12.77	14.26			
L1	Area (mm ²)		62.84	27.01	9.47	14.09	30.93	144.34		268.86
	% of total wood	0.00	43.54	18.71	6.56	9.76	21.43			
L2	Area (mm ²)	6.80	51.45	22.00	13.84	8.73	19.20	122.02	2.99	291.18
	% of total wood	5.57	42.17	18.03	11.34	7.15	15.74			
L3	Area (mm ²)	41.71	46.57	7.46	12.60	9.67	44.18	162.18	3.85	251.02
	% of total wood	25.72	28.72	4.60	7.77	5.96	27.24			
L4	Area (mm ²)	5.96	54.53	27.10	20.44	18.35	41.85	168.23	2.10	244.97
	% of total wood	3.55	32.41	16.11	12.15	10.91	24.87			
L5	Area (mm ²)	5.67	71.13	30.68	20.72	11.16	64.19	203.56	1.85	209.64
	% of total wood	2.79	34.94	15.07	10.18	5.48	31.53			

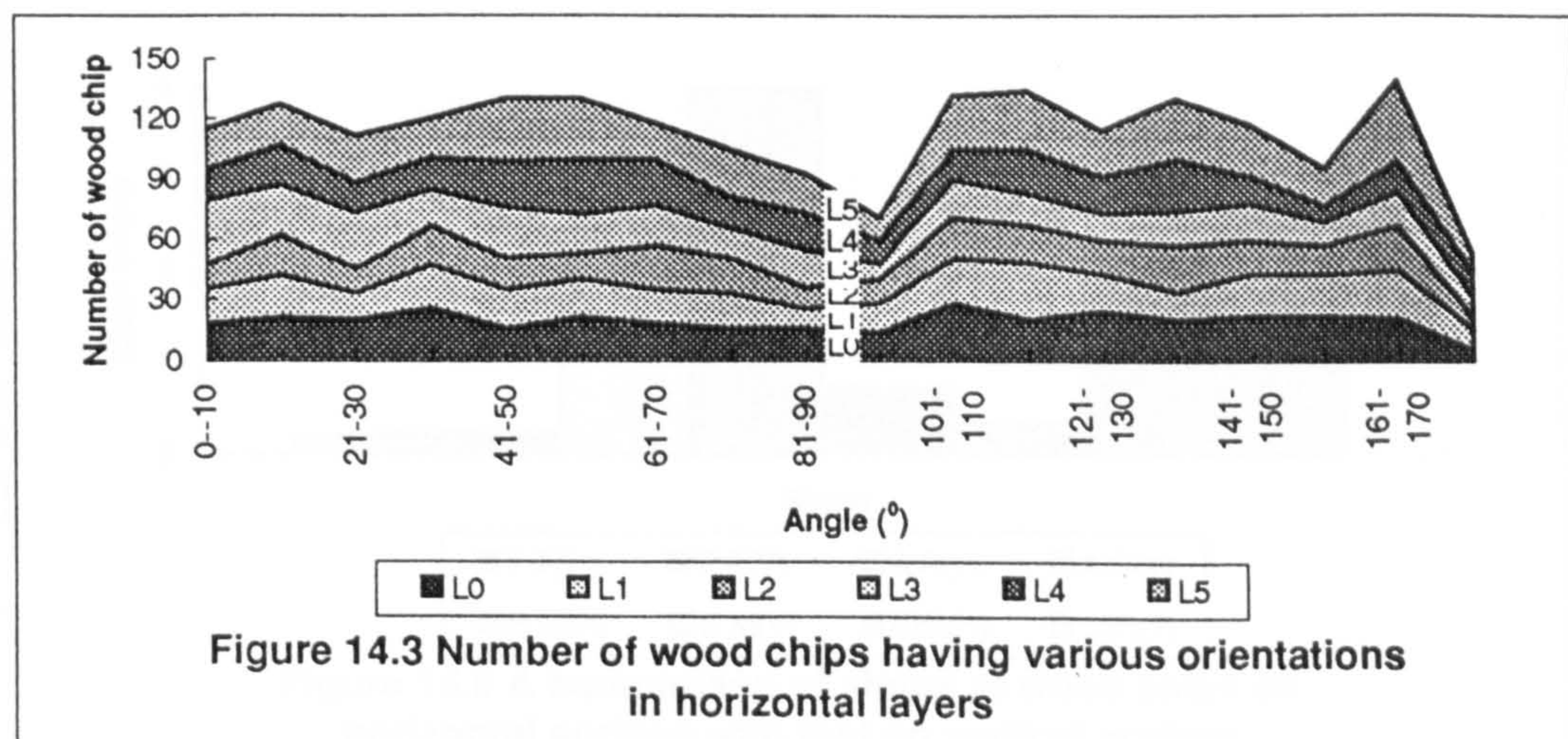
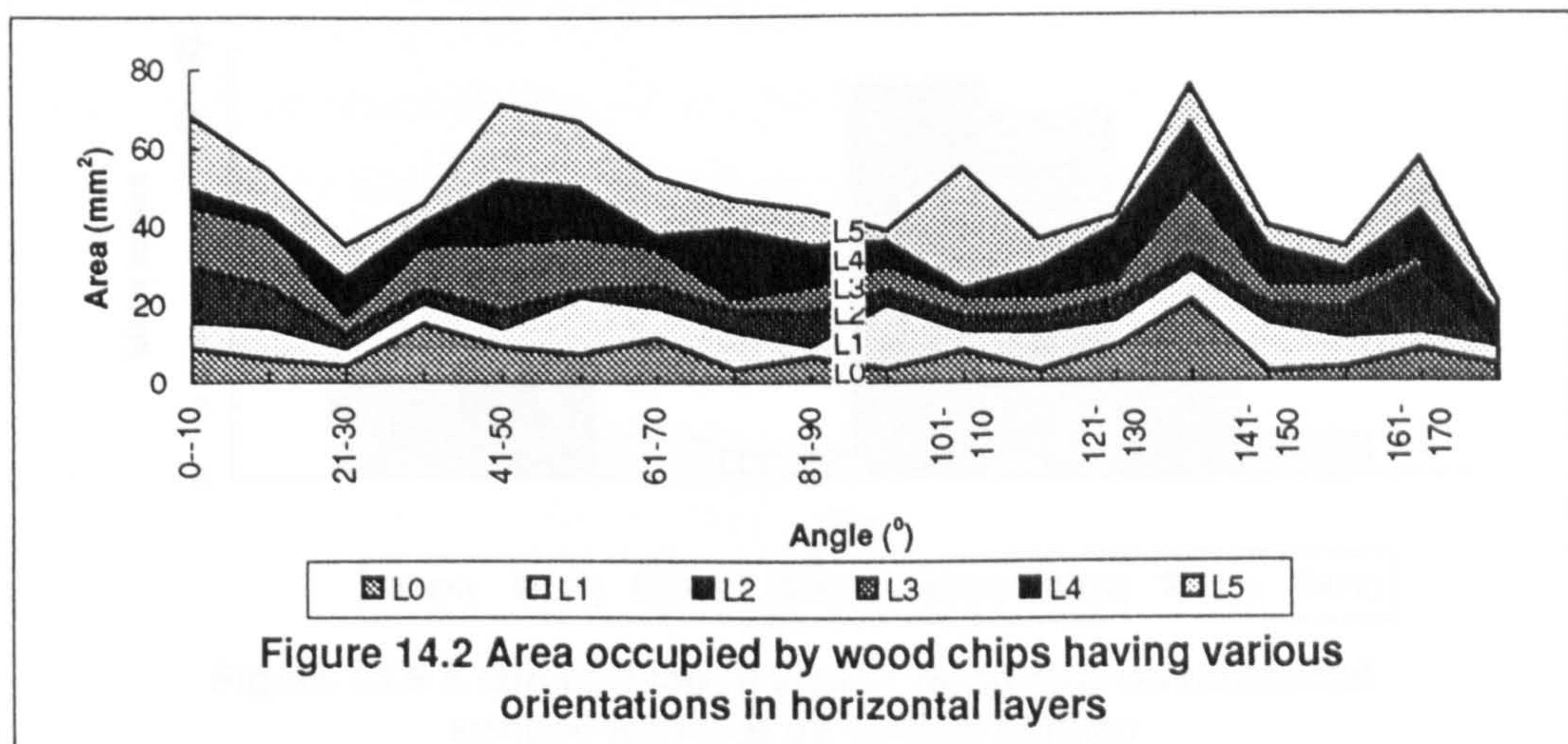
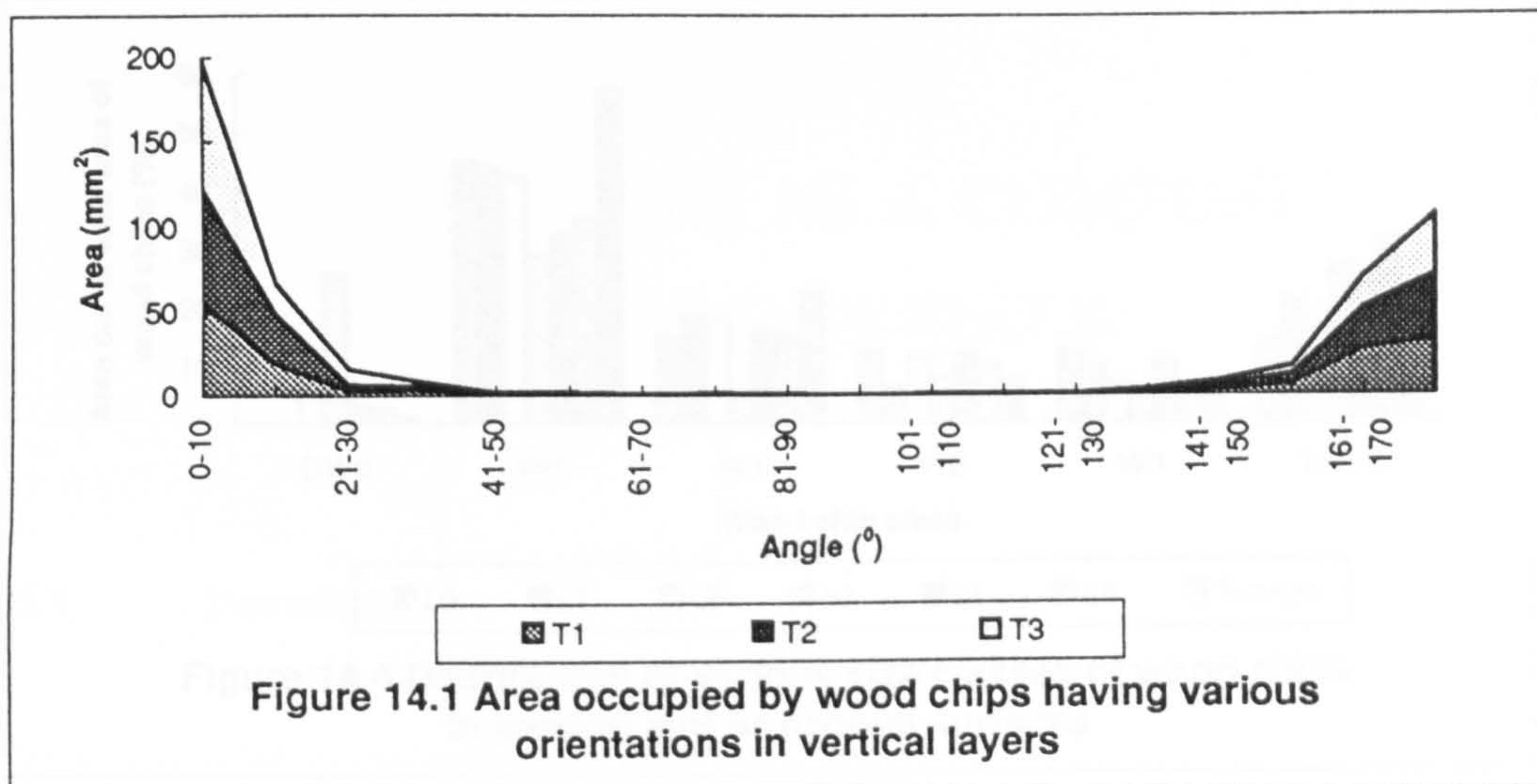
Table 14.7 Area occupied by various classes of wood chips in three vertical faces of CBPB

Sample	DW	Wood0	Wood1	Wood2	Wood3	Wood>=4	Total wood	Pore	Cement paste
	Count	14	410	33	5	2	1	465	51
T1	Area (mm2)	2.33	82.76	51.04	12.70	7.58	7.17	163.58	2.90
	% of total wood	1.42	50.59	31.20	7.76	4.63	4.38	100	
	COV (%)	88.26	104.98	19.35	9.79	3.73	0.00		
	Count	1	513	20	7	4	3	548	20
T2	Area (mm2)	0.11	105.59	28.42	18.20	12.86	18.21	183.39	0.96
	% of total wood	0.06	57.58	15.50	9.92	7.01	9.93	100	
	COV (%)	0.00	99.41	18.27	13.61	4.28	19.49		
	Count	14	521	25	4	3		567	55
T3	Area (mm2)	4.46	108.20	37.11	10.52	10.38		170.67	3.99
	% of total wood	2.61	63.40	21.74	6.16	6.08		100	
	COV (%)	101.19	106.92	22.12	16.16	13.27			
	Area (mm2)	2.30	98.85	38.86	13.81	10.27	8.46	172.55	2.62
	% of total wood	1.37	57.19	22.81	7.95	5.91	4.77	100	
	p	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05		>0.05

Table 14.8 Shape of pores and wood chips in six horizontal layers making up
the thickness of CBPB

		Form factor		Aspect ratio		Minor ellipse		Circularity	
Layer	Count	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
Pore (0-1mm ²)									
L0	6	0.16	37.13	3.00	41.94	0.11	37.01	2.61	15.53
L2	47	0.30	47.17	2.01	33.33	0.15	32.18	2.02	27.32
L3	44	0.29	44.40	2.80	46.02	0.15	43.31	2.00	23.34
L4	29	0.26	41.13	2.06	30.85	0.15	42.14	2.11	25.61
L5	31	0.21	38.98	2.65	46.07	0.12	37.40	2.29	18.98
p		< 0.01		<0.01		>0.05		<0.01	
DW									
L0	4	0.19	62.72	2.09	37.15	0.13	13.39	2.65	37.77
L2	38	0.17	70.58	2.42	43.62	0.20	53.67	2.87	33.65
L3	59	0.25	43.05	2.54	46.31	0.37	75.33	2.20	31.25
L4	27	0.16	68.82	2.30	39.27	0.22	49.41	2.95	39.34
L5	35	0.17	48.85	2.10	34.08	0.19	62.03	2.66	26.54
p		<0.01		>0.05		<0.01		<0.01	
Wood (0 - 1 mm ²)									
L0	318	0.32	40.43	2.50	40.65	0.23	55.13	1.89	23.65
L1	303	0.37	37.64	2.28	37.74	0.26	53.50	1.75	21.61
L2	236	0.24	48.49	2.50	42.19	0.22	58.52	2.27	31.45
L3	271	0.23	56.58	2.64	41.37	0.19	63.26	2.43	35.02
L4	264	0.28	46.91	2.41	50.78	0.23	55.95	2.08	30.33
L5	351	0.32	45.63	2.38	45.67	0.23	57.36	1.95	28.79
p		<0.01		<0.01		<0.01		<0.01	
Wood (1 - 2 mm ²)									
L0	16	0.21	50.84	2.58	44.88	0.65	26.56	2.42	30.35
L1	20	0.28	37.64	2.81	49.24	0.69	23.60	1.99	18.54
L2	14	0.13	43.42	3.30	34.75	0.56	25.28	3.03	23.75

L3	5	0.23	45.22	3.58	41.90	0.62	17.20	2.20	19.54
L4	18	0.21	57.02	2.40	44.14	0.72	21.39	2.52	31.80
L5	21	0.25	41.38	2.77	44.75	0.69	27.80	2.17	26.49
p		<0.01		>0.05		>0.05		<0.01	
Wood (2 - 3 mm ²)									
L0	7	0.19	35.39	2.47	32.53	0.89	14.60	2.38	18.17
L1	4	0.15	31.10	2.75	25.05	0.79	24.41	2.67	12.55
L2	5	0.11	35.42	2.06	5.20	0.95	10.37	3.10	18.07
L3	5	0.18	53.59	3.12	63.20	0.85	31.84	2.66	37.51
L4	8	0.22	39.78	3.10	55.43	0.87	23.45	2.25	22.91
L5	8	0.15	54.83	2.87	51.16	0.92	32.99	3.01	40.71
p		>0.05		>0.05		>0.05		>0.05	
Wood (3 - 4 mm ²)									
L0	5	0.21	36.45	1.93	24.88	1.21	14.13	2.26	18.67
L1	4	0.22	34.89	2.85	65.90	1.20	25.79	2.25	23.14
L2	2	0.07	0.00	4.29	35.15	0.77	3.67	3.87	2.01
L3	3	0.25	18.35	2.31	15.82	1.08	14.37	2.03	9.19
L4	5	0.23	41.34	2.74	69.58	1.13	29.10	2.24	24.72
L5	3	0.22	41.67	2.30	22.61	1.11	3.11	2.25	24.79
p		>0.05		>0.05		>0.05		<0.01	
Wood (>= 5 - 6 mm ²)									
L0	3	0.23	21.57	2.10	43.53	1.71	7.33	2.11	12.03
L1	4	0.13	37.16	2.12	32.84	1.62	26.33	2.88	16.18
L2	3	0.09	26.96	2.47	16.63	1.20	10.69	3.40	15.46
L3	6	0.16	37.86	2.86	32.96	1.42	48.97	2.61	24.39
L4	7	0.14	18.12	2.70	29.05	1.27	14.49	2.69	10.74
L5	6	0.19	46.32	2.75	25.47	1.77	47.37	2.48	24.47
p		>0.05		>0.05		>0.05		>0.05	



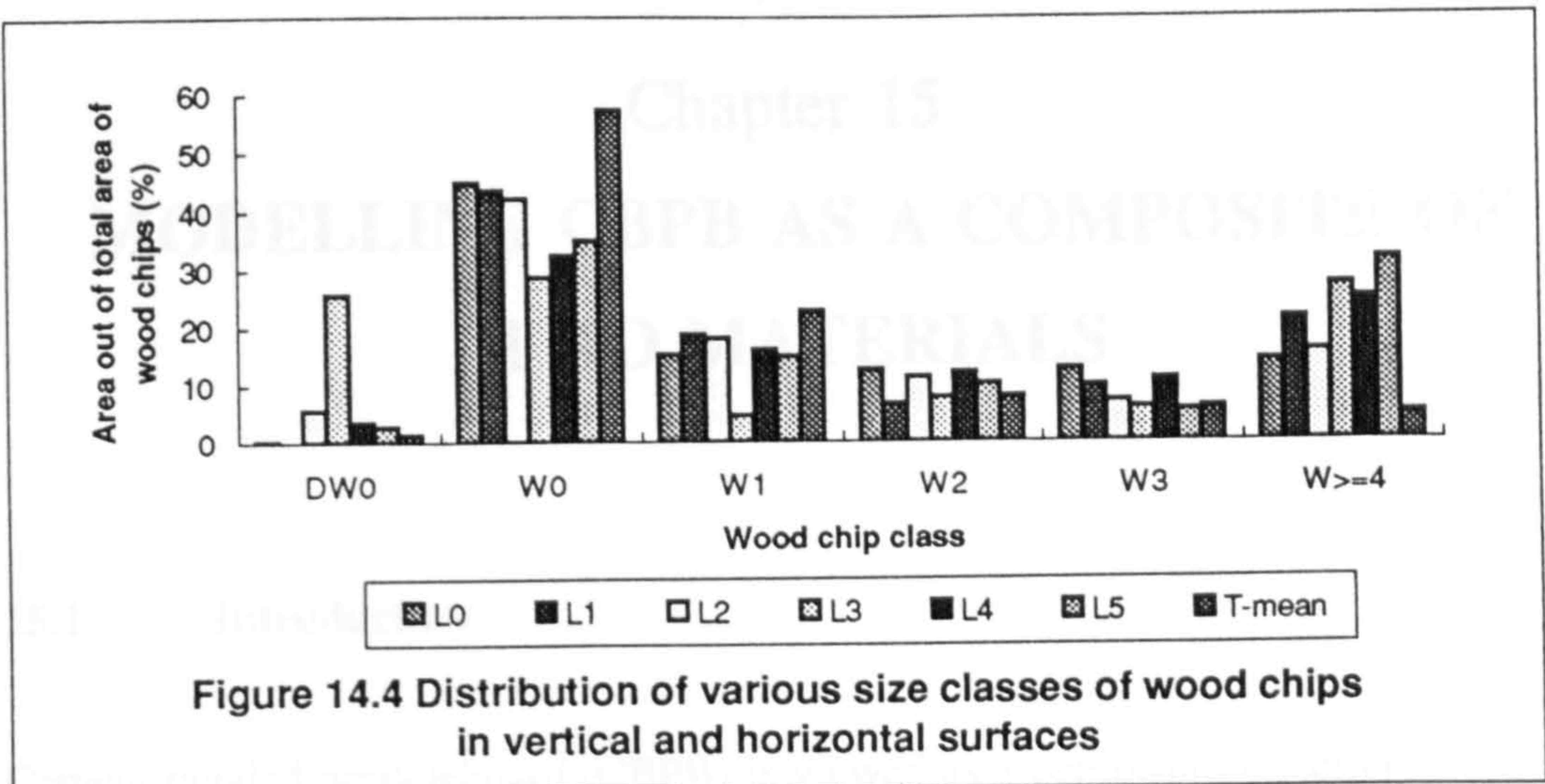


Figure 14.4 Distribution of various size classes of wood chips in vertical and horizontal surfaces

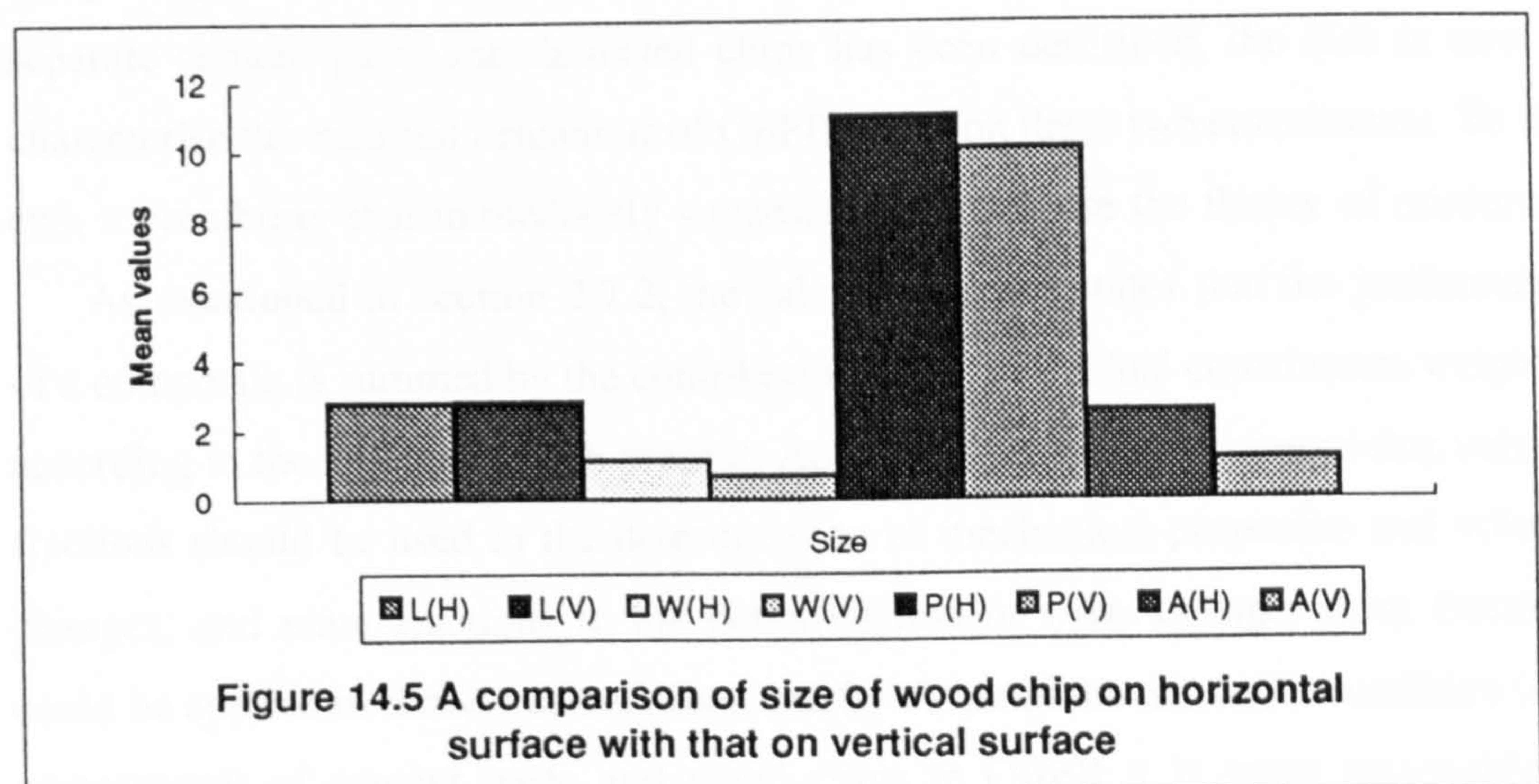


Figure 14.5 A comparison of size of wood chip on horizontal surface with that on vertical surface

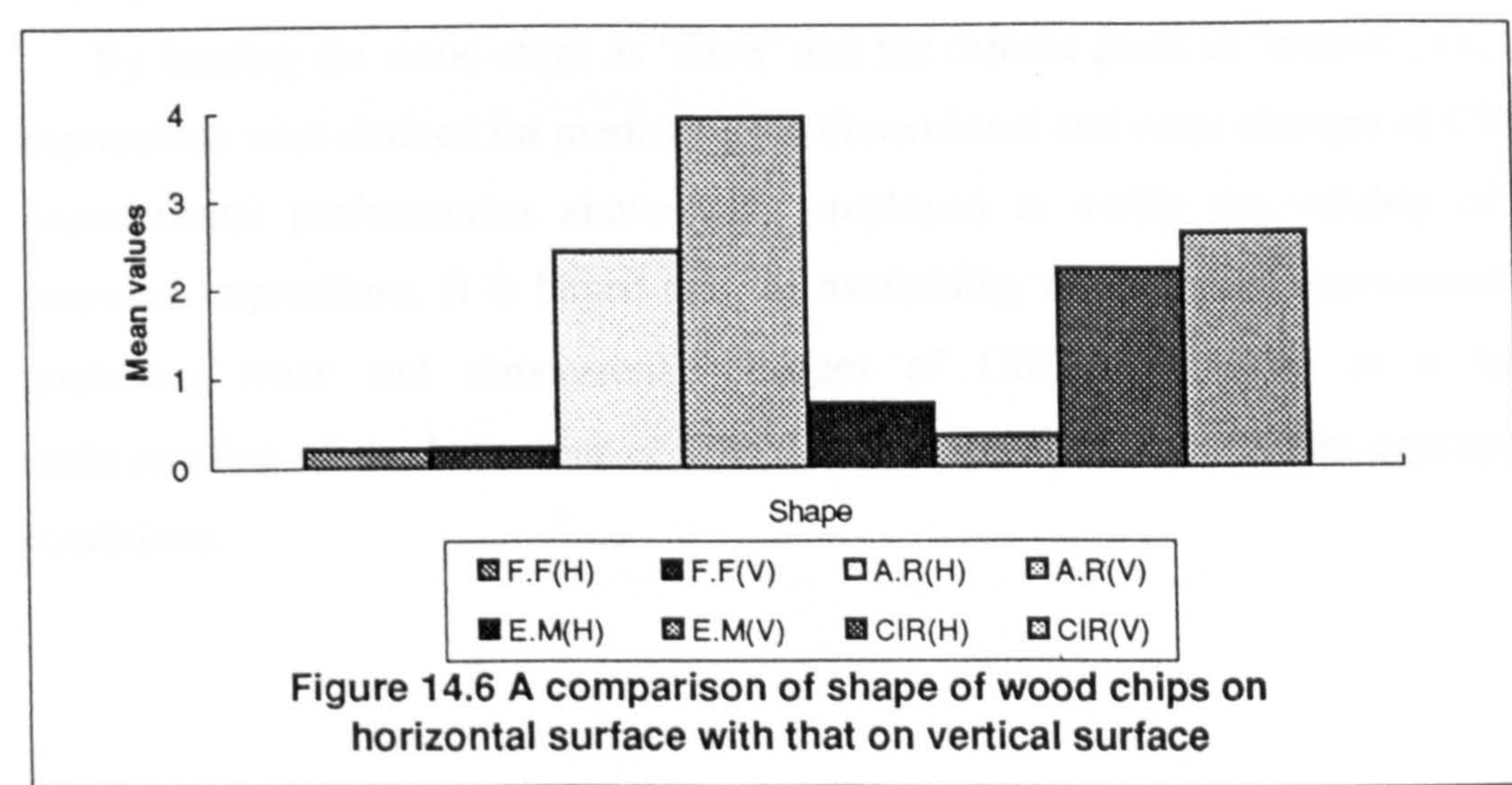


Figure 14.6 A comparison of shape of wood chips on horizontal surface with that on vertical surface

Chapter 15

MODELLING CBPB AS A COMPOSITE OF TWO MATERIALS

15.1 Introduction

Cement bonded particleboard (CBPB) is viewed as a composite material or mixture comprising two phases: cement paste and wood chips. Now that the modelling of separate cement paste and dissected chips has been described, the task is now to characterise the material behaviour of CBPB based on these two constituents. To this end, a possibility that immediately suggests itself is to use the theory of mixtures.

As mentioned in section 2.7.2, the rule of mixtures states that the performance of a composite is summed by the contribution of the individual constituents weighted according to the amount of each present. Accordingly it can be proposed that volume fractions should be used in the determination of mechanical properties and volume changes, and mass fractions in the determination of mass change. Both fractions could be applied in density calculations, but by virtue of the unnatural condition (e.g. compressed) of cement paste and wood chips in CBPB it is more reasonable to employ the mass fraction.

By treating the wood chips as "fibre" and the cement paste as "matrix", explicit expressions were derived for predicting the dimensional and mass changes of CBPB. Experimental performances above were employed to verify the validity of the proposed expressions. It is hoped that the availability of analytical expressions for predicting mass and dimensional changes of CBPB will lead to a better understanding of the behaviour of CBPB and encourage its use under appropriate conditions.

15.2 Mass and Volumetric Fractions of Wood Chip and Cement Paste in CBPB

It is known that the CBPB tested was made using 65 % cement paste and 35 % wood chip (by weight). Therefore the mass fraction of the components in unit mass of the CBPB are:

$$m_{pf} = 0.65$$

$$m_{wf} = 0.35$$

The oven dry densities of cement paste and wood chip were calculated after their moisture content and corresponding densities had been determined:

$$\rho_{p0} = 1857.78 \text{ kg / m}^3$$

$$\rho_{w0} = 342.22 \text{ kg / m}^3$$

By use of the relationship between mass, density and volume, the volume of the cement paste and wood chip in unit mass of the CBPB can be calculated as:

$$V_p = M_{cp} / \rho_p = 3.50 \times 10^{-4} \text{ m}^3$$

$$V_w = M_w / \rho_w = 10.23 \times 10^{-4} \text{ m}^3$$

Thus, the volume of the CBPB in unit mass is:

$$V_{cp} = V_p + V_w = 13.73 \times 10^{-4} \text{ m}^3$$

Therefore, the volume fractions are:

$$V_{pf} = 0.26$$

$$V_{wf} = 0.74$$

15.3 Theoretical Considerations

15.3.1 Assumptions

The following assumptions are made in predicting the stress - strain curve of the CBPB:

- 1) All the chips are straight and have identical geometrical and mechanical properties;
- 2) The length direction of the wood chips is in the longitudinal direction of wood;

3) The radial and tangential directions of the wood chips are uniformly orientated (360°) and the mean values of radial and tangential properties represents the overall transverse properties of the board;

4) The wood chips are uniformly distributed with equal probabilities of orientation in the length and width direction of CBPB and can be represented by an equivalent volume or effective number of wood chips. This assumption was proved by the results of image analysis (chapter 14);

5) The strain between the wood chips and cement paste matrix is compatible;

6) Distortion of the wood chips due to moisture change is negligible compared to the change in the three directions (thickness, length and width) of CBPB.

15.3.2 Density Prediction

An equation for the density of CBPB was developed applying to the rule of mixtures: Case 1, by using volume fraction. The density of CBPB is

$$\rho_{cp} = \sum \rho_k V_{kf} \quad 15.1$$

Case 2, by using mass fraction. The density of CBPB can be calculated as:

$$\rho_{cp} = \sum \rho_k m_{kf} \quad 15.2$$

In the equations, "k" denotes "p" or "m" representing cement paste or wood chips.

15.3.3 Mass Change Prediction

Applying the rule of mixtures, the change in mass of CBPB during sorption could be expressed as:

$$\Delta M_{cp} = \Delta M_p m_{pf} + \Delta M_w m_{wf} \quad 15.3$$

Substituting from Equations 13.27 and 13.28:

$$\Delta M_{cpj} = 100[m_{pf}\left(\frac{M_{pif}}{M_{pji}} - 1\right)E_{pj} + m_{wj}\left(\frac{M_{wif}}{M_{wji}} - 1\right)E_{wj}] \quad 15.4$$

On adsorption, the condensation on the cement paste within the dissected chips must be corrected because it overlaps part of the condensation in the cement paste. The "correction coefficient" is approximately equal to the ratio of mass change of dissected chips on desorption to that on adsorption, assuming similar behaviour in the adsorption and desorption of wood under normal environment.

The value was calculated to be about 0.66.

15.3.4 Predicting Dimensional Changes by Using Values Relating to its Constituents

When CBPB are subjected to changing environments, it is the swelling or shrinking stresses which produce dimensional (volume) changes. This sharply departs from most theories proposed to date which consider performance of composites as relating to externally applied stresses. It is necessary to devise an appropriate law for dimensional changes due to internal stresses by first considering the relationship of stresses between the wood chip and cement paste, the nature of cement paste and wood chips, and the structure of CBPB.

The overall stresses of CBPB due to sorption is:

$$\sigma_{cp\alpha} = \sigma_p V_{pf} + \sigma_{w\alpha} V_{wf} \quad 15.5$$

The " α " in the Equation is related to the orientation of the wood chips.

$$\sigma_p = e_p \epsilon_p \quad \sigma_{w\alpha} = e_{w\alpha} \epsilon_{w\alpha} \quad 15.6$$

Substituting in Equation 15.5,

$$\sigma_{cp} = V_{pf} e_p \epsilon_p + V_{wf} e_{w\alpha} \epsilon_{w\alpha} \quad 15.7$$

Three models have been assumed for predicting the property of two - phase materials (section 2.7). In view of the suitability of the models, the feature of stresses due to moisture change, and the structure of CBPB (chapter 12 and 14), model 3 was

chosen.

Assuming the compatibility of strain in wood chip and cement paste and by applying Hooke's Law the dimensional change of CBPB can be given as:

$$\epsilon_{cp\alpha} = \sigma_{cp\alpha} \left(\frac{1 - \sqrt{V_{wf}}}{e_p} + \frac{1}{\left(\frac{1}{\sqrt{V_{wf}}} - 1 \right) e_p + e_{w\alpha}} \right) \quad 15.8$$

Substituted with Equation 15.7, means the dimensional change of CBPBs can be calculated as:

$$\Delta L(T)_{cp\alpha} = [V_{pf} e_p \Delta L(T)_p + V_{wf} e_{w\alpha} \Delta L(T)_{w\alpha}] \left[\frac{1 - \sqrt{V_{wf}}}{e_p} + \frac{1}{\left(\frac{1}{\sqrt{V_{wf}}} - 1 \right) e_p + e_{w\alpha}} \right]$$

$e_{w\alpha}$ and $\delta_{w\alpha}$ are in compliance with the orientation of the wood chips (the angle between the grain of the wood chips and the surfaces or edges of CBPB). $e_{w\alpha}$ can be calculated by transforming the stress or strains from the rotated to the principal axes.

$$e_\varphi = \frac{1}{\frac{\cos^4 \varphi}{e_L} + \frac{\sin^4 \varphi}{e_R} + \left(\frac{1}{G_{LR}} - \frac{2\nu_{LR}}{e_L} \right) \sin^2 \varphi \cos^2 \varphi} \quad 15.10$$

Image analysis showed that almost all chips lie flat in the CBPB. The effective angle between wood chips and the horizontal surface is 11.1° . Thus, for the thickness direction of CBPB, $\varphi = 78.9^\circ$

However, it was found that the effect of orientation of wood chips on the change in length of CBPB should be very similar to that in the width due to the random distribution of wood chips in the horizontal surfaces. Because of this the mean effective angle cannot directly be used. $e_{w\alpha}$ should be produced by integration, θ ranging from 0 to $\pi / 2$.

$$\bar{e}_\theta = \frac{\int_0^{\frac{\pi}{2}} \frac{1}{\frac{\cos^4\theta}{e_L} + \frac{\sin^4\theta}{e_R} + \left(\frac{1}{G_{LR}} - \frac{2\nu_{LR}}{e_L}\right)\sin^2\theta\cos^2\theta} d\theta}{\int_0^{\frac{\pi}{2}} d\theta} \quad 15.11$$

Similarly, $\sigma_{w\alpha}$ was produced after transformation by the use of force and moment equilibria as:

$$\sigma_\varphi = \sigma_L \cos^2\varphi + \sigma_{R(T)} \sin^2\varphi + \sigma_{LR(T)} \sin 2\varphi \quad 15.12$$

As for the moduli of elasticity, for the modelling of length / width changes, σ_{wi} should be integrated:

$$\bar{\sigma}_\theta = \frac{\int_0^{\frac{\pi}{2}} \sigma_L \cos^2\theta + \sigma_{R(T)} \sin^2\theta + \sigma_{LR(T)} \sin 2\theta d\theta}{\int_0^{\frac{\pi}{2}} d\theta} \quad 15.13$$

15.4 Numerical Tests

A general theory of the behaviour of CBPB during sorption has been outlined which would appear to exhibit great potential as a basis for a numerically systematic explanation of the observed material behaviour due to swelling or shrinkage stresses. To completely fulfil the objectives, it remains to check the ability of the theory to reproduce the available data and the suitability of the model for use in computation.

15.4.1 Comparison of Calculated Density of CBPB with Experimental Values

Firstly concerning density. Using Equations 15.1 and 15.2, densities of CBPB are calculated as follows:

By using volume fraction:

at 35 %RH, $\rho_{cp} = 774.6 \text{ kg / m}^3$,

at 65 %RH, $\rho_{cp} = 798.16 \text{ kg / m}^3$

at 90 %RH, $\rho_{cp} = 875.28 \text{ kg / m}^3$

By using mass fraction:

at 35 %RH, $\rho_{cp} = 1371.3 \text{ kg / m}^3$

at 65 %RH, $\rho_{cp} = 1408.2 \text{ kg / m}^3$

at 90 %RH, $\rho_{cp} = 1528.9 \text{ kg / m}^3$

It is apparent that the densities calculated using the mass fraction were in good agreement with experimental data. The deviation between the values calculated and measured was only about 2 %, 3 % and 6 % at 35 %RH, 65 %RH and 90 %RH respectively. However, the deviations calculated by using the volume fraction range from 38.8 to 50.1 %. This confirms that the more closely related (more significantly influencing) fraction should be chosen in the application of the rule of mixtures.

15.4.2 Application of the Rule of Mixtures for Mass Change of CBPB

To evaluate the performance of the rule for mass change of CBPB, changes in the mass of CBPB on moving from 35 to 90 %RH and from 90 to 35 %RH were predicted by using model 15.4. The predicted and experimentally determined values are compared and plotted in Figure 15.1. As may be seen, mass increase and decrease were correctly predicted, the model accurately capturing the relevant features of the response. The deviation of the maximum increase on adsorption was about 8.4 % and that of maximum decrease on desorption was only 1.9 %. The higher values predicted in the early stages were due to the size effect on the values arising from wood chip and cement paste (particles of wood chips and cement paste have higher exposed surfaces compared to CBPB in unit volume).

15.4.3 Dimensional Change of CBPB

The final set of comparisons concerns the dimensional change of CBPB. Models 15.9 - 15.13 were used to compare the idealised and experimental results. In the prediction of length change, stress relief was considered in view of results from image analysis (chapter 14). The predicted and experimentally determined values are illustrated in Figure 15.2 and 15.3. The close agreement between the experimentally and theoretically predicted values further validates the proposed models.

A comparison of the predictions shows a much higher correlation for thickness change than for length change. This may be attributable to a difference between the assumption and reality of the distribution of the wood chips in the CBPB.

15.5 Interim Conclusions 11

- 1) It has been shown in this chapter how the theory of mixtures can be brought to bear on the constitutive behaviour of CBPB due to swelling or shrinkage stresses. This is a novel application of these ideas. The approach gives a simplified method for predicting idealised mass and dimensional change of CBPB and a physical interpretation of the mechanism of the movement of CBPB. Numerical tests demonstrated good agreement of the predictions of the theory with experimental data.
- 2) Mass fraction was applicable for the mass and density predictions, and volume fraction for the dimension prediction, showing that in using the rule of mixtures, the most closely related fraction should be chosen.
- 3) In employing the values for constituents, overlapping changes or phenomena should be considered.
- 4) The values of change predicted for early stages were higher than those determined experimentally, reflecting the size effect of the composite constituents.
- 5) The correlation between prediction and experimental determination was very high

for mass and thickness change. Higher deviations for length changes suggested that the accurate prediction of the distribution of the wood chips within CBPB is vital when applying models in the behaviour of CBPB.

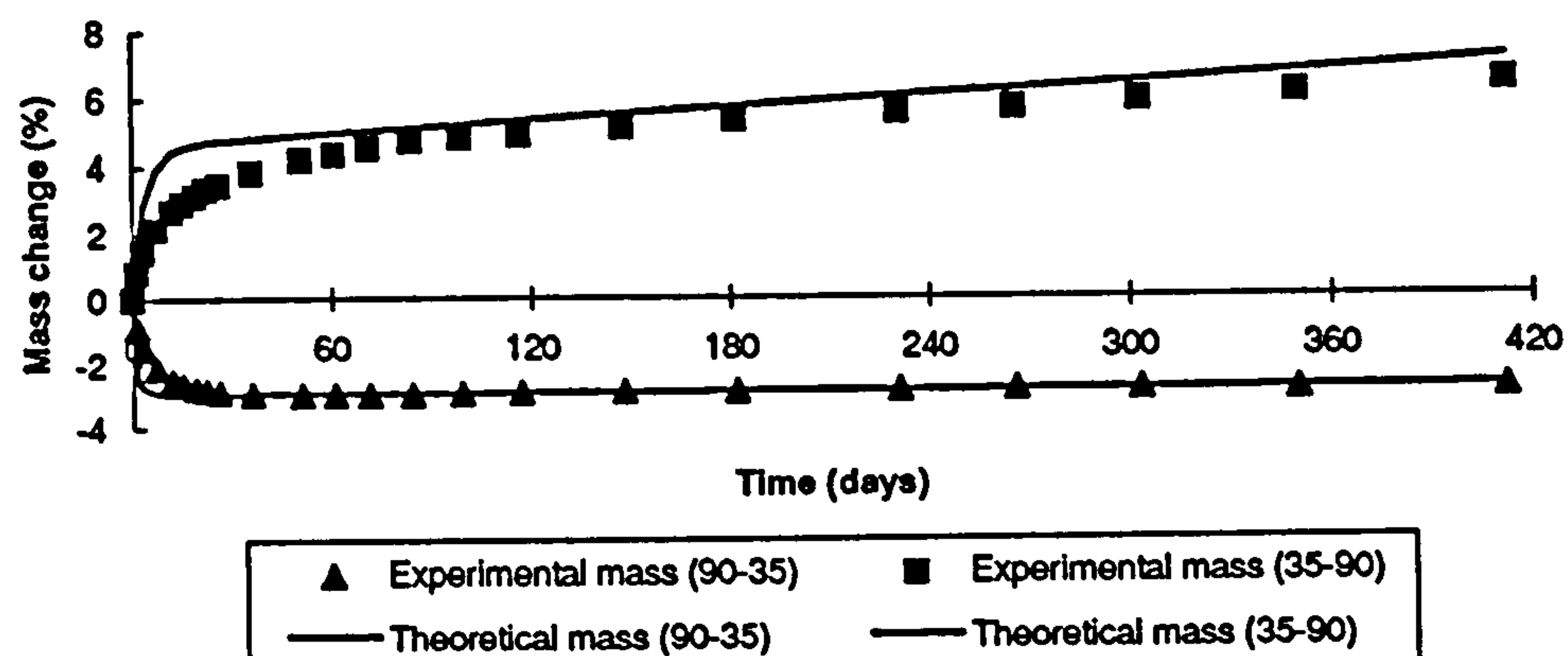


Figure 15.1 Idealised and experimental mass change of CBPB both on adsorption and desorption

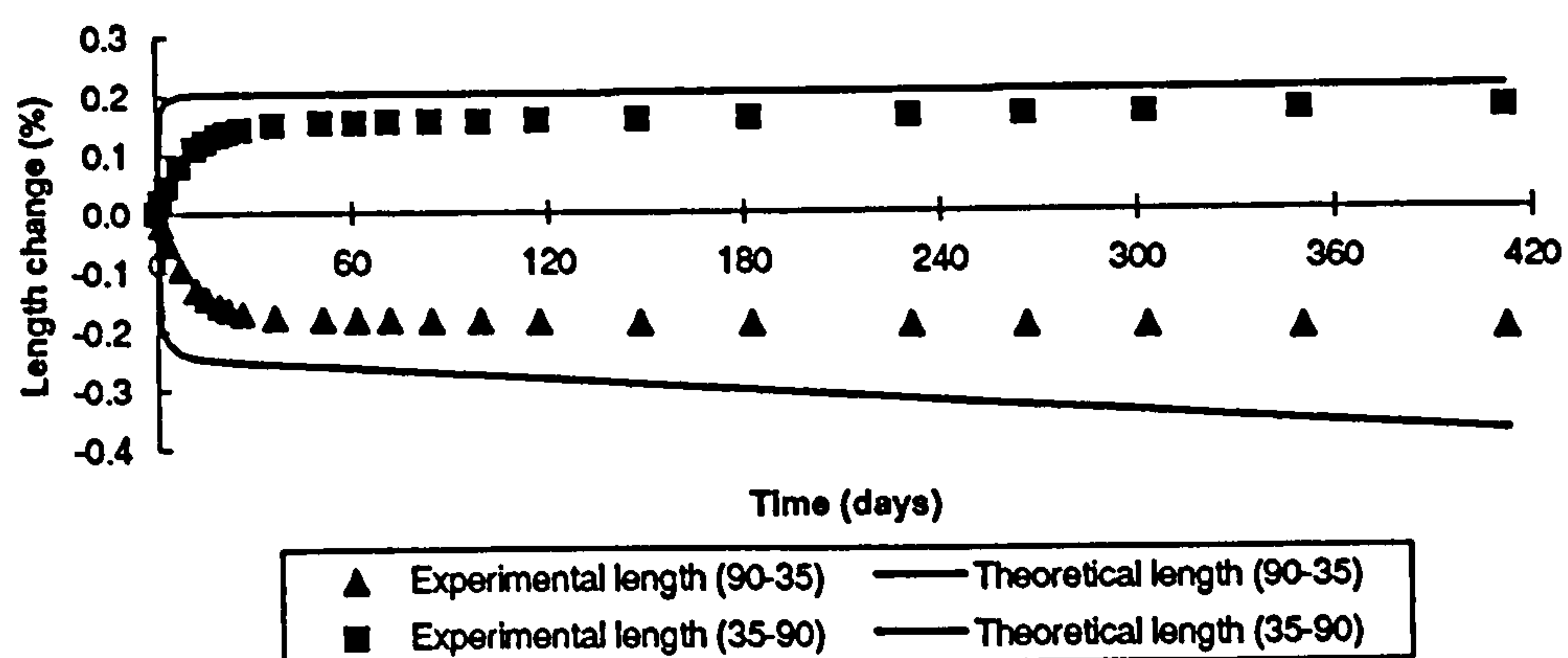


Figure 15.2 Idealised and experimental length change of CBPB both on adsorption and desorption

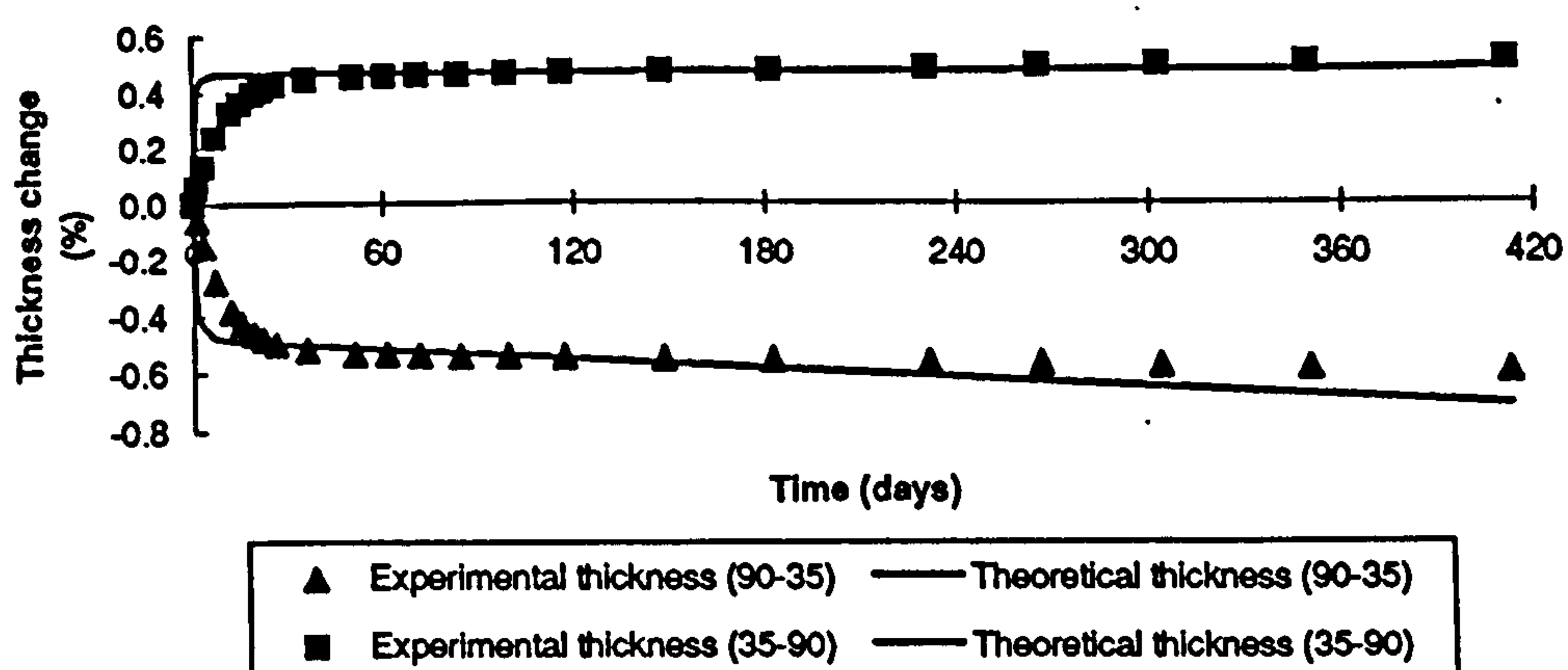


Figure 15.3 Idealised and experimental thickness change of CBPB both on adsorption and desorption

PART 4

TREATMENT

PROCESSES FOR CBPB

Chapter 16

THE EFFECT OF STORAGE TIME AND PRE-DRYING ON THE BEHAVIOUR OF CBPB

16.1 Introduction

CBPB exhibits the characteristic of swelling and shrinkage in response to variation in RH at normal ambient temperature. There is a strong relationship between the dimensional and mass change, and both mass and dimensional changes are highly time-dependent (Fan, *et al*, 1996). Therefore attention was focused on whether the structure change of CBPB with time and whether the behaviour of CBPB under cyclic RH is related to those changes. The work described in this chapter was conducted to determine the effect of storage time prior to exposure on the dimensional stability of CBPB and the effect of pre-drying on the mass and dimensional changes of CBPB under cyclic RH.

Like other cementitious materials, the setting and hardening of CBPB are brought about by the hydration of the cement constituents resulting in the chemical bonding and micro-chemical bonding which is supposed to play a significant role in the total bonding (Ahn and Moslemi, 1980; Steward, 1988). Note that if the wood chips remain constant under constant environment, then the change of CBPB during prolonged storage could be attributed to the behaviour of the cement paste, and irreversible characteristics of cement paste should play an important role in the change of CBPB under drying pretreatment. The properties of hardened paste depend, to an appreciable extent, on its degree of hydration, which is a chronic process. The rate of hydration of cement paste is affected by the age of paste, cement composition, fineness of the cement, W/C ratio, temperature and admixtures, etc. (Soroka, 1979; Powers, *et al*, 1959). Prolonged storage will increase the degree of hydration, resulting in increases in the volume of the solid, bringing about stiffening of the cement paste and increasing the density of the paste; further hydration reduces the porosity of the hardened paste and thereby its strength increases. Chemically bonded

water increases with age. It was also observed that the prolonged storage of hydrated cement paste resulted in slow change in the structure (Powers, *et al*, 1959; Helmuth and Turk, 1967). Capillaries in fresh paste are continuous but sufficient increase in hydration results in blocking of original capillaries by gel and creating capillary cavities (Powers, *et al*, 1959).

There is a delayed recovery of wood when re-wetting (Dinwoodie, 1981; Skaar, 1988). The phenomenon of drying shrinkage in cement paste has been discussed in great detail (Helmuth and Turk, 1967; Ishai, 1966; Roper, 1966). A portion of the shrinkage shown by cement paste on first drying is irreversible. After sufficient drying has occurred however, the paste becomes stabilized to the point where subsequent swelling and shrinkage is reversible. Helmuth and Turk (1967) concluded that the stabilization process which occurs during first drying is related to fundamental changes in paste structure, including a decrease in the pore volume and in the specific surface area of the hydrated cement pastes. Paste heated at atmospheric pressure exhibits considerable volume instability due to the effect of, at least thermal expansion, contraction accompanying the removal of non - evaporable water and contraction accompanying the removal of evaporable water. Contractive deformations dominate the deformation behaviour of heated pastes as evidenced by a permanent contraction after heating (Lankard and Shook, 1970). If the paste in CBPB is not completely hydrated, the temperature effect would be the case when CBPB is under temperature pre - drying. It was found temperature treatment affects the structure of the paste and its composition, with the drying shrinkage of dried paste being much lower than that of normal cured paste (Soroka, 1979).

16.2 The 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 stabilization when they were exposed before service. Conditioned CBPB were stored at 20 °C / 65 %rh for 2, 4, 8 and 12 months prior to cyclic exposure, and then conditioned at 20 °C / 90 %rh.

16.2.1 The Behaviour under Desorption and Adsorption

Results

Increase and decrease in mass exhibited by this group of samples under adsorption and desorption are shown in Figure 16.1 and 16.2. The degree of dimensional change is presented as a function of the mass change, i.e. through the relationship between the dimensional change and mass change. Length change to mass change under desorption is shown in Figure 16.3 and thickness change to mass change shown in Figure 16.4. The dimensional change to mass change on moving samples from 35 %RH to 65 %RH and then to 90 %RH is plotted in Figure 16.5 and 16.6. Equilibrium points are labelled with the corresponding RH values (35 %RH, 65 %RH and 90 %RH).

Table 16.1 gives the coefficients of the equations 13.22 and 13.26 which were fitted to the experimental data.

Discussion

For all CBPB, both decrease and increase in mass were rapid at an early stage of exposure and slowed down with time. Desorption resulted in a progressive decrease in mass over the whole range of RH tested (Figure 16.1), whilst, in the lower RH range, the mass did not recover to its original level but higher RH produced a much higher weight gain than their previous values (Figure 16.2). Overall the level of mass change, whether under adsorption or desorption, decreased with the increasing storage period of CBPB. Comparison of 2 months with 12 months storage period shows that the total decrease in mass under desorption is about 27 % higher for 2 months storage than that for 12 month storage, and the total increase under adsorption is about 29 % higher for 2 month storage compared to that of 12 month storage.

The ratios of mass decrease of CBPB after 2, 4, 8 and 12 month storage periods on moving samples from 90 % to 65 %RH were similar to that from 65 % to 35 %RH due to the similar rate of mass change occurring in both stages of RH.

However, the deviation in mass change of CBPB with different storage periods was not observed in moving samples from 35 % to 65 %RH, and much greater ratios were produced when transferring samples from 65 % to 90 %RH.

In Figure 16.3 and 16.4, a linear relationship between dimensional and mass change appears to cover the whole range of cyclic RH tested (under desorption) for various storage periods of CBPB. However, under adsorption, only curves for RH from 35 % to 65 % are well represented by a straight line, and moving samples from 65 % to 90 %RH resulted in a decline in the ratio of dimensional changes to mass change. A good correlation between dimensional changes and mass change is in agreement with the results of CBPB without the pretreatment, as aforementioned. The effect of carbonation in later stages of exposure was again observed.

The relationship between the dimensional changes to mass change under both adsorption and desorption was found to be well fitted to the corresponding theoretical prediction equations 13.22 and 13.26 (Table 16.1), but with different coefficients.

It is apparent that the effect of storage period on the relationship of dimensional change to mass decrease could be illustrated by the different values of coefficients, A, K and C, and the storage period did not affect the ratio of dimensional change to mass decrease very considerably. However, since substantial reduction in mass decrease occurred (Figure 16.1 and 16.2) when the CBPB was subjected to a certain period of storage, absolute dimensional change decreased simultaneously. Little increase in the rate of dimensional change to mass decrease with increasing storage period indicated that further hydration may proceed during the storage, (but note that the dimension of raw wood chips remained constant under constant environmental storage). In cement paste, the higher the degree of hydration, the higher the gel content of the paste. The increase in gel content increases the volume of gel pores at the expense of capillary pores. Assuming that drying or swelling from gel pores causes greater shrinkage or swelling than that from capillary pores, greater shrinkage is to be expected.

16.2.2 The Behaviour under Cyclic RH

The effect of initial storage period on the mean mass and dimensional change is

summarized in Table 16.2. The changes are based on the maximum values measured at 90 %RH and presented as the maximum value of mass and dimensional changes at each stage of the RH cycle.

Discussion

In Table 16.2, It appears that the storage time had a significant influence on the magnitude of mass and dimensional changes during subsequent cycling of RH. With increasing period of storage from 2 to 12 months, there was a progressive reduction in the magnitude of the changes. Several reasons were thought to be related to this reduced susceptibility to water.

CBPB undergoes a consistent carbonation, as discussed in previous papers (Fan, *et al*, 1996), resulting in a reduction in permeability. This carbonation-induced reduction in permeability is probably caused by the precipitation of calcite and other carbonation products on the surfaces and in the cavities of the chips in contact with CO₂-charged solutions, thereby effectively reducing the effective radius of the cavity. This has been recorded for grout (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, *et al*, 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, the volume of gel pores and the resulting water content in the low pressure range should be greater, since 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 the result under 90 %RH does show this characteristic. 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 still existing in the CBPB) 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 consequentially changed the radius of the pores and the amount of water held in the gel pores. The fact that prolonged storage at intermediate RHs reduces the ultimate

shrinkage during drying and results in slow changes in the structure of the hydrated cement paste was also observed by Helmuth and Turk (Helmuth and Turk, 1967). The overall change was balanced by the increases and decreases of shrinkage which are associated with the degree of un - hydrated cement in the CBPB.

16.3 The 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. CBPBs were exposed at 20 °C / 65 %RH, 20 °C / 35 %RH or oven drying at 105 °C until equilibrium. After initial drying treatments, the CBPBs were reconditioned at 20 °C / 65 %RH, and then subjected to 20 °C / 90 %RH before cycling.

16.3.1 The Effect on the Behaviour under First Adsorption at 90 %RH

Figure 16.7 shows the mass change of CBPB subjected to re-wetting and further wetting after three different pre-drying regimes. The CBPB after 2 months storage under a normal environment after manufacture were firstly conditioned at 65 %RH, and then subjected to different drying regimes: 35 %RH, 65 %RH and oven drying. After drying the CBPB were re-wetted to 65 %RH and then furthered to 90 %RH. The ultimate values and final rate of length and thickness change under 65 %RH and 90 %RH are provided in Table 16.3.

The length and thickness changes versus mass change during further wetting are given in Figure 16.8 and 16.9. The coefficients of fitting lines are presented in Table 16.4.

Discussion

As shown in Figure 16.7, CBPB dried under 35 %RH or 105 °C showed considerable irreversible mass change, 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 the mass increase after further wetting were found to be

independent of pre-drying, although they somewhat depend upon the time to reach a constant value. After further wetting, all samples reached a similar level of mass change, increased by about 2.1 %, though with considerable irreversible initial mass decrease. The end points of mass gain lay on a straight line which are nearly parallel to the X - axis.

Unlike the behaviour for mass, depending on the drying schedules used, CBPB shows very different behaviour regarding changes in dimensions. There existed considerable irreversible dimensional shrinkage after re-wetting (see Table 16.3) - 0.023 % length change of CBPB with 35 %RH drying remained irreversible under 65 %RH re-wetting, and 5 times more remained with 105 °C drying. 0.085 % and 0.185 % of thickness shrinkage were irrecoverable for the former and the latter dried CBPB respectively. Moreover, further wetting resulted in different dimensional changes. CBPBs with drying pretreatment showed lack of recoverability in dimensions. The degree of irreversibility strongly depended on the degree of drying. Even after 90 %RH exposure, CBPB after 105 °C pre-drying did not expand to its original value at 65 %RH pre-conditioning, but with 65 %RH prolonged exposure had 0.06 % expansion and with 35 %RH drying produced 0.034 % expansion. A similar situation was seen in thickness changes (Table 16.3). These results indicate that pre-drying reduced the ultimate expansion on re-wetting and suggests that a stabilization process occurs in CBPB during pre-drying.

Comparing the difference in irreversible values between the different drying schedules for length with that for thickness under 65 %RH or 90 %RH re - wetting, or the different ultimate values between length and thickness (Table 16.3), it is suggested that there existed a structural change for cement paste in CBPB during drying, and that 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 unable to produce the capillary effect under low RH (65 %RH).

During further wetting, the dimensional changes plotted as a function of the mass change show different trends for different pre-drying treatments, though the theoretical predictive equations (13.26) fit. The ratio of the dimensional changes to mass change of CBPB apparently depends on the pre-drying schedules. The CBPB

with 105 °C drying had the lowest slope, that is, was stabilized most, the CBPBs with 35 %RH pre-drying had a slower change than that of the CBPB when only stored at 65 %RH prior to further exposure. The position of $\Delta L/\Delta M$ with different drying regimes was the same as that of $\Delta T/\Delta M$.

Since the mass upon wetting appeared to be recoverable but the length and thickness changes seemed to be irreversible it became very important to find out whether these changes were really irreversible, or the recovery was merely very slow. To answer this question, Helmuth and Turk (1967) conducted several experiments on cement paste. They found that although all pastes continued to expand throughout the re-wetting period, the prolonged expansions of these wet specimens are not believed to be slow recovery following drying shrinkage. The expansion rates are the same as the normal expansion rates. Also, it was found that the time required to re-wet depends upon the drying history. No more than a few days are required to re-wet the thin slab after short or mild drying exposures, though after severe or prolonged drying several weeks of re-wetting may be required. Re-wetting may be considered complete when the normal expansion rate for the paste during moist exposure is observed. In terms of the changing rates of CBPB tested (Table 16.3), it was concluded that the procedure of drying or wetting was complete and there did exist irreversible changes in both length and thickness, and whatever the drying histories are, the mass can recover to its original values.

The question arises as to why both the mass and dimensions are irreversible under re-wetting at 65 %RH, but further wetting resulted in a compensation of the mass decrease, while the dimensions remained irreversible? Part of the reason for this phenomenon was discussed in some detail in a previous paper (Fan, *et al*, 1996). In addition to this, there are some other factors, as described in chapter 12. One of the main reasons is attributable to 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, which are considered to be capillaries, or the behaviour of the hydroxyl groups in both the cellulose and lignin: on drying these groups are thought to satisfy each other and on re-wetting some continue to do so and are not available for water adsorption, or the plasticity which is related to

irreversible inelastic exchange of hydroxyl groups between neighbouring cellulose molecules (Skaar, 1988); a similar mechanism was found in cement paste: drying results in the closing of gaps between gel particles and between intercrystal layers of cement paste following expulsion of water confined between adjacent surfaces. The contraction of such small inter-solid gaps is accompanied by 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. Another possibility is that of temperature effects: it was found that the heating treatment affects the structure of the paste and its composition, and this effect is reflected in the properties of the paste. Generally speaking, heating results in a considerable reduction in shrinkage (Powers, *et al*, 1959). No pores of 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 (decrease) (Figure 16.7).

A combination of the fact that the mass change under 90 %RH was independent of initial drying with the dependence of dimensional changes on the initial drying conditions strongly 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.

16.3.2 The Effect on the Behaviour under Cyclic RH

After firstly exposing at 90 %RH, CBPB were subjected to cyclic RH. The mass and dimensional changes are shown in Figure 16.10, 16.11 and 16.12. The ultimate changing values of the CBPB under each condition in three cycles are presented in Table 16.5. Although the time dependence of the irreversible change will not be dealt with extensively in this thesis, two effects must be noted. Overall, for all samples, with the exposing time / increase in cycle numbers, the mass consistently increased

but the dimensions decreased.

Discussion

CBPBs processed by different pre-drying regimes show similar relationships between mass, length or thickness and exposure time / cycle. However, close scrutiny of the graphs indicates the values of each change in the CBPB under a certain period of RH exposure decreased under 35 %RH or 105 °C drying (Table 16.5). The order of changes is (whether mass or length or thickness) changes of CBPB with 65 %RH exposure > that of CBPB with 35 %RH drying > that of CBPB with 105 °C drying (with the exception of mass change under first 90 %RH and second 65 %RH exposure). Oven drying reduced the adsorption of the un-dried board 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.

The combination of results obtained from the first re-wetting and further wetting with those from cyclic RH exposure illustrated that drying resulted in the permanent stabilization 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.

16.4 Interim Conclusions 12

1) It has been shown that storage time had a significant influence in sorption behaviour of CBPB. Stabilization of CBPB after prolonged storage occurred by further hydration, carbonation or both. About 1/3 reduction in mass change was obtained for CBPB with 12 months 20 °C / 65 %RH exposure compared to that of 2 months under both adsorption and desorption.

2) The trend of changes versus time was similar for all three types of CBPBs, with

rapid change at the early stage of exposure.

3) The ratio of mass decrease of CBPBs between three different storage periods on moving from 90 %RH to 65 %RH was similar to that on moving from 65 %RH to 35 %RH. However, adsorption from 35 %RH to 65 %RH did not bring about observable differences, and adsorption from 65 %RH to 90 %RH resulted in a significant difference in mass increase between the three materials.

4) The rate of dimensional change to mass change slightly increased with increase in storage period. This must be related to the solid volume increase due to the further hydration of cement paste in CBPB. Over the range of RH tested the relationships between the mass decrease and drying shrinkage was represented by straight lines, but the decline in the rate of the relationship between mass gain and wetting swelling on moving samples from 65 % to 90 %RH indicated that there were two different types of water, adsorption and condensation.

5) The relationship of dimensional change to mass change was correlated to storage period, environmental and constituents parameters. The theoretical predictions (Equations 13.22 and 13.26) fitted the experimental data well but with different slopes and coefficients.

6) The ultimate values of mass and dimensional change at each stage within cyclic RH reduced with increasing storage periods, illustrating the further hydration or carbonation of cement paste in CBPBs. The most significant effect occurred when samples were subjected to 90 %RH, showing the effect of the condensation of moisture in mini pores of cement paste in CBPBs.

7) The behaviour of pre - dried CBPB was shown to depend strongly upon the drying schedules. 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.

8) The mass change of CBPBs, however, was independent of the pre-drying schedules after exposure at 90 %RH, indicating a structural change of CBPB after it had been pre - dried and the loss of some capillary function under lower RH, but greater size of pores were available for moisture condensation under high RH.

9) The ultimate irreversible values in dimensions, after re - wetting at 65 %RH, was about 0.02 % in length and 4 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. The permanent shrinkage must be a result of alternations of structure during the stabilisation process in terms of 1) different values of length or thickness changes between different drying schedules; 2) difference between the length and thickness at various drying schedules; 3) different rates of dimensional change to mass change (Figure 16.8 and 16.9) for CBPB with different pre-drying; 4) decrease in maximum values at each stage of cyclic RH (Figure 16.10, 16.11 and 16.12).

10) Predictive Equation 13.26 was applicable to the relationship between length (or thickness) and mass change. Slopes of fitted lines were dependent on the drying schedules, showing that drying stabilized the CBPBs

11) The stabilization by pre - drying treatments was reflected more significantly in the dimensions than in the mass. The reduction in dimensional change at each stage of consecutive cyclic RH was 105 °C drying > that with 35 %RH drying > that with 65 %RH exposure pretreatment.

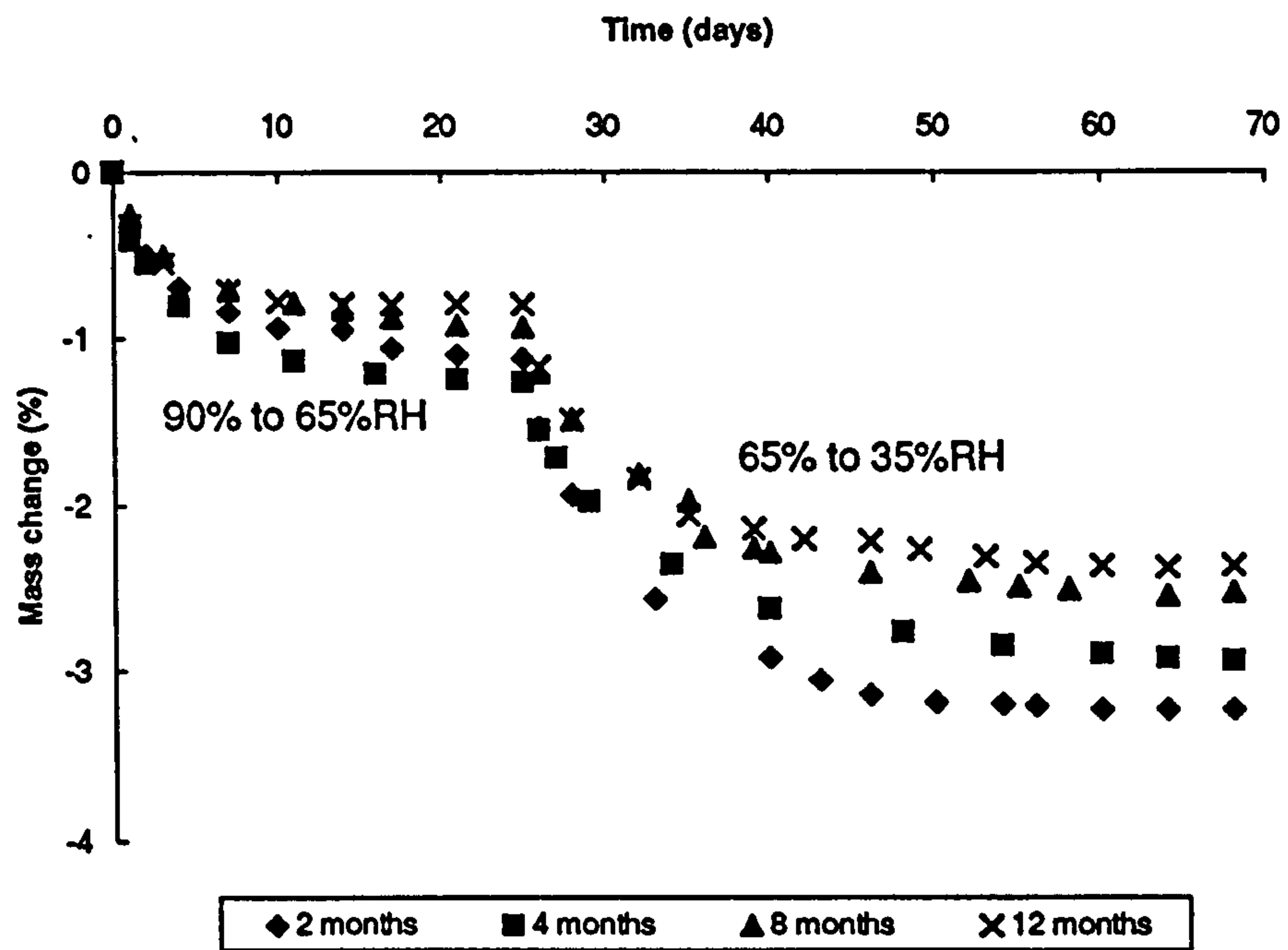


Figure 16.1 Effect of storage period on desorption of CBPB

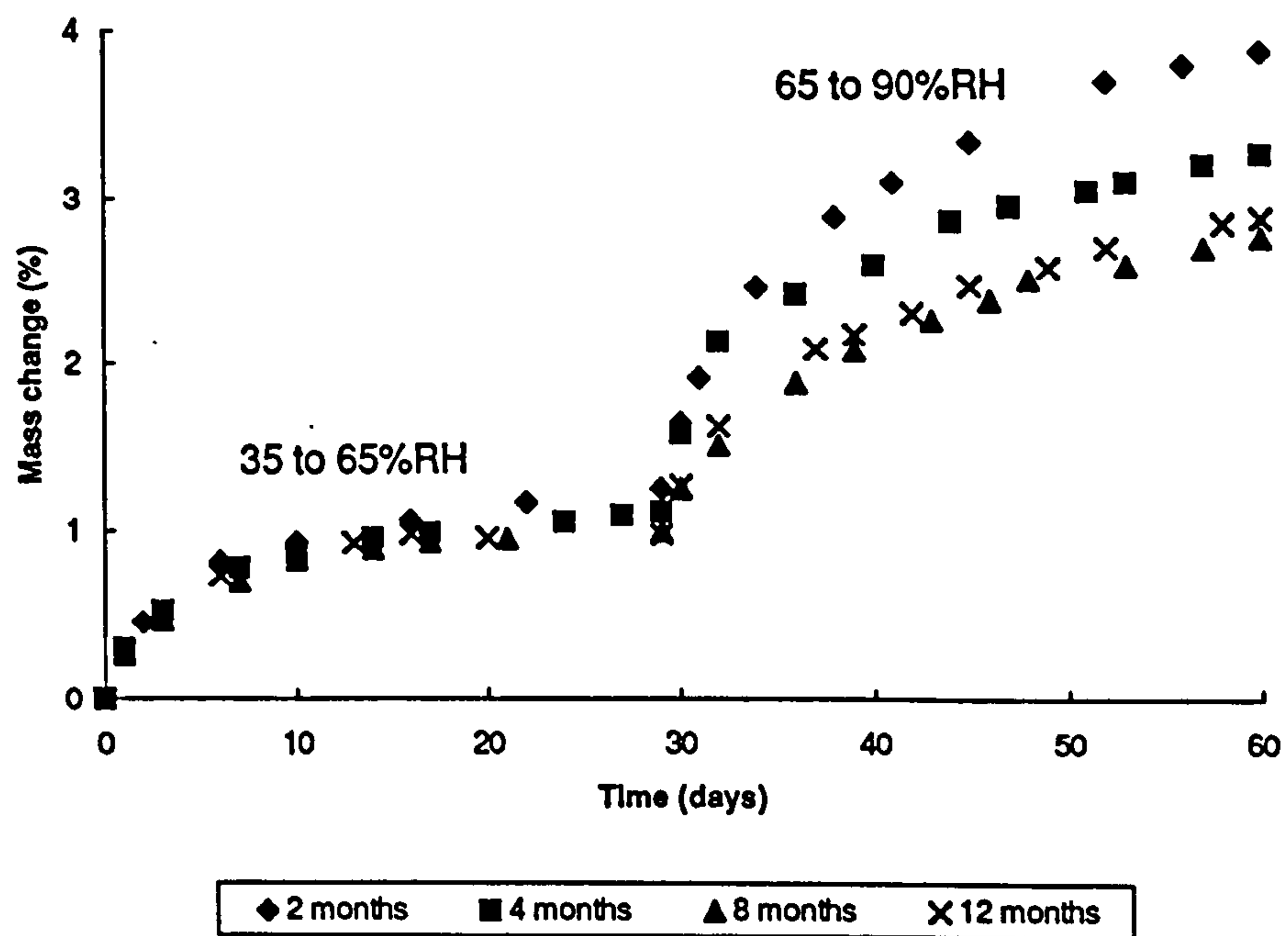
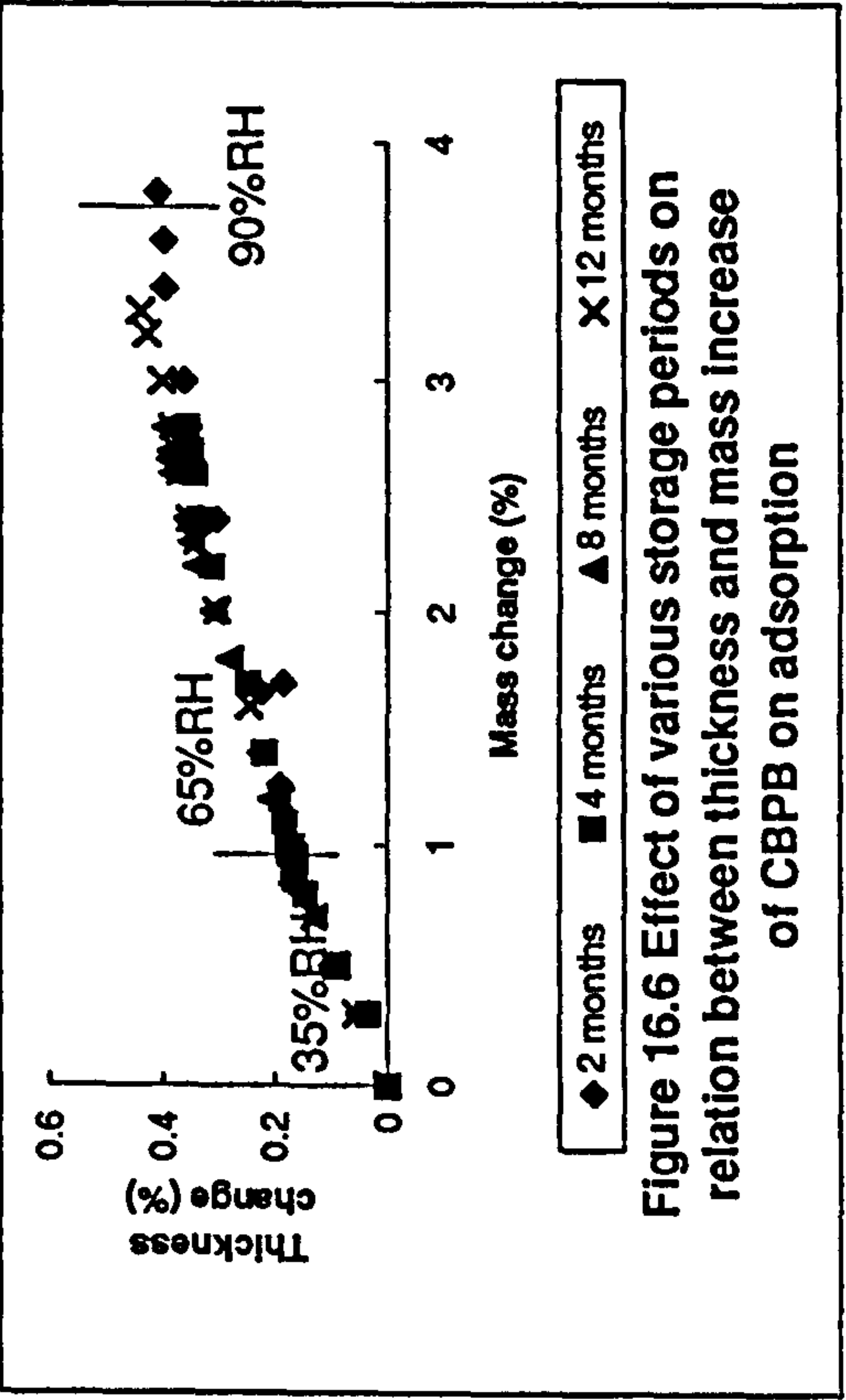
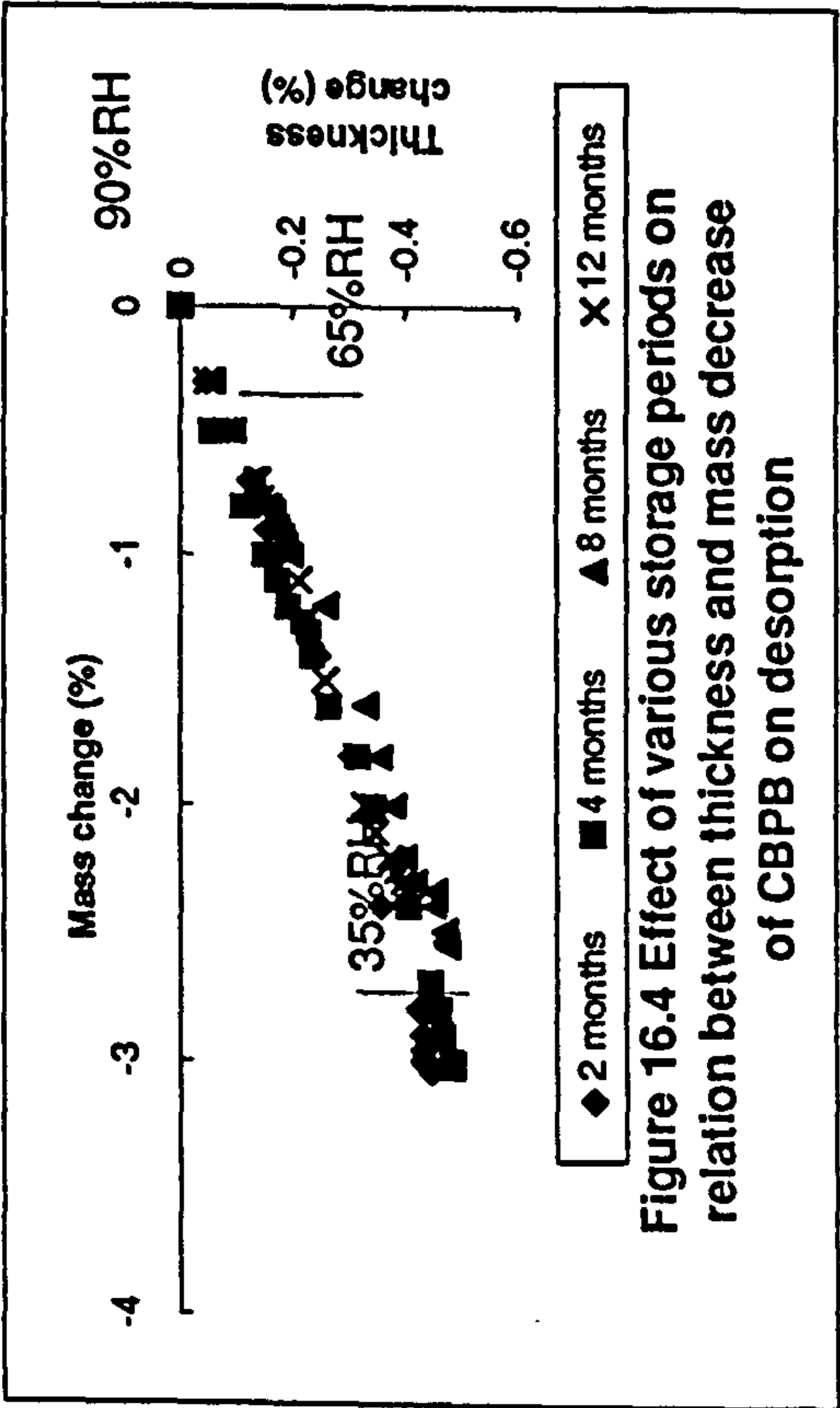
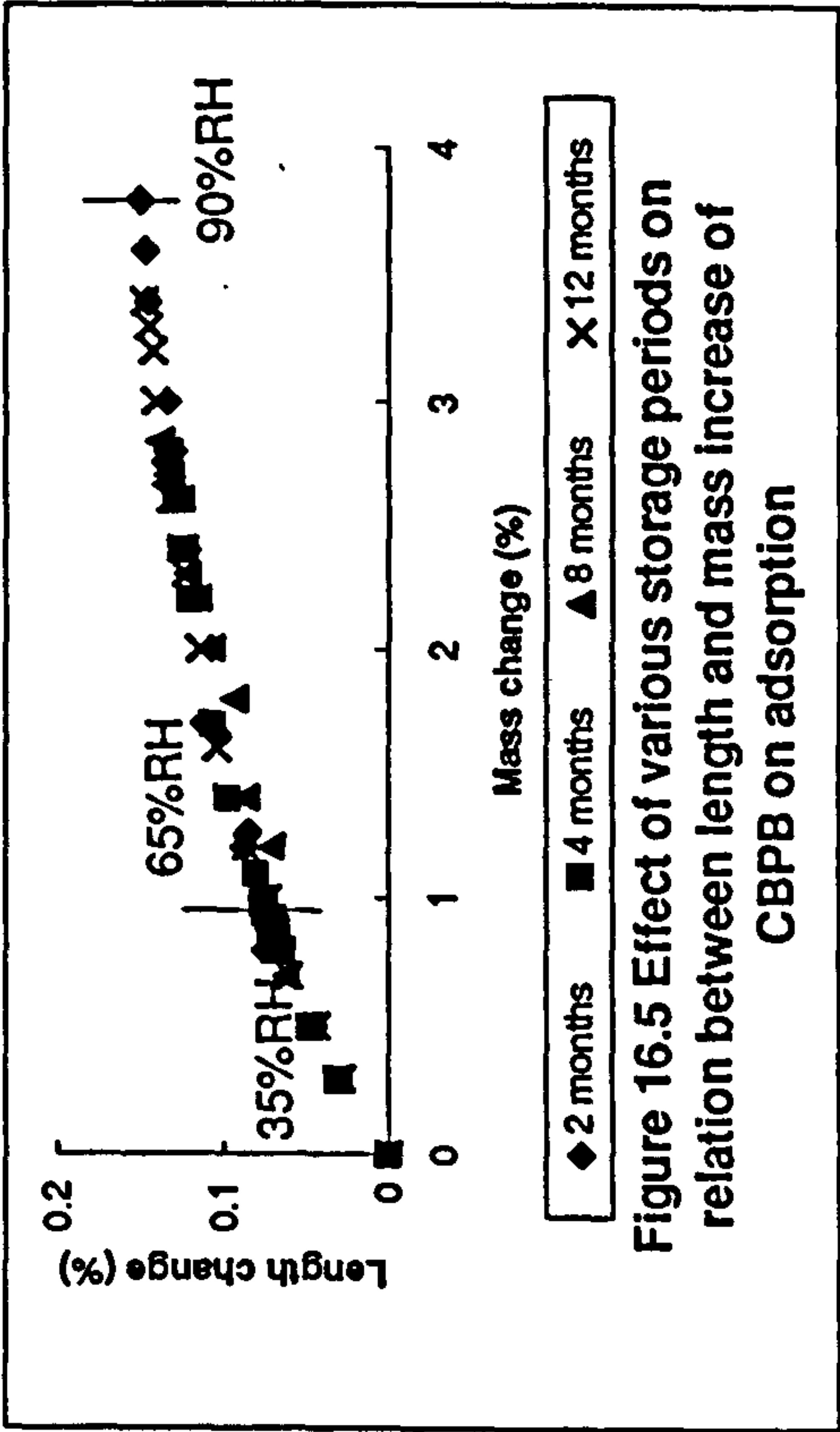
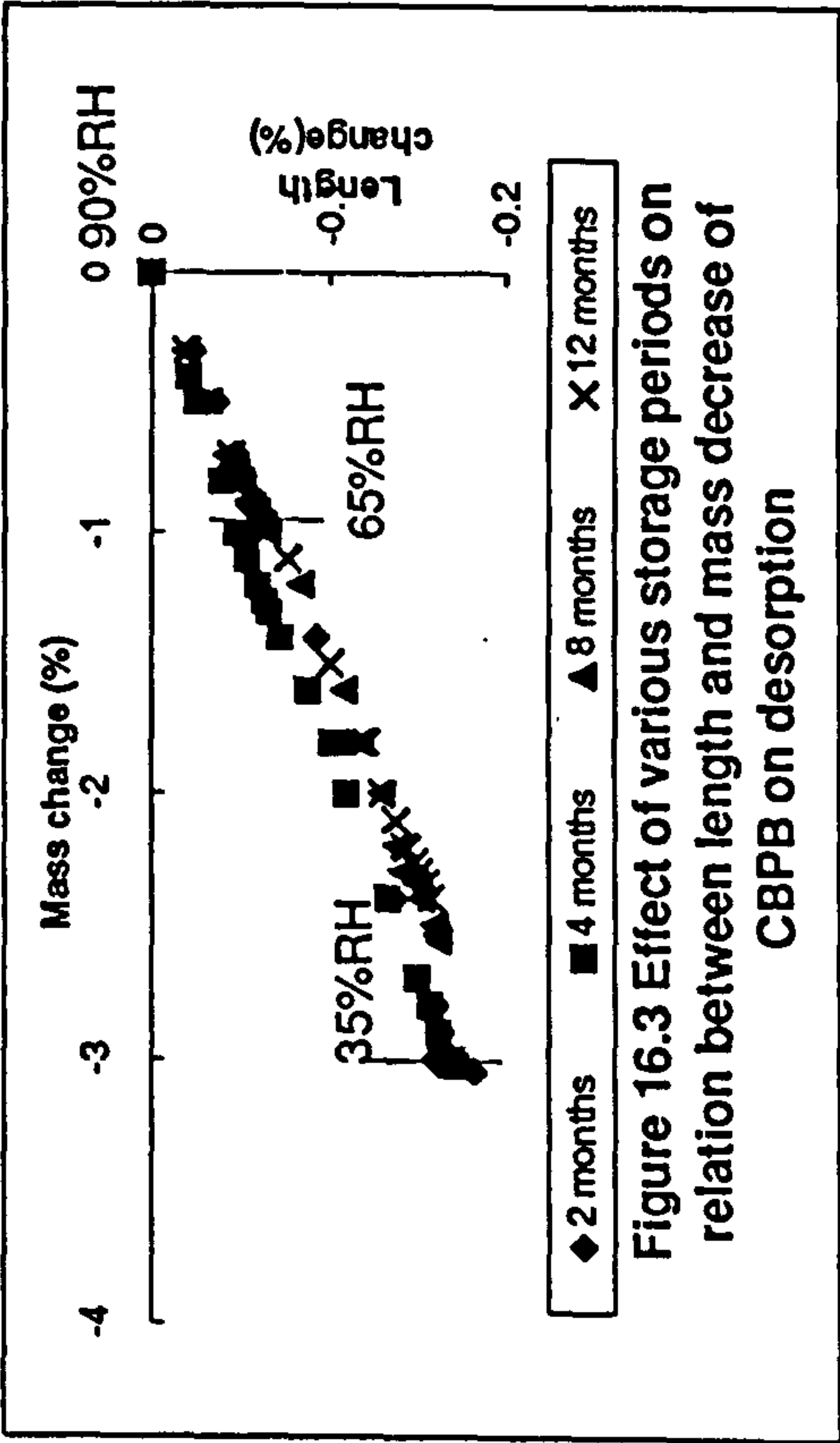
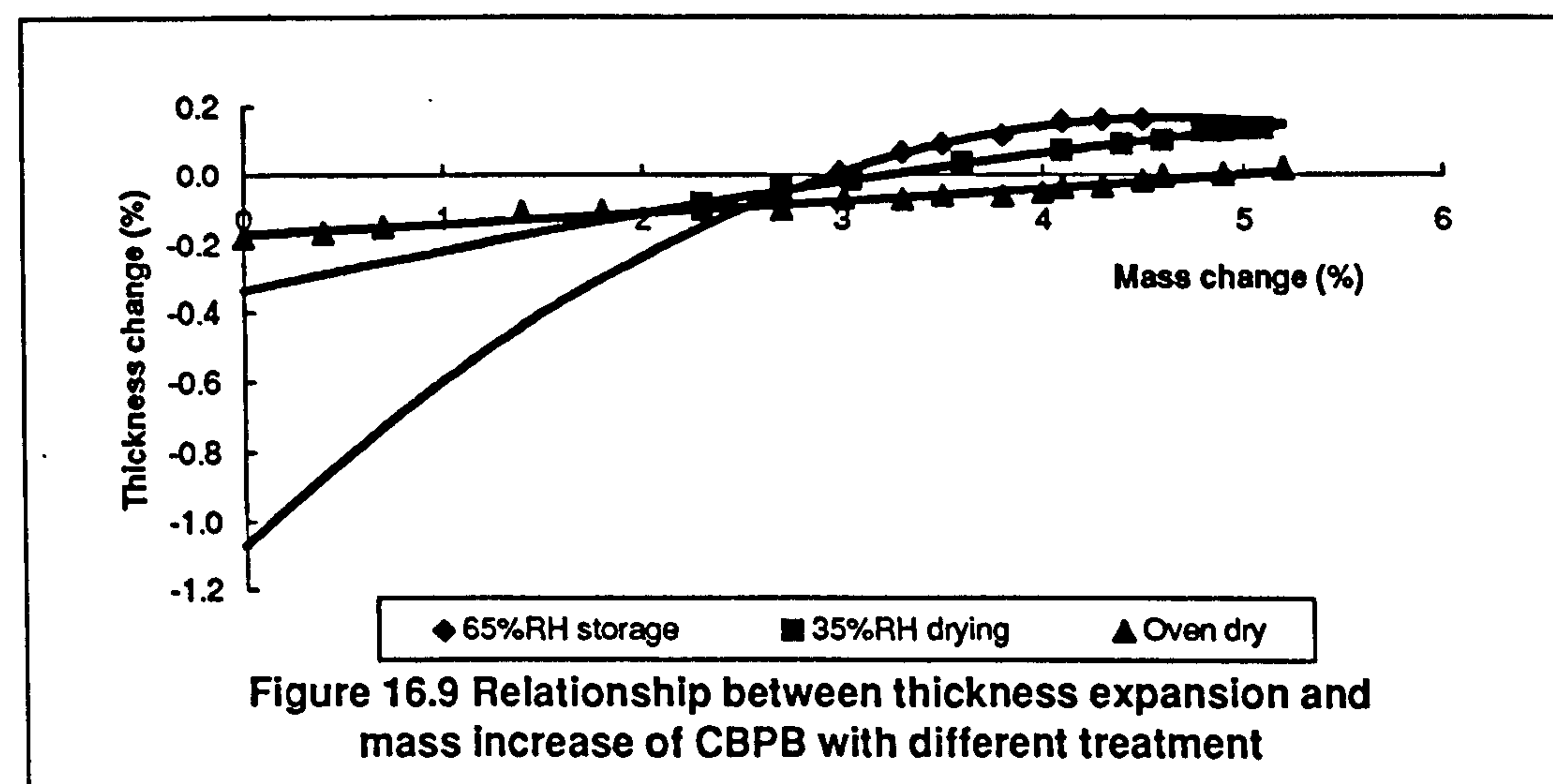
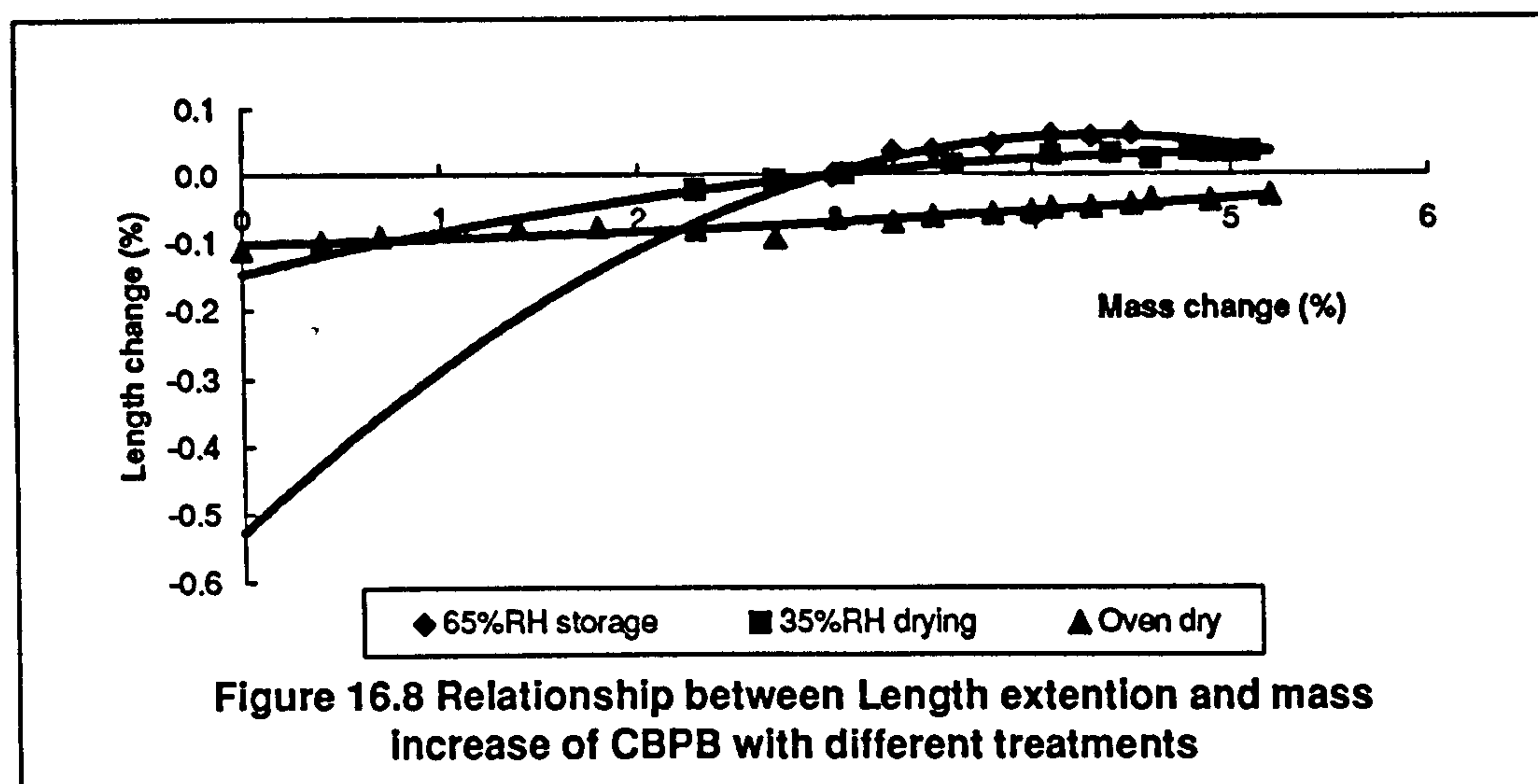
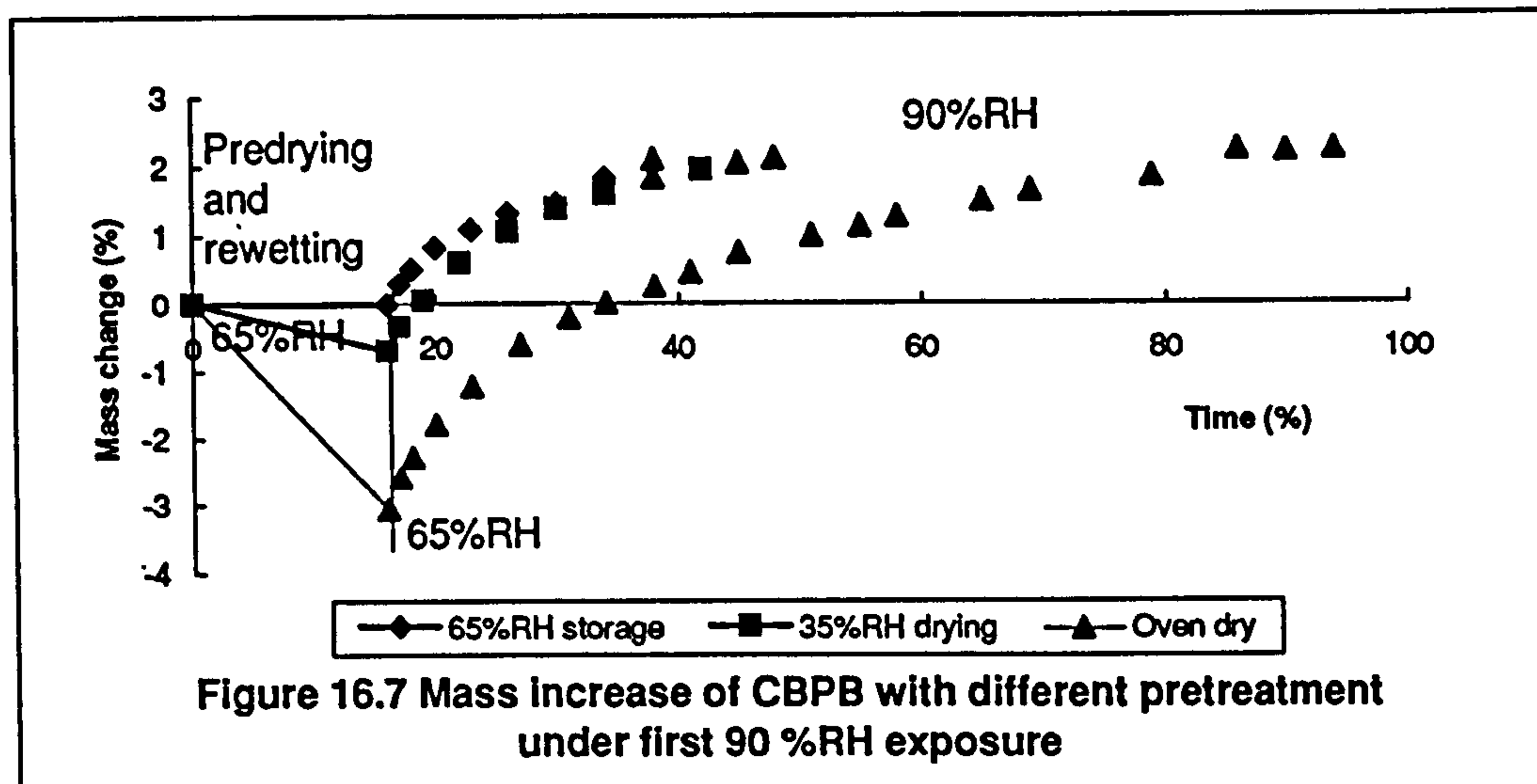


Figure 16.2 Effect of storage period on adsorption of CBPB





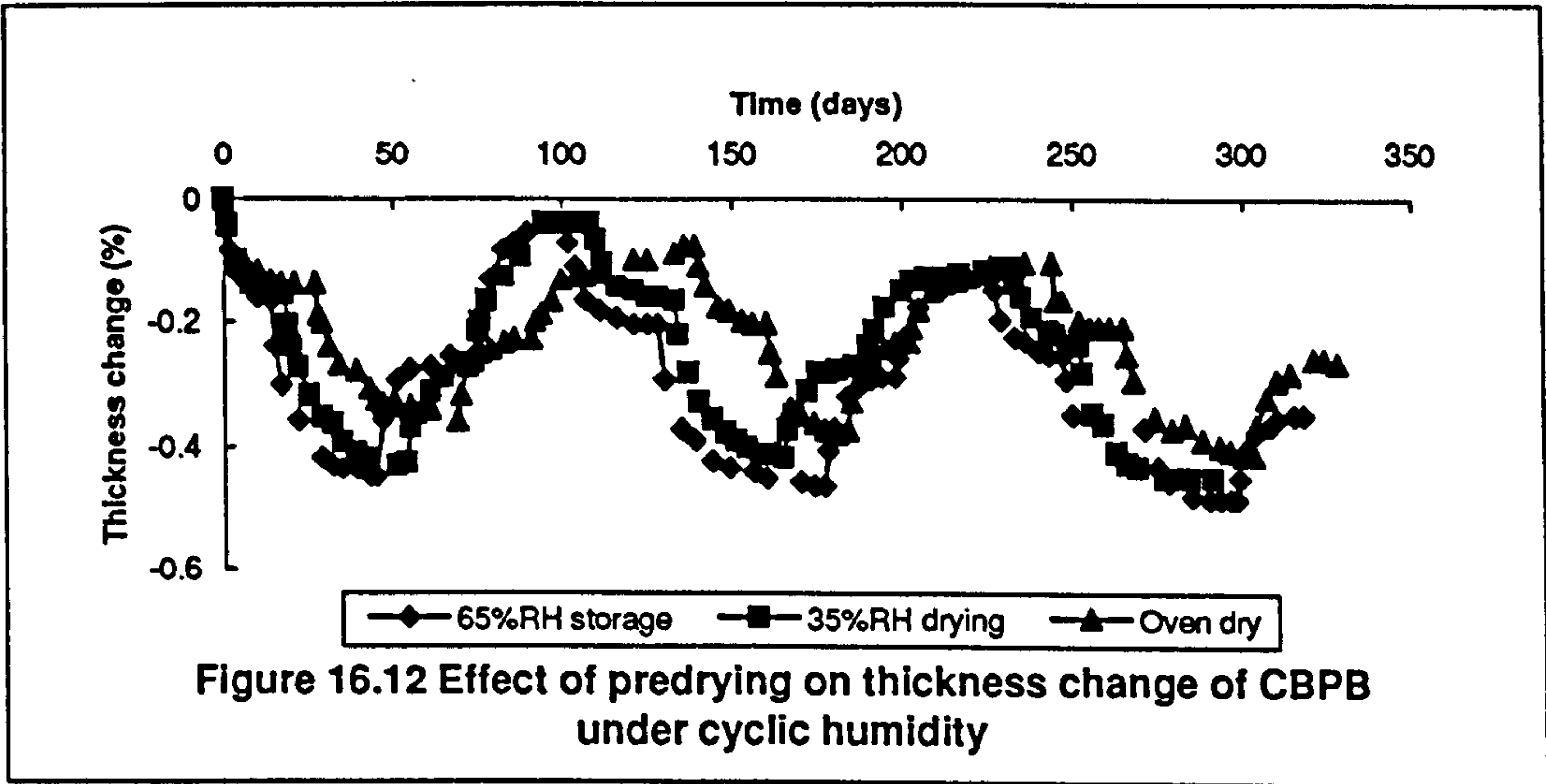
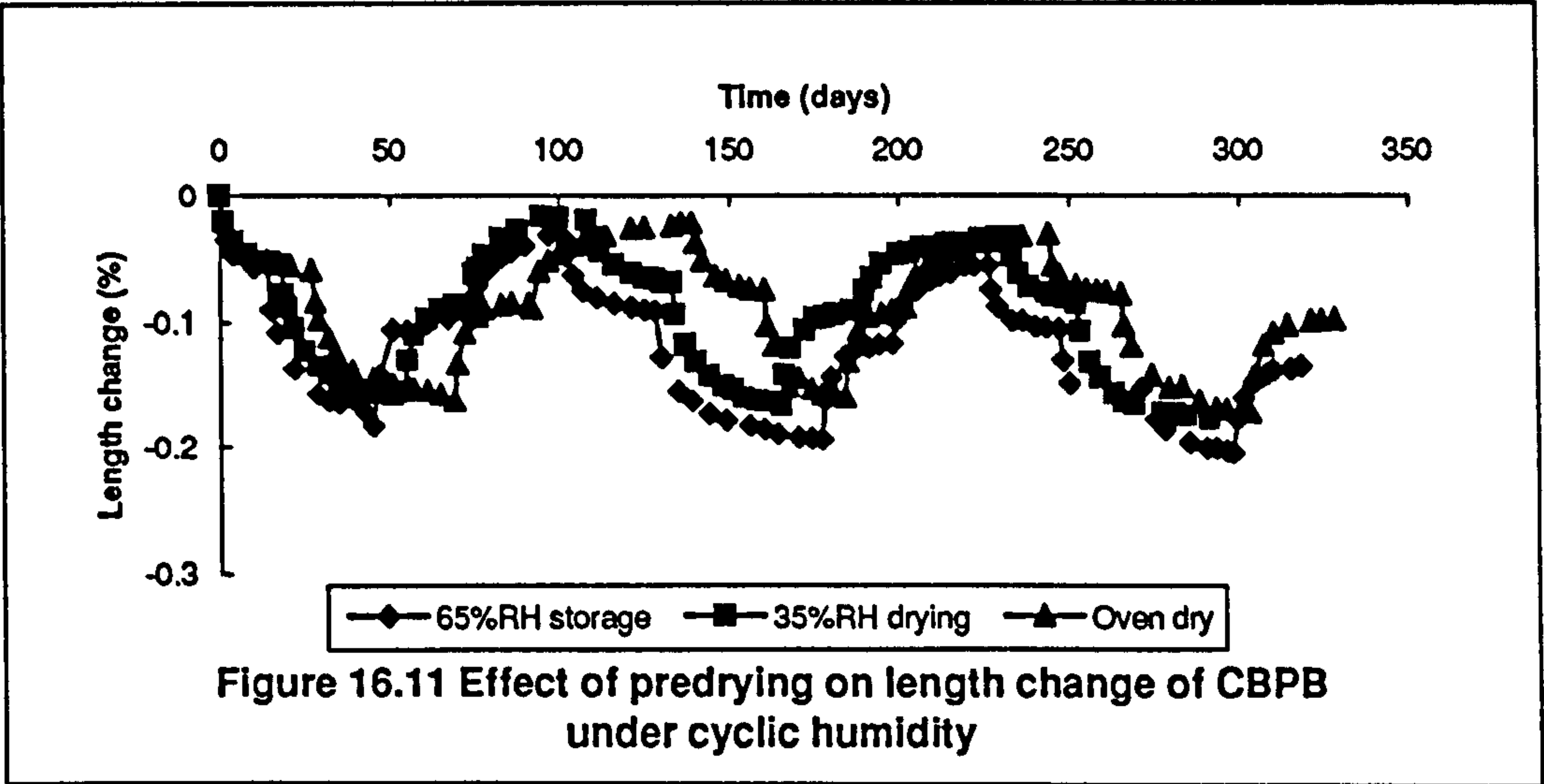
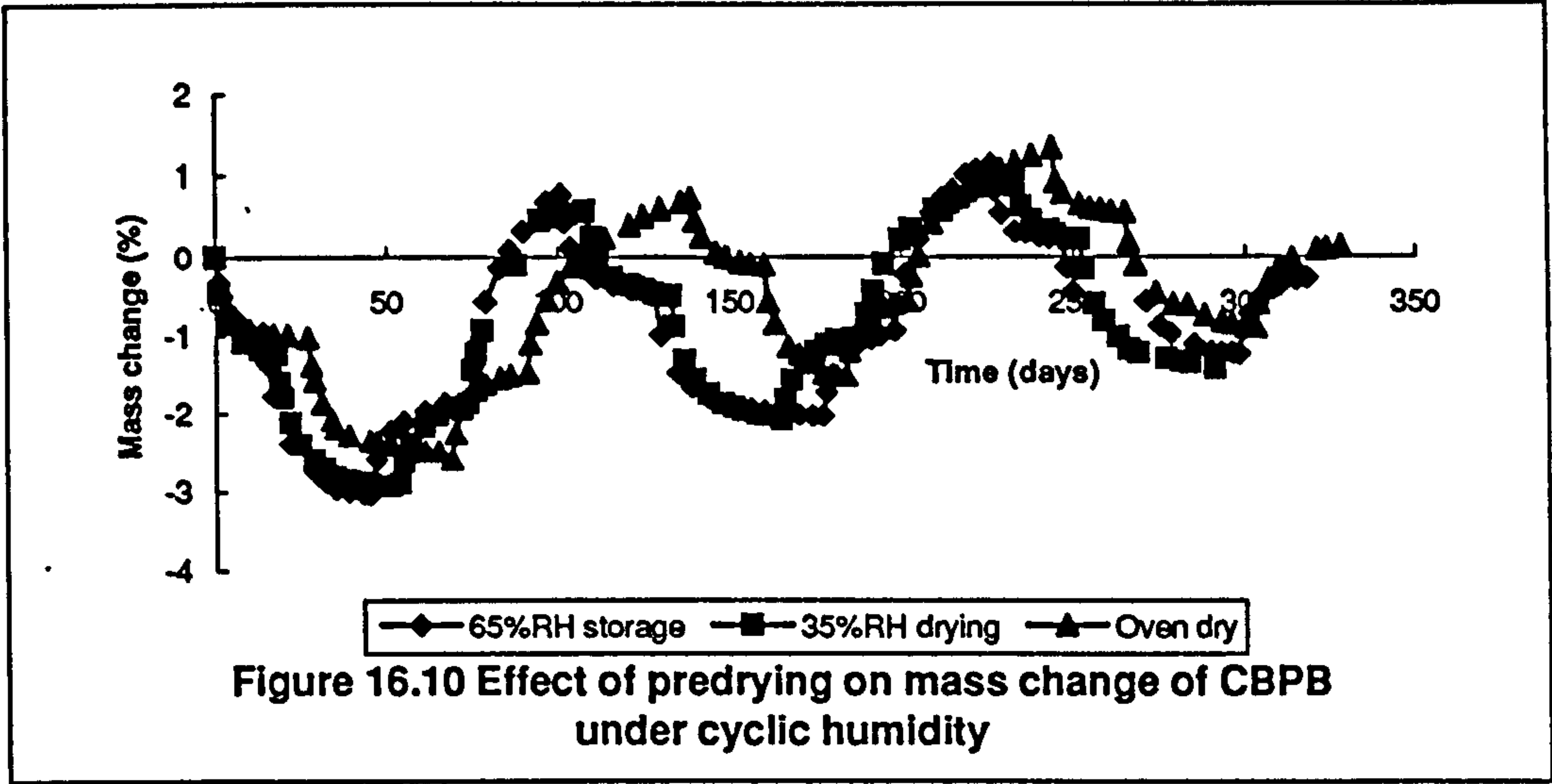


Table 16.1 The values of the coefficients A, K, C and R^2

Relation between	Storage period	A	K	C	R^2
		Desorption			
length and mass change	2		0.055	-0.006	0.99
	4		0.058	0.006	0.99
	8		0.064	-0.001	0.99
	12		0.066	0.000	0.99
thickness and mass change	2		0.143	-0.021	0.99
	4		0.166	0.003	1.00
	8		0.185	-0.010	1.00
	12		0.167	-0.010	1.00
Adsorption					
length and mass change	2	-0.0102	0.074	0.011	0.98
	4	-0.0152	0.087	0.005	1.00
	8	-0.0076	0.065	0.011	0.98
	12	-0.0110	0.077	0.007	0.99
thickness and mass change	2	-0.0114	0.146	0.021	0.98
	4	-0.0253	0.199	-0.005	0.99
	8	-0.0191	0.194	0.003	1.00
	12	-0.0154	0.180	0.007	1.00

Table 16.2 The effect of storage period on movement of CBPB subjected to cyclic RH

(the values represent the maximum change for each change in RH)												
RH (%)	Mass change (%)				Length change (%)				Thickness change (%)			
	2 months	4 months	8 months	12 months	2 months	4 months	8 months	12 months	2 months	4 months	8 months	12 months
90	2.124	2.141	1.713	1.698	0.076	0.063	0.056	0.047	0.231	0.191	0.202	0.162
65	-1.055	-1.350	-0.990	-0.786	-0.061	-0.065	-0.058	-0.051	-0.192	-0.188	-0.180	-0.156
35	-2.087	-1.631	-1.530	-1.550	-0.127	-0.103	-0.093	-0.104	-0.279	-0.252	-0.252	-0.246
65	1.255	1.095	0.947	0.953	0.085	0.080	0.071	0.071	0.190	0.179	0.174	0.168
90	2.531	1.802	1.701	1.946	0.066	0.057	0.057	0.066	0.188	0.180	0.171	0.218
65	-1.154	-0.838	-0.768	-1.046	-0.056	-0.045	-0.046	-0.054	-0.168	-0.135	-0.129	-0.173
35	-1.593	-1.408	-1.565	-1.003	-0.103	-0.098	-0.102	-0.097	-0.257	-0.224	-0.286	-0.246
65	1.090	0.899	0.970	0.920	0.077	0.068	0.076	0.074	0.172	0.157	0.190	0.162
90	2.052	1.761	1.607	1.552	0.061	0.057	0.057	0.057	0.162	0.147	0.191	0.167
65	-0.911	-0.767	-0.797	-0.686	-0.049	-0.046	-0.046	-0.045	-0.128	-0.129	-0.129	-0.106
35	-1.437	-1.460	-1.480	-1.428	-0.095	-0.096	-0.095	-0.092	-0.229	-0.258	-0.241	-0.229
65	1.080	1.050	0.900	0.902	0.073	0.077	0.073	0.070	0.170	0.180	0.213	0.158

Table 16.3 The ultimate values and final rate of length and thickness change of CBPB under 65% and 90%RH

Predrying	Length				Thickness			
	65%RH		90%RH		65%RH		90%RH	
	Ultimate value (%)	Final rate (%/day)	Ultimate value (%)	Final rate (%/day)	Ultimate value (%)	Final rate (%/day)	Ultimate value (%)	Final rate (%/day)
65%rh exposure	0	2.50E-04	0.06	2.50E-04	0	1.25E-03	0.151	1.25E-03
35% drying	-0.0233	2.50E-04	0.0335	2.50E-04	-0.084	1.26E-03	0.134	1.26E-03
105°C	-0.1144	2.60E-04	-0.036	2.60E-04	-0.185	1.39E-03	0.017	1.39E-03

Table 16.4 The slope and coefficients B, C and R²

Relation	between length and mass change				between thickness and mass change			
	65 %RH	35 %RH drying	105 °C oven drying		65 %RH	35 %RH drying	105 °C oven drying	
Pretreatment								
A	-0.0313	-0.0066	0.0013		-0.0571	-0.0061	0.0017	
B	0.2708	0.0688	0.0070		0.5311	0.1246	0.0264	
C	-0.5283	-0.1472	-0.1035		-1.0708	-0.3383	-0.1724	
R²	0.96	0.98	0.91		0.99	1.00	0.97	

Table 16.5 The effect of initial pretreatment on behaviour of CBPB subjected to cyclic RH

RH (%)	Duration (days)	Mass change (%)				Length change (%)				Thickness change (%)			
		65%RH exposure	35%RH drying	105°C oven dry	65%RH exposure	35%RH drying	105°C oven dry	65%RH exposure	35%RH drying	105°C oven dry	65%RH exposure	35%RH drying	105°C oven dry
90	10	1.334	1.758	2.440	0.059	0.050	0.042	0.156	0.151	0.095			
65	14	0.947	0.709	0.967	0.054	0.052	0.051	0.168	0.156	0.134			
35	31	2.087	1.694	1.418	0.127	0.103	0.094	0.279	0.274	0.199			
65	21	1.255	1.039	1.113	0.085	0.069	0.076	0.190	0.157	0.129			
90	27	2.531	2.354	1.802	0.065	0.068	0.056	0.218	0.229	0.122			
65	21	1.154	1.047	0.810	0.058	0.049	0.052	0.168	0.123	0.129			
35	32	1.530	1.572	1.402	0.095	0.098	0.084	0.257	0.251	0.168			
65	21	1.090	1.039	0.948	0.077	0.076	0.071	0.172	0.145	0.140			
90	28	2.052	1.747	1.527	0.061	0.058	0.053	0.162	0.157	0.123			
65	21	0.911	0.732	0.789	0.049	0.048	0.047	0.128	0.127	0.106			
35	39	1.320	1.624	1.436	0.091	0.091	0.090	0.223	0.211	0.202			

Chapter 17

EFFECT OF EDGE SEALING ON THE VAPOUR UPTAKE OF CBPB

17.1 Introduction

Flow of moisture through a material may be by virtue of its permeability, by which fluid is forced through the material in response to an imposed absolute pressure, or by diffusion, by which fluid is driven by the action of a chemical moisture potential, such moisture giving rise to surface forces and surface tension forces in the capillaries. There are many factors affecting the flow in both cement paste and wood materials. However, since cement paste is an isotropic material, the flow, as well as the volumetric change, resulting from RH changes, is the same in all directions. This is in contrast to wood, with its anisotropic nature, where the flow in the three principle axes is considerably different: longitudinal permeability is about 10^4 times the transverse permeability.

The raw materials used in CBPB manufacture are cement and wood chips. The cement particle is relative uniform but is much smaller in size compared to the chips; in addition to this, wood "chips" in fact covers everything from wood flour to large chips and slivers. With these materials the resultant structure of CBPB is characterised by a much more uniform bulk density for the surface layer (but lower than in the core) with a homogeneous core section (confirmed in chapter 4). On forming most chips in CBPB fall flat, depending on the types of forming machine and process parameters.

When CBPBs are cut the more complex edge surfaces are exposed compared to the structure of bottom or top faces, and a higher percentage of the side face area is occupied by the wood chips. The combined effect of size of particle, different properties of raw materials, structure and different constituents along the different directions, may contribute to a significant degree to the flow of moisture when CBPBs are subjected to changing RH. This chapter was undertaken with the purpose

of examining these effects. The results obtained from both coated and uncoated CBPB are presented and compared.

17.2 The Ratio of Exposed Area of CBPB with Edges Unsealed to that with Edges Sealed

To examine the effect of exposed edges on mass and dimensional changes due to the moisture flow CBPB samples were subdivided into two groups, with the edges of one group being sealed with two coats of epoxy (section 3.2.4), and the other group being exposed unsealed. The percentage of exposed area for the CBPBs both with and without edge sealing was calculated in order to quantitatively evaluate the effect of edge flow when CBPB is subjected to cyclic RH.

The size of CBPB used was 600 x 300 x 18 mm and the ratio of exposed area of CBPB with edges unsealed to that of CBPB with edges sealed was

$$R = \frac{LB + LT + BT}{LB} = 1.09$$

Where L, B and T are the length, width and thickness of samples respectively.

17.3 Effect of Edge Sealing on the Behaviour of Uncoated CBPB

Results

The mean values of mass, length and thickness change of CBPB under three complete cycles (65 - 90 - 65 - 35 %RH) are presented in Figures 17.1, 17.2 and 17.3 . In these Figures results obtained from uncoated sealed and unsealed CBPB are given. According to the ratio, R, the mean change values unsealed were corrected, and modified values for mass, length or thickness change are plotted in the corresponding graphs, (those curves without marker). If the flow through the top and bottom faces of the boards is the same as that through the side faces, the modified curves should coincide with the curves derived from the CBPB with sealed edges.

For simplicity, only the behaviour of samples within one complete cycle was

detailed. Figure 17.4 A is given for this purpose, illustrating a numerical comparison of the maximum percentage change of mass, length and thickness of CBPB over various durations within the first complete cycle. Figure 17.4 B is the ratio of maximum change of unsealed to sealed CBPB over the corresponding regimes as those in Figure 17.4 A.

However, as the number of cycles increases, the efficacy of the edge seal may change. The relationship between the number of cycles and the effect of edge seal on the behaviour is shown in the Figure 17.5, the markers, such as "I - de", in the X - axis refer to the first cycle and whole desorption, covering from 90 %RH to 65 %RH and then to 35 %RH.

The significance of the effect of edge sealing is calculated in Table 17.1, which summarises the t - test analysis of variance for mass, length and thickness changes between uncoated CBPBs with edges both sealed and unsealed.

Discussion

The values obtained from the uncoated CBPBs with and without edge sealing at a given imposed RH are fairly close (Figures 17.1, 17.2 and 17.3), producing very similar trends of change in mass, length and thickness. Overall the behaviour of both groups of CBPBs followed the principle rule of the behaviour mentioned earlier: as the number of cycles increases, the mass increases but dimensions decrease.

The modified curves, in Figures 17.1, 17.2 and 17.3, show that edge flow has a greater effect on the mass change than on the dimensional change, especially when CBPB were exposed under adsorption (Figure 17.4 A). The modified curves for mass change lie between the curves arising for the CBPB with and without sealed edges, while the modified curves for length and thickness changes do not always lie between those curves, particularly exceptions being for those curves representing CBPB under desorption: in this case, the modified curves are above curves of CBPBs having both sealed and unsealed edges. These indicate that flow through edges is higher than that through the top or bottom faces of CBPB due to the different structure of the side and top or bottom faces. However, this does not bring about the same effect on the dimensional changes. By virtue of these phenomena, two

possibilities are suggested: one is that most of the moisture through the edge may become located in the larger pores within CBPB, which consequently results in lower percentage dimensional changes; another situation is that the higher percentage of exposed area of chip on the side faces could adsorb more moisture, but resulting dimensional changes in the individual particles are restrained by the cement paste.

The ratio of maximum change of CBPB with edges sealed to edges unsealed over the various conditions confirm the above results (Figure 17.4 B). The ratio of mass change is about 1.15 for first adsorption, when samples were moved from 65 %RH to 90 %RH, higher than the ratio of area (1.09), while the ratios for length and thickness are both lower than 1.09, and there is no difference observed for the thickness changes.

The effect of edge sealing is also related to the level of RH and the history of sorption (Figure 17.4 B). Three facts could be derived from this Figure: whether for mass or dimensions, the effect of edge flow increases with the level of imposed RH (comparison of changes over 65 %RH to 90 %RH with those over 35 %RH to 65 %RH); the effect of edge flow under adsorption is more pronounced than under desorption, particularly for the first adsorption - desorption cycle; and the third result is that the degree of the effect of edge flow on the mass change > length change under adsorption, but the level of the effect on mass change < length change under desorption.

Overall, the effect of edge flow on the mass, length and thickness changes of CBPBs is decreasing as the number of cycles increases (Figure 17.5). The ratios of maximum changing values of unsealed to sealed CBPB under the first desorption (from 90 %RH till 35 %RH) are 1.023, 1.037 and 0.996 for mass, length and thickness respectively, and under the third desorption the ratios are 1.018, 1.022 and 0.968. A slightly more significant reduction is observed during adsorption, with only 97 %, 96 % and 97 % of the effect under the second adsorption from 35 %RH to 90 %RH compared with the first adsorption.

In Figure 17.5, there is also an indication of an overall reduced change in the thickness of CBPB without sealed edges compared to that with sealed edges, the values of the ratios of maximum change of unsealed to that sealed are below 1.00. This phenomenon, in contrast to the changes in both mass and length, is not difficult

to explain. If the behaviour of CBPB discussed earlier is reconsidered, the principle trend is that the maximum change values of CBPB under a certain exposure, whether mass, length or thickness, decreases with the number of cycles or the exposure duration. This suggests that when unsealed CBPBs were subjected to an atmospheric environment, local effects on edges occurred, and the degree of change in the edge was greater compared to the total effect of the surrounding air on the CBPB, with the maximum change of thickness measured near the edges of the samples over the period being less than that of sealed CBPBs over the same duration.

Although edge flow has a certain influence on the mass, length and thickness of CBPB, it is unknown if it is significant when considering the whole change of CBPB under service environments. This was examined in Table 17.1.

The analysis shows that edge flow had no significant effect on both mass and dimensional change of uncoated CBPB. The t - values for length and thickness changes are extremely low. The higher t - values for mass change also confirm the above discussion.

17.4 Effect of Edge Sealing on the Behaviour of Coated CBPB

A summary of the ratios of the maximum changes of CBPB with edges sealed to that of edges unsealed, before the boards were coated with two coats of CPB sealer, acrylic sealer or styrene butadiene sealer, is presented in Table 17.2. A summary of the t - test analysis is shown in Table 17.3.

Like the results from uncoated CBPBs, there is a certain effect of edge flow on the mass, length and thickness when CBPBs were exposed to cycling RHs. However, compared to the values arising from the uncoated CBPB, a greater deviation was produced: that is because only very slight changes in mass and dimensions of CBPBs after coating with sealers can be observed in this case.

Like the behaviour in the thickness of uncoated boards, CBPBs coated with acrylic sealer (water-borne) with their edges unsealed had a reduced mass and length change compared to the CBPBs coated with CPB or styrene butadiene sealer. The explanation for this phenomenon can be discussed primarily in terms of the properties of the sealers. A comparison of the properties of the three sealers shows

that the acrylic sealer had a lower solid content, and the penetration was higher than those of other two sealers. This water borne sealer also exhibits less efficacy on the reduction of mass and dimensional changes of CBPB subjected to changing RH (see chapter 18). The further penetration of acrylic on the edges, when the sealer was dried, may result in greater blocking of flow or create barriers to water contact within CBPB compared to the CBPB coated and edges sealed CBPB.

The t - test analysis on the mass, length and thickness changes of coated CBPB for sealed and unsealed edges (whatever the types of sealers are) also show that the edge flow had no effect on the whole results evaluated.

17.5 Interim Conclusions 13

- 1) The results obtained in this part of the study showed that edge flow had an influence on the mass, length and thickness changes of both uncoated and coated CBPB. However, the t - test analysis showed that from the results obtained it was not significant.
- 2) The flow through the edges of CBPB was higher than that through the top or bottom faces because of the difference in the structure of both top / bottom and side faces. However, the principle trends of changes in mass and dimensions of CBPB with edges unsealed under cyclic RH were still similar to those of CBPB with edges sealed: that is, as the number of cycles increased, the mass increased but the dimensions decreased.
- 3) The results further demonstrated three facts: whether for mass or dimensions, the effect of edge flow was increased with the level of imposed RH; the effect of edge flow under adsorption was more pronounced than under desorption (particular for first adsorption - desorption cycle); the degree of the effect of edge flow on the mass change > on the length change under adsorption, but the level of effect was on the mass change < on the length change under desorption.
- 4) A reduction of the effect of edge flow can be induced by a prolonged exposure

period or by increasing the number of cycles.

5) Edge exposure promoted the carbonation of cement paste, resulting in local favourable effects on the local thickness change but an adverse effect on the mass change of CBPB under cyclic RH.

6) The effect of edge sealing was dependent of the types of sealers. The capability of penetration played an important role on the behaviour of coated CBPB due to the effect of edge flow. The sealer with higher penetration brought about a favourable effect on the mass and dimensional changes of CBPB under cyclic RH.

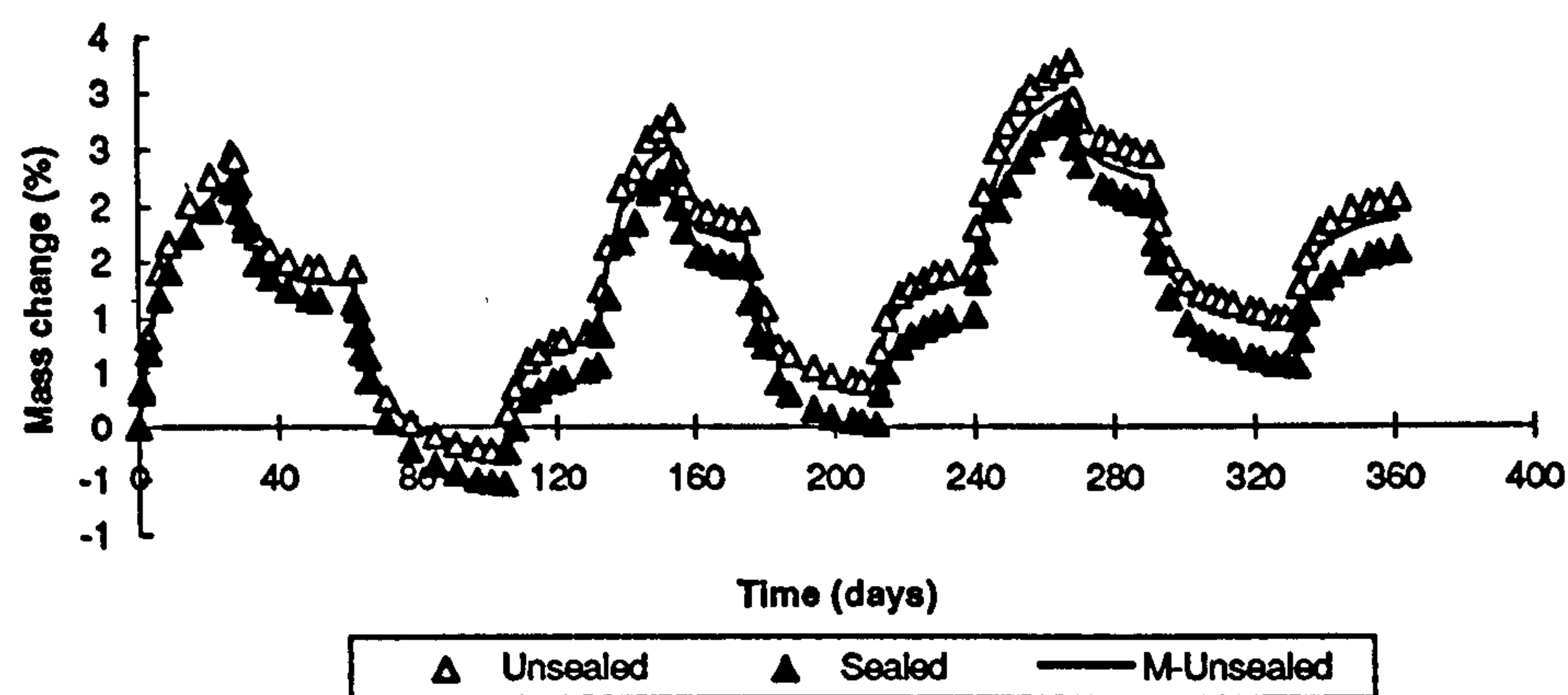


Figure 17.1 Effect of edge sealing on mean mass change of uncoated CBPB under cyclic RH

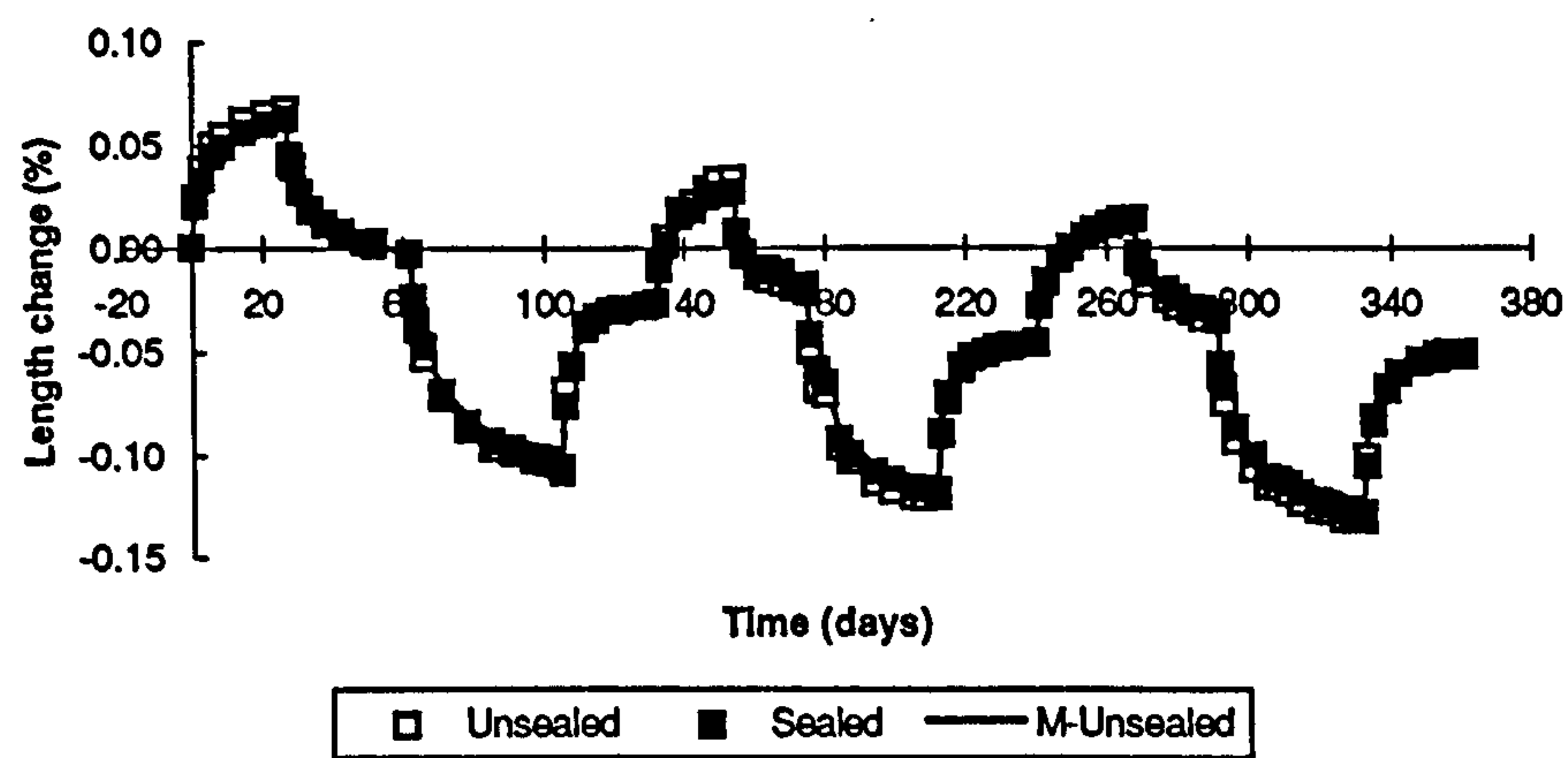


Figure 17.2 Effect of edge sealing on mean length change of uncoated CBPB under cyclic RH

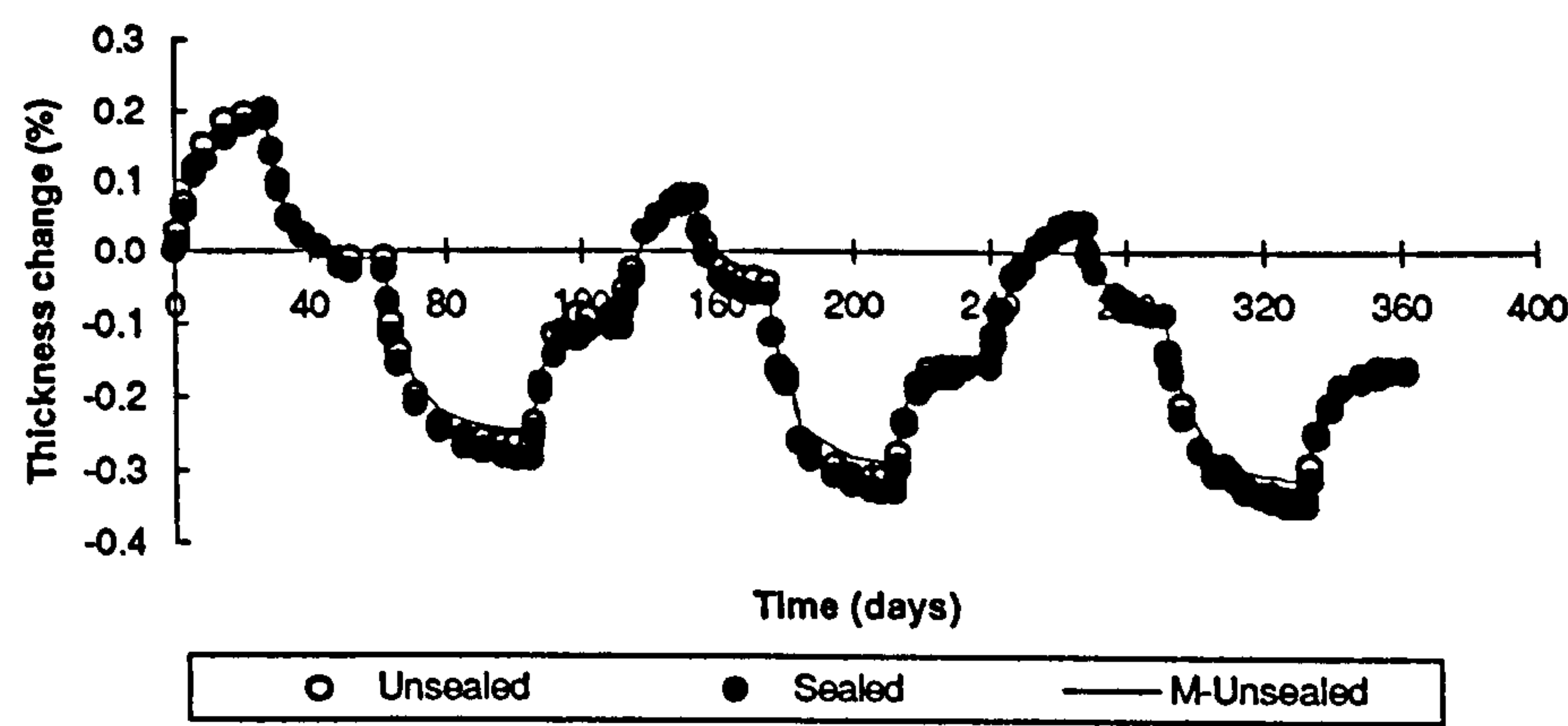


Figure 17.3 Effect of edge sealing on mean thickness change of uncoated CBPB under cyclic RH

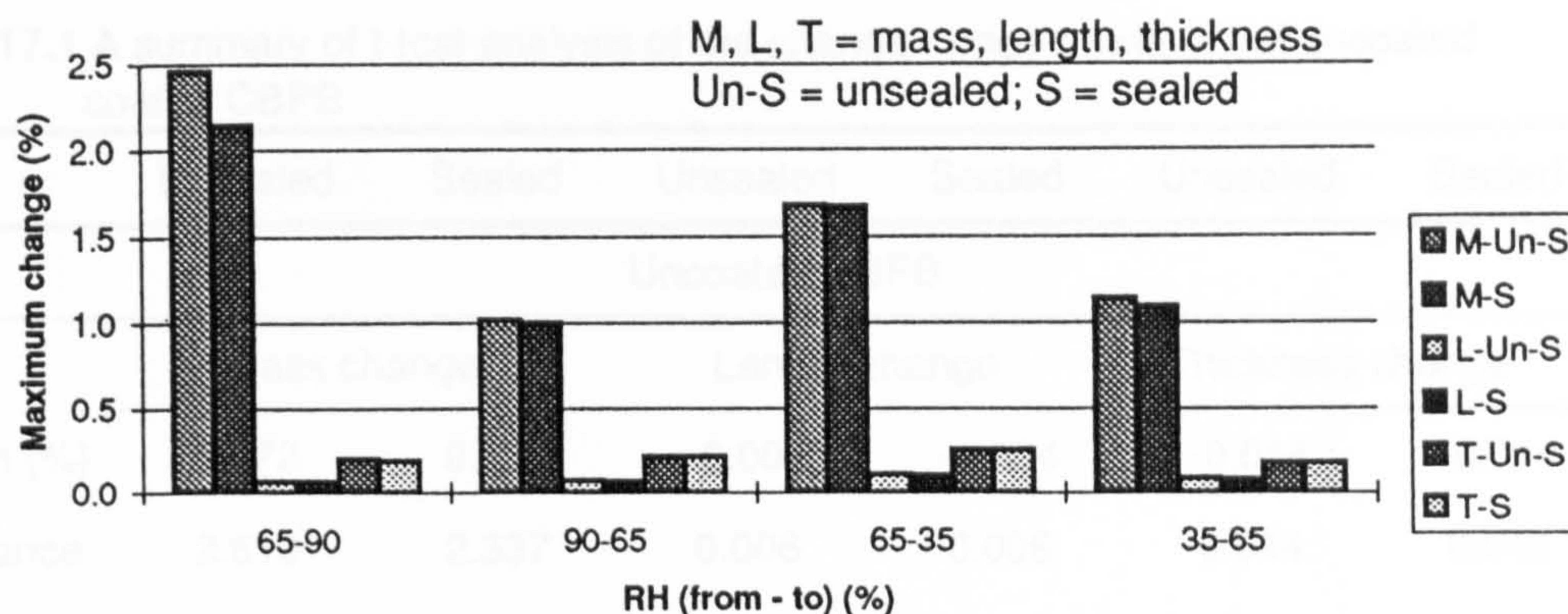


Figure 17.4A Maximum percentage change in values of mass, length and thickness of CBPB over various conditions within first complete cycle

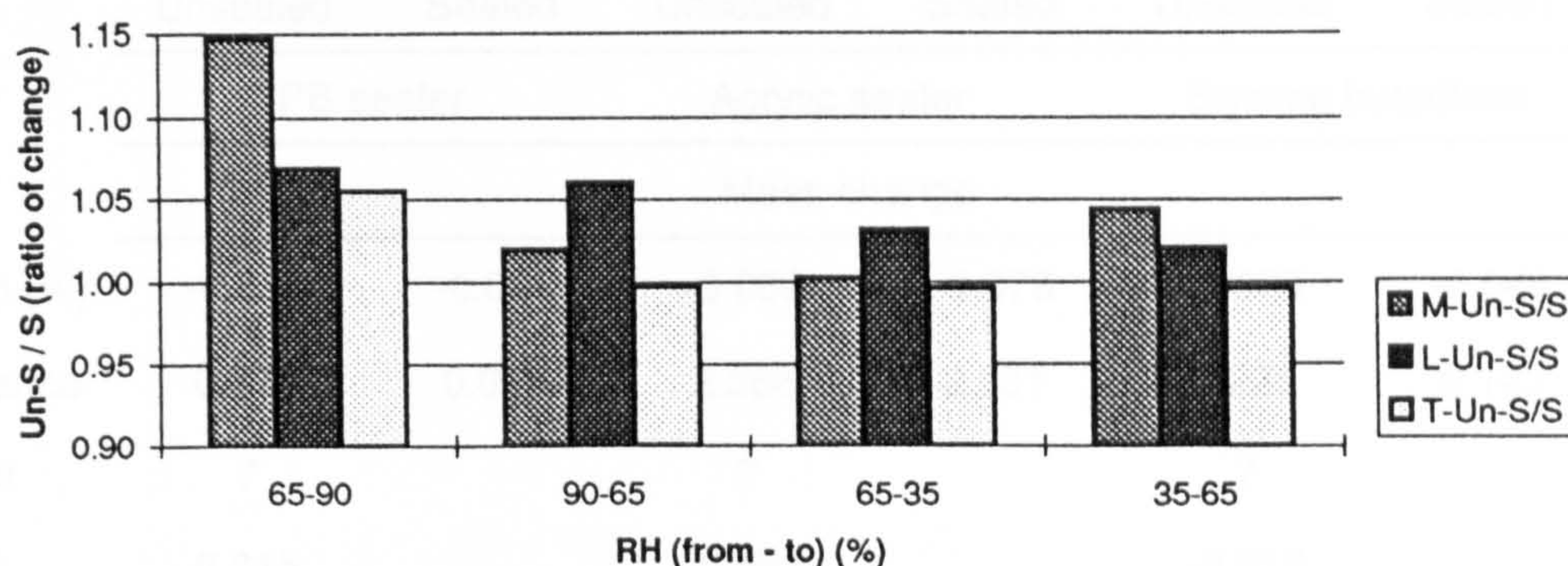


Figure 17.4B The ratio of maximum change of unsealed CBPB to sealed CBPB over various conditions within first complete cycle

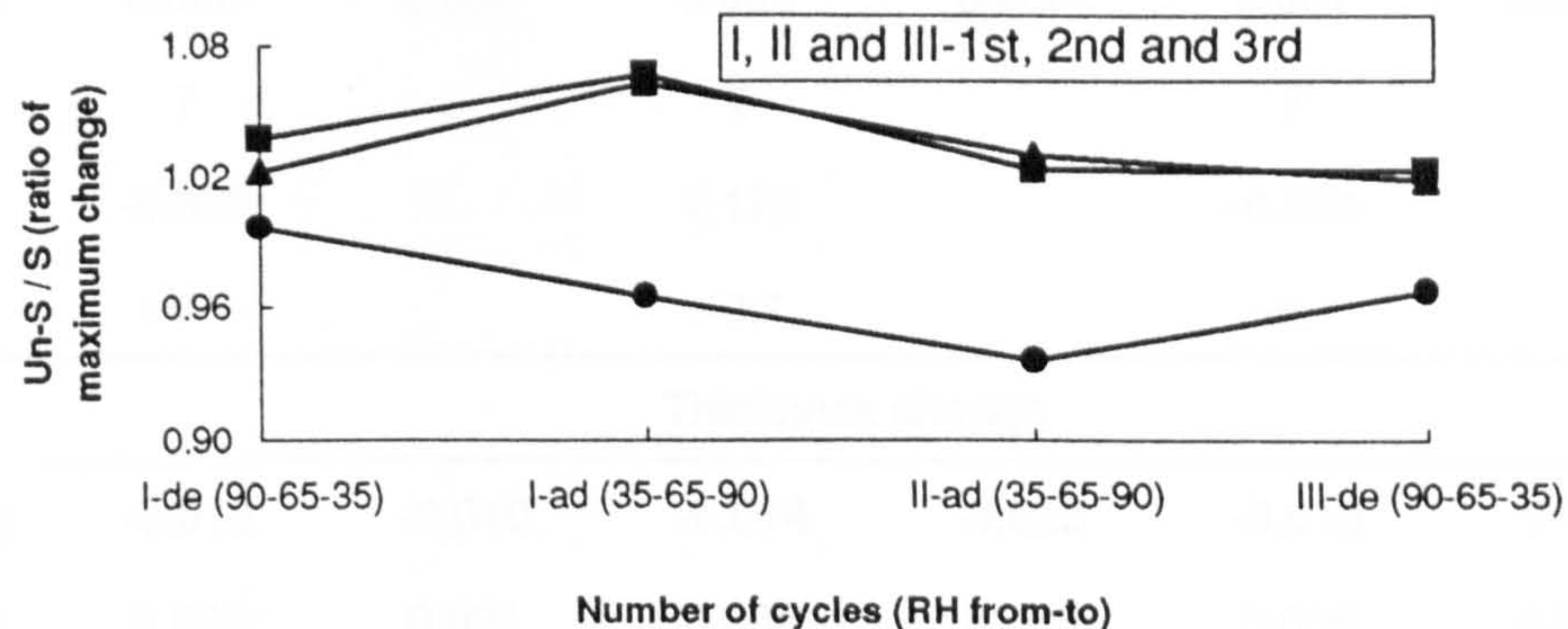


Figure 17.5 Reduction of the effect of edge sealing with number of cycles

Table 17.1 A summary of t-test analysis of the change - edge treatment of uncoated coated CBPB

	Unsealed	Sealed	Unsealed	Sealed	Unsealed	Sealed
Uncoated CBPB						
	Mass change		Length change		Thickness change	
Mean (%)	0.172	0.133	-0.004	-0.004	-0.014	-0.014
Variance	2.613	2.337	0.006	0.006	0.044	0.045
df	11		11		11	
t	1.147		-0.107		0.191	
p	> 0.1		> 0.1		> 0.1	
Coated CBPB						
	Unsealed	Sealed	Unsealed	Sealed	Unsealed	Sealed
	CPB sealer		Acrylic sealer		Styrene butadiene	
	Mass change					
Mean (%)	-0.034	-0.037	-0.089	-0.076	-0.056	-0.048
Variance	0.076	0.064	2.386	2.531	0.226	0.145
df	7		7		7	
t	0.315		-0.683		-0.216	
p	>0.1		>0.1		>0.1	
	Length change					
Mean (%)	-0.003	-0.002	-0.002	-0.003	-0.004	-0.003
Variance	0.000	0.000	0.005	0.006	0.001	0.001
df	7		7		7	
t	-0.323		1.172		-0.289	
p	>0.1		>0.1		>0.1	
	Thickness change					
Mean (%)	-0.013	-0.010	-0.014	-0.023	-0.018	-0.015
Variance	0.002	0.001	0.038	0.035	0.005	0.003
df	7		7		7	
t	-1.001		1.301		-0.457	
p	>0.1		>0.1		>0.1	

Table 17.2 The ratio of maximum change of unsealed CBPB to that of sealed CBPB over various conditions within two cycles

Condition (%) (from - to)	for maximum mass change				for maximum length change				for maximum thickness change			
	CPB-S	Acr-S	Sty-S		CPB-S	Acr-S	Sty-S		CPB-S	Acr-S	Sty-S	
65-90	1.11	0.95	1.15		1.07	1.01	1.05		1.00	1.10	0.99	
90-65	1.14	0.98	1.22		1.23	0.98	1.20		1.67	1.02	1.28	
65-35	1.05	0.99	1.28		1.10	0.99	1.16		1.33	1.02	1.38	
35-65	1.48	0.97	—		1.25	0.99	1.72		—	1.07	1.99	
65-90	1.11	0.98	1.31		1.14	1.00	1.17		1.00	0.96	1.55	
90-65	1.13	0.97	1.34		1.29	1.00	1.26		1.00	0.95	—	
65-35	1.07	0.98	1.27		1.06	0.97	1.20		1.08	1.00	1.25	
35-65	—	0.94	—		1.43	0.98	1.61		—	1.52	—	

Note: CPB-S = CBPB coated with 2 coats of CPB sealer; Acr-S = CBPB coated with 2 coats of acrylic sealer; Sty-S = CBPB coated with 2 coats of styrene butadiene sealer.

Chapter 18

THE PERFORMANCE OF SURFACE COATING ON REDUCING THE MAGNITUDE OF THE DIMENSIONAL INSTABILITY OF CBPB

18.1 Introduction

This chapter presents the development of surface coatings to protect CBPB from external environmental conditions and discusses the dimensional stability of CBPB after such coatings.

18.2 The Assessment of Candidate Sealers

There was some concern regarding the cost, labour requirement and handling difficulties if sealers were applied to full-sized boards, so for comparative purposes it was decided to subject all sealers to the small sized sample tests described previously. The moisture uptake of the systems tested are shown in Table 18.1 and Figure 18.1. The values given are the arithmetic means of the duplicate panels.

Discussion

It appears that all the sealers tested reduced the moisture absorption by CBPB, though there were wide differences in performance. 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. After nearly 1000 days exposure, panels coated with model formulations exhibited similar mass gains to the uncoated CBPB panels, the effectiveness of water-borne acrylic in proprietary system reduced to about 24 % reduction of adsorption, while both solvent-borne systems retained a reduction of adsorption of the uncoated board by about 45 %. The high

moisture uptake in water-borne systems is probably attributable to the much higher permeability (Miller and Boxall, 1984) of water-borne coatings, although the effects of long term wetting on the coating and the CBPB (substrate) interface may bring about adhesion failure (Miller, 1981). More impermeable solvent-borne coatings produced a consistent moisture uptake during 90 %RH exposure.

The results of this test indicate that all proprietary formulations are effective moisture barriers, with the solvent-borne coatings being the most effective. The model formulations would be eliminated due to their nearly complete loss of effectiveness in reducing moisture uptake.

18.3 Large - sized Sample Tests

Quarter-sized CBPB coated with three selected proprietary coatings and uncoated samples (as controls) were subjected to cyclic RH regimes ranging from 35 % to 90 %RH to represent severe service environments. The mass and dimensional changes with cycle / time are shown in Figure 18.2, 18.3 and 18.4.

Discussion

The results confirmed those from the tests on small sized of samples: the water-borne coating was less effective compared to solvent-borne coatings. Moreover, the degree of stabilization of substrate strongly depended on the level of the changing RH. Taking the first complete cycle as example, the RH change from 65 % to 90 % resulted in only a small change in the length but had a strong influence on mass. During the cycle 90 % - 65 % - 35 % - 65 % - 90 %RH, the ratio of mass change for the different stages of the cycle was 1.0 : 1.3 : 1.3 : 2.5 and 1.0 : 1.6 : 1.2 : 2.5 respectively for uncoated and acrylic coated boards, and the ratio of length change was 1 : 2 : 2 : 1 and 1.0 : 2.2 : 1.7 : 1.0 respectively. The similar relationship between the movement and RH for uncoated and acrylic sealer coated material reflects the characteristic of acrylic coating having a relatively higher permeability. The rate of moisture penetration of CBPB was observed to be not significantly different in the three directions (chapter 3 and 17) due to the isotropic nature of the

cement paste and the complex surface of CBPB, at least for the surface including the outer surface skin of chips, the layer of cement paste and the gaps between them. Therefore, the permeability characteristics of the coating are crucial in determining the extent of the movement of CBPB.

CBPB coated with solvent-borne sealers exhibited significant effectiveness over the testing ranges of RH, with the exception of moving from 65 % to 90 %RH, which resulted in a consistent increase in both mass and dimensions. A change of RH from 90 % to 65 % brought about about 70 % reduction in mass change (CPB sealer), and about 40 % and 75 % of length change reduction respectively with the styrene butadiene and CPB sealer. Again the greatest efficacy lay in lower RH exposure. The ratio of the mass change of uncoated CBPB : CBPB with styrene butadiene : CBPB with CPB sealer was 3.4 : 2.2 : 1.0 on changing RH from 65 % to 35 %, and 12.0 : 3.1 : 1.0 from 35 %RH to 65 %RH; the ratio of length change was 4.1 : 1.7 : 1.0 and 7.7 : 2.4 : 1.0 respectively. For solvent-borne coatings water penetration was restricted due to reduced permeability, at least for the rate of moisture uptake. CBPB coated with CPB sealer proved to be the most effective, partly due to the inner filler added to the sealer to reduce moisture absorption. The high increases in both mass and dimensional changes of coated CBPB under 90 %RH exposure were possibly due to condensation of moisture on the surfaces or permeation of water into coatings if the coatings did not withstand water. Therefore, it is generally desirable that the development of high moisture in service be prevented. It should be noted that the change in the thickness of coated CBPB was very similar to that in the length, though by the different amounts.

18.4 The Effect of Film Thickness on the Movement of Coated CBPB

Based on the consistent reduction in the movement of the substrate during testing of quarter-sized boards, another group of boards were coated with two and three coats of the most promising sealer to further investigate the effect of film thickness (Table 18.2). The values are based on the values obtained after reconditioning at 90 %RH.

Discussion

It is apparent that an increase in the film thickness (ie number of coats) of water-borne acrylic did not produce reduced movement of substrate, but an increase in the film thickness of solvent-borne sealers had a pronounced effect. Close scrutiny of the data in Table 18.2 indicates that CBPB with one and two coats of acrylic sealant demonstrated very similar behaviour under cyclic RH, with the exception of the first desorption where doubling of the number of coats increased the moisture loss to about 40 % that of a single coat in moving from 90 % to 65 %RH, and about 5 % and 20 % for both length and thickness reduction from 90 % to 65 % and 65 % to 35 %RH respectively. This again manifests the affinity of acrylic coatings for moisture. A thicker film may undergo greater movement itself, but after first drying the penetration proceeded further and the formation of film was possibly improved.

By contrast, for the CPB sealer, increase in film thickness resulted in a significant reduction of adsorption and a decrease in desorption over the whole range of cyclic RH. A doubling of the number of coats (taking the first cycle as example) reduced mass changes to about 57 %, 52 %, 59 % and 60 % respectively of a single coat following the transfer of samples from 90 % to 65 %RH, 65 % to 35 %RH, 35 % to 65 %RH and 65 % to 90 %RH. Similarly, 67 %, 45 %, 70 % and 45 % for length changes and 21 %, 59 %, 47 % and 34 % for thickness changes. Further increasing film thickness did not bring about much further efficacy in reducing the movement of the substrate: tripling of the number of coats only reduced the moisture change to about 25 % to 30 % of that of two coats and 10 % to 40 % for length changes and 50 % to 60 % for thickness changes over the different RH ranges in the first cycle (with the exception of moving from 35 % to 65 %RH). The exception and variation in the reduction of length and thickness change is to be expected in the light of only slight movement of CBPB with CPB coating.

It is clearly in the interests of good performance of coated CBPB that a higher permeability of sealer is preferable. However, adhesive durability and extensibility of coating have not been taken into account. It has been observed that generally low molecular weight sealers do not sufficiently prevent moisture movement, and sealers with high molecular weight ensure better substrate stability, but tend to fail by

flaking (Miller, 1981). Based on economic and effective aspects, two coats are recommended. Too thick a film may also cause cracking and displacement of the coating from the substrate if the film does not provide sufficient flexibility and adhesive properties.

18.5 The Effect of Board Thickness

The performance of CBPBs uncoated or coated with water - borne sealer, acrylic, solvent - borne sealer, and CPB sealer, is shown in Table 18.3. The ratio of the change for 18 mm and 12 mm CBPBs under various stages of RH is calculated and provided in the same Table.

A t - test was carried out to detect if the differences in change between different thickness was significant. A summary of the analysis is given in Table 18.4.

Discussion

From Table 18.3 it appears that for uncoated CBPB the changes in both mass and dimensions of 18 mm boards were generally higher than those of 12 mm boards under various stages of cyclic exposure. The difference may be attributable to the difference in the percentage distribution of cement paste and wood chips across the thickness or internal stress due to the moisture gradient, though the parameters of production of CBPB cannot be excluded.

For the CBPBs coated with water borne sealer (acrylic) the change in the mass of 18 mm boards was lower than that of 12 mm boards with an exception of the change under desorption in the first cycle. However, the change in dimensions of 18 mm boards was higher than that of 12 mm CBPBs. There appeared to be a deviation in the change of CBPBs coated with solvent borne sealer (CPB sealer). This phenomenon seems to be due to lack of experimental sensitivity, because the great efficacy of the sealer only brought about a very little change in both mass and dimensions when subjected to changing RH.

A t -test analysis was carried out to determine if the changes obtained for the different thickness of CBPBs were significantly different or not. The results obtained,

listed in Table 18.3, show that no systematic effect of thickness of CBPB, whether uncoated or coated with water borne or solvent borne sealer, was apparent. This indicates that the response of CBPB from different sources may be the same or very similar to the moisture effects.

18.6 Tests of the Durability of CPB Sealer and its Prediction

The final aspect of the study was to subject the selected coating sample to a series of cycles. The experiment contained both uncoated CBPB and CBPB with two coats of CPB sealer to allow a direct comparison of the coating effectiveness and durability. The results of the test are presented in Figure 18.5 and 18.6.

As the number of cycles increases the behaviour of CBPB coated with CPB sealer changes, due to the deterioration of the coating. The trend of increase in the change of mass and length is shown in Figure 18.7 and 18.8. The predictive equations and their coefficients are given in Table 18.5.

It should be noted that the thickness change exactly followed that of length, though with a different amount of change.

Discussion

It appears that the change in both mass and length increased with increasing number of cycles, and the effectiveness of the coating clearly reduced consistently. The degree of increase in the mass and length with cycle was different under various levels of RH exposure, the most significant increase being under 90 %rh exposure (Figure 18.7 and 18.8). The deterioration of the sealers, causing an increase in both mass and dimensional change, are thought to be attributable to several mechanisms. Under RH exposure, the coating firstly swells causing a change in residual stresses of the coating and possibly microcrack formation. Secondly the coating may be plasticized, thus causing an decrease of the elongation to failure of the coating. Thirdly the interface between CBPB and coating may be affected, which in turn would influence the durability. Fourthly long-term exposure of coatings to wet conditions may lead to a deterioration in the mechanical properties, as a result of

hydrolysis. After 10 cycles, mass increased by 1.04 % in desorption in 65 %RH and 0.81 % in adsorption in 65 %RH, and 0.01 % for length increase in both adsorption and desorption in 65 %RH.

A consistent deterioration of coatings with cycle or time under cyclic RH can be modelled (Figures 18.7, 18.8 and Table 18.5). The lines were fitted to the maximum values of changes at 90 %RH, 65 %RH (both adsorption and desorption) and 35 %RH. It is interesting that the difference between lines (changes) arising from coated CBPBs under 35 %RH and under 65 %RH adsorption was much less than that between changes of coated CBPB under 65 %RH adsorption and under 65 %RH desorption or that between changes under 65 %RH desorption and under 90 %RH adsorption. Obviously coated CBPB was very stable in low RH exposure even after a series of cycles. However, as long as the air (moisture) penetrated into the CBPB, physical and chemical reactions could take place and therefore it did not recover to its previous form under desorption.

Durability of coating systems depends not only on the coating itself but also on the substrate to which it is applied and the environment to which it is exposed, including light, moisture, temperature and even trace elements. The results above can only serve as a general guide in practice in terms of that, so far, there are no officially recognised, published data from natural weathering exposure, which enable one to equate the coating performance with that under natural environment.

18.7 Sorption and Dimensional Change Isotherms (Hysteresis Loops)

The combined adsorption and desorption parts of a cycle of RH gave rise to a hysteresis loop. An example of this is illustrated in Figures 18.9 and 18.10. It should be noted that in each complete cycle the higher curve was obtained by exposing the CBPB (with two coats CPB sealer) to successively lower RHs and permitting sufficient time to reach essential mass equilibrium (dimensions were constant at each level of RH). The lower curve was the adsorption line obtained when the sample regained moisture at the same RHs to which it was exposed during desorption. There was a consistently vertical movement of the loops in successive cycles, with the first loop at the bottom for both mass and dimensions. This is in contrast to that of

uncoated CBPB in which the top loop is the first one (for dimensions). The details of this were presented in chapter 7 and in a previous paper (Fan, *et al*, 1996). A similar shape of loop was found for both length and thickness.

Discussion

These results (Figures 18.9 and 18.10), indicate that the sorption - dimension change relationship for coated CBPB was considerably different to that of uncoated CBPB. The movement of coated CBPB followed that of mass - that is, both mass and dimensions increased with cycle number.

Similar behaviour also occurred in the response of mass and dimensions to RH ranges. Only very slight increases were found when samples were moved from 35 % to 65 %RH, but a considerable increase was observed as moving samples from 65 % to 90 %RH. Mass and dimensional decreases were consistent over the whole range of desorption exposure, whether from 90 % to 65 % or from 65 % to 35 %RH, and linear lines could be fitted to these change. However, the slope of the line for length decrease is clearly greater than that for mass decrease. Much wider loops were produced for the CBPB with two coats of CPB sealer due to the discontinuity in adsorption. This considerably deviated from that of uncoated CBPB (chapter 7), showing an adverse effect of coating on the performance of coated CBPBs. The sealer with lower permeability is resistant to moisture penetration, resulting in a lesser degree of sorption in CBPB which, in turn, proves to be more stable under adsorption under RH. However, the prevention of sorption is not absolute - as long as the water is absorbed into the CBPBs, the more resistant the sealer, the more difficult is moisture evaporation under desorption.

The vertical movement of the loop clearly indicates an appreciable increase in mass with each successive cycle. From the first to the fifth and from the first to the tenth exposure to 90 %RH, the mass increased by 0.7 % and 1.3 % respectively, and 0.020 % and 0.025 % for length. These results again imply that the CPB sealer deteriorated with time or cycles and is more sensitive to high than to low RH.

18.8 The Resistance to Carbon Dioxide of Coated CBPBs

Discussion

The results above show not only the effectiveness of the coatings in reducing the instability of CBPB but also the potential resistance of coatings to carbon dioxide penetration. The resistance to carbonation of surface coatings applied to concrete has been investigated by several authors (Davies, 1990; Davies and Rothwell, 1989). The mechanism of a coating applied over the exterior surface to reduce the rate of carbonation is that 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 . In fact it also prevents ingress of liquid water. The resistance to carbonation of every system tested is illustrated in Figures 18.2, 18.3 and 18.4. In terms of the nature of carbonation, the mass of uncoated CBPB increased consistently with increasing number of cycles (Figure 18.2) and the dimensions decreased (Figures 18.3 and 18.4). However, these trends considerably damped down for coated CBPB and even disappeared in some cases.

A wide range in the resistance occurred from one coating system to another due to different physical and chemical changes on film formation or on exposure to air (moisture). It is of interest that the water-borne acrylic did not produce significant dimensional stabilization but did show a considerable resistance to carbon dioxide. With cycle number increase, the absolute values of both mass and dimension changes of CBPB coated with acrylic were decreasing. This is because when the sealer was applied to the surface of the CBPB, the coating provided both a penetrative/bonded layer (such as electro-static bonding, hydrogen bonding, Van der Waal's force or capillary force) and a complete surface layer, these possibly preventing the ingress of carbon dioxide.

Cycling did not affect the behaviour of the CBPB coated with both solvent-borne sealers. The slight increase in mass of CBPB with CPB sealer is not thought to arise in carbonation (by virtue of the same trend in length), but is probably due to the deterioration of the coatings. This can be confirmed by the behaviour on moving from 35 % to 65 %RH, in which only a very slight increase was observed in both

mass and dimensions of CBPB coated with CPB sealer compared to the significant increase for uncoated CBPB.

A correlation between coating thickness and resistance to carbonation seemed not to be reflected in the results obtained (Table 18.3) though permeability clearly decreased with greater coating thickness. It is thought that the movement due to moisture change may have overwhelmed the slight deviation of movement due to carbonation between a single coat and multicoats.

It seems that the similar effectiveness in resistance to carbonation covered the whole range of RH. This was also reported in the concrete area (Davies, 1990).

The benefit produced by the resistance of coatings to carbonation can be seen when considering long-term exposure (Figure 18.5 and 18.6). There is a considerable amount of mass increase and dimensional decreases after 10 cycles of uncoated CBPB, however only slight increases were found in both mass and dimensional increases for coated boards. These results also indicate that CBPB with two coats of CPB sealer possessed a permanent resistance to carbonation, although there might be some degree of deterioration of the coating with time or cycles, and there existed a certain degree of penetration of the coating into the CBPB and the deterioration (including rubbing, scraping or eroding which tends to progressively remove the material from surface) possibly happened on the coating surface.

18.9 Visual Inspection

One of the essential characteristics in the coating evaluation is its retention of appearance. The results in this work show no flaking or embrittlement occurred, but an uneven patchiness in colour changes was readily seen. Overall, the coatings tested have maintained an acceptable appearance after cycles. Colour retention of water-borne acrylic is superior to that of both solvent-borne coatings. There was a tendency to yellowing for solvent-borne systems but not for the acrylic system. When CBPB with CPB sealer were retained at 90 %RH algal growth appeared on the top face of the panel due to the condensation of the water vapour giving the coating a dirty appearance. It was reported (Roy, *et al*, 1996; Gillat, 1991; Patel, 1991) that algal growth is an important paint deterioration mechanism and can lead to, and even

accelerate, further paint failure. It also causes serious disfigurement and water retention which results in dampness of surfaces.

18.10 Interim Conclusions 14

1) There is a restricted list of sealers applicable to the surface of CBPB. The ranking order of the effectiveness of sealers was: Proprietary systems > model systems; solvent - borne sealers > water - borne sealers.

2) Among the sealers tested, CPB sealer was most effective, producing a reduction of the adsorption of the uncoated board by about 50 % after 1000 days exposure at 90%rh.

3) The behaviour of coated CBPB reflected the changes of RH. The values of the change of CBPB coated with the acrylic were close to those of uncoated CBPB, but the trends of the changes were different.

4) CBPB with CPB sealer did not exhibit a very promising effectiveness on moving from 65 % to 90 %RH. However, a change of RH from 90 % to 65 % brought about 70 - 75 % reduction in both mass and length; a change of RH from 65 % to 35 % and from 35 % to 65 %RH had a reduction of 70 - 80 % and 87 - 92 % respectively. Obviously it is desirable to avoid a high RH environment in service.

5) The efficacy of the solvent - borne coating significantly increased with film thickness (number of coatings), but only slightly increased for the acrylic coating. A doubling of the number of coats reduced the mass change to about 60 % of that a single coat during cyclic RH exposure, and 45 - 70 % for length and 20 - 60 % for thickness changes over the same RH frame, depending on the different RH levels. The level of reductions were considerably reduced as the number of coats increased.

6) The change in both mass and dimensions of uncoated CBPB under cyclic RH for 18 mm CBPBs was higher than that for 12 mm CBPBs. However, this did not clearly

appear to be the case if CBPB was coated with effective sealers.

7) A t - test showed that the difference in the changes in both mass and dimensions was not significant between 18 mm and 12 mm CBPBs, indicating the behaviour of various kinds of commercial CBPBs may be the same or very similar.

8) There was a consistent deterioration of CBPB with CPB sealer subjected to multicycles or long-term exposure. Both mass and dimensional changes increased with the number of cycles, instead of decreasing in length as for uncoated CBPBs.

9) CBPBs coated with two coats of CPB sealer were very stable under lower RH even after 10 cycles of RH change. However they were not resistant to moisture penetration under higher RH (high pressure).

10) Mathematical models could be developed to predict this behaviour. The R-square values ranged from 0.90 to 0.99. The equations for both mass and dimensional changes under 90 %RH were different from those arising from the maximum values under 35 %RH and 65 %RH of adsorption or desorption, confirming a much greater increase in changes at 90 %RH.

11) The rate of changes of coated CBPB was different between adsorption and desorption giving rise to hysteresis loops. The loops for CBPB coated with CPB sealer were much flatter than those for uncoated CBPB, indicating a resistance to moisture sorption or evaporation on adsorption or desorption.

12) The width of hysteresis loops for coated CBPBs were greater than those for uncoated CBPBs, indicating a greater different increase in mass of coated CBPB between adsorption in 35 - 65 %RH and in 65 - 90 %RH .

13) The loops for both mass and dimensional changes moved upwards, the reverse of that for dimensional changes of uncoated CBPB, showing the deterioration of coated CBPBs with cycle.

14) For all sealers the substrate showed a strong resistance to carbonation. Unlike the behaviour in uncoated CBPB, consistent increase in mass and decrease in dimensions with increasing the number of cycles or time was not observed.

15) The water - borne acrylic sealer was not very effective in reducing either mass or dimensional change under changing RH. However, the efficacy of preventing carbonation was very significant (Figure 18.2, 18.3 and 18.4).

16) The effect of the thickness of sealers on the carbonation of coated CBPBs was clearly not reflected, though it had an effect on the change in both mass and dimensions.

17) The resistance of coatings to carbonation was clearly not affected by multi-cycling under changing RH, distinguishing the significant benefit of long term performance of CBPB.

18) The coatings maintained an acceptable appearance after a series of cycles though there was a tendency to yellowing after prolonged periods of time. Algal growth appeared on the top face of CBPB coated with CPB sealer due to the condensation of water vapour under 90 %RH, giving the coating a dirty appearance.

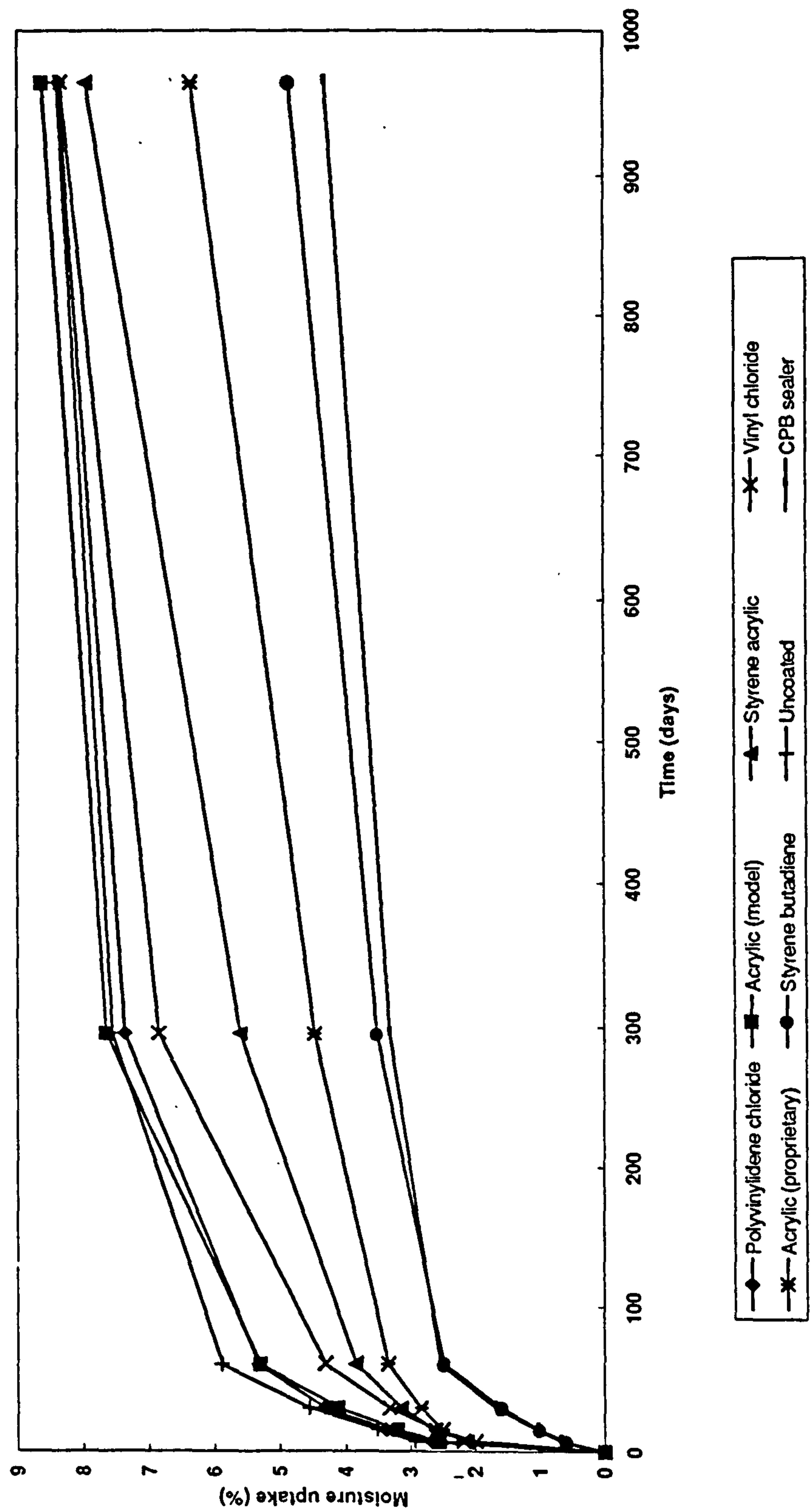


Figure 18.1 Absorption of moisture vapour (mass %) with time by coated and uncoated CBPB in a climate of 20 °C / 90 %RH.

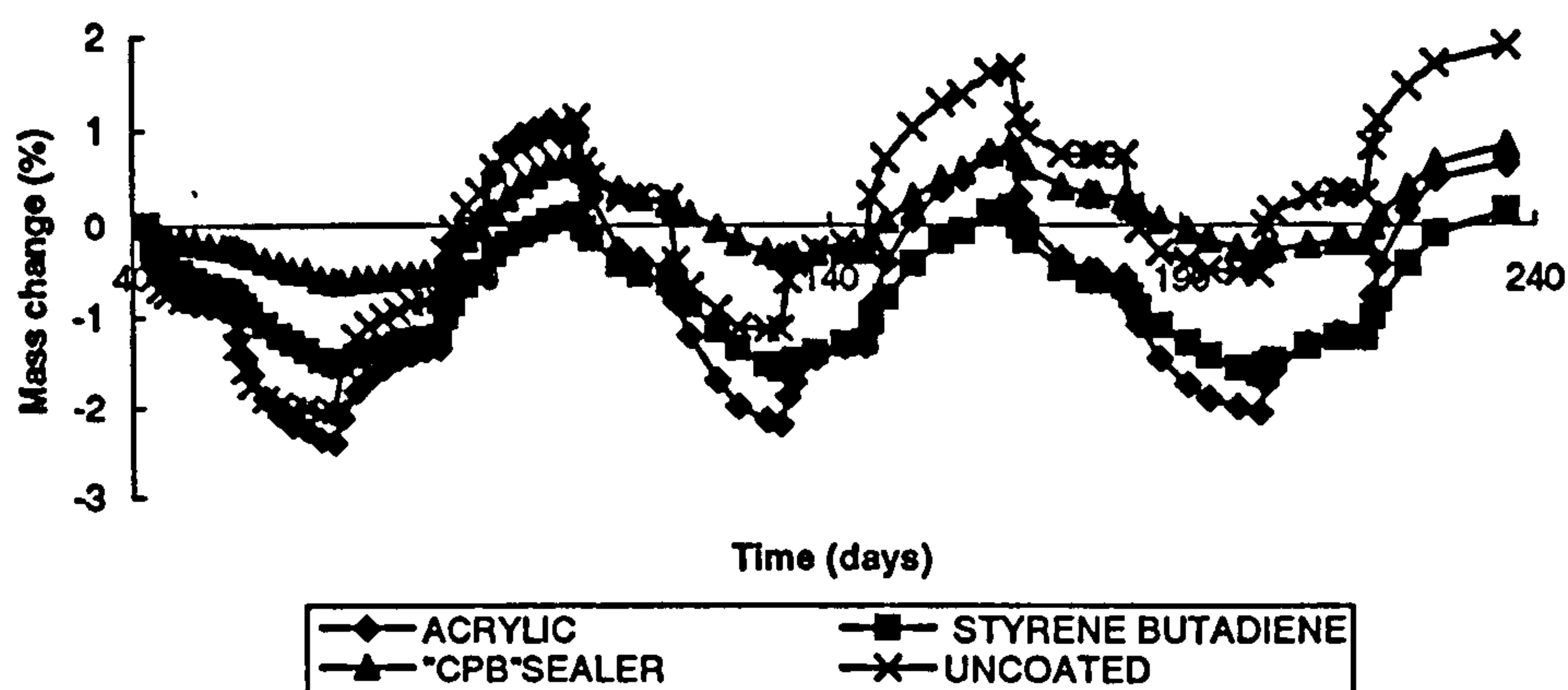


Figure 18.2 Effect of various coatings on mass change of CBPB under cyclic RH

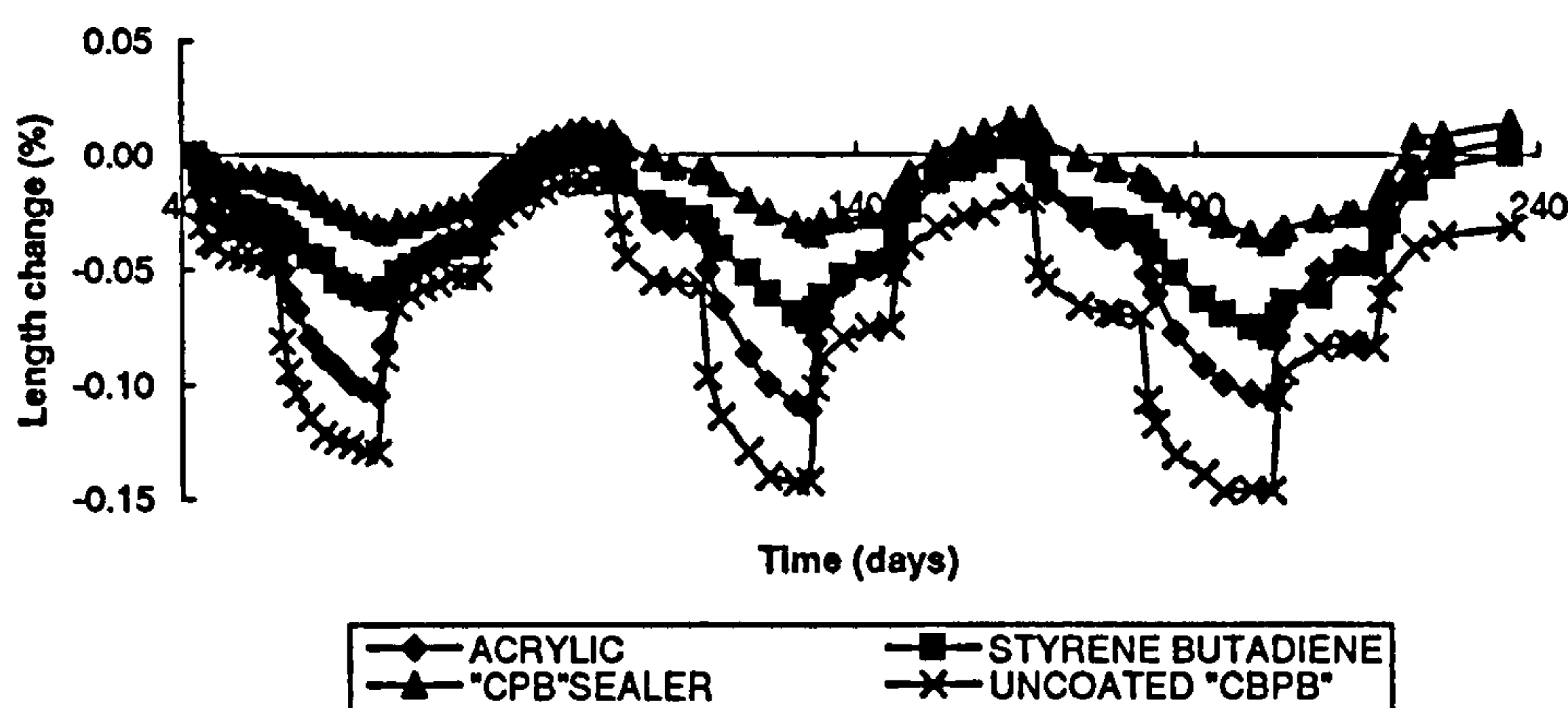


Figure 18.3 Effect of various coatings on length change of CBPB under cyclic RH

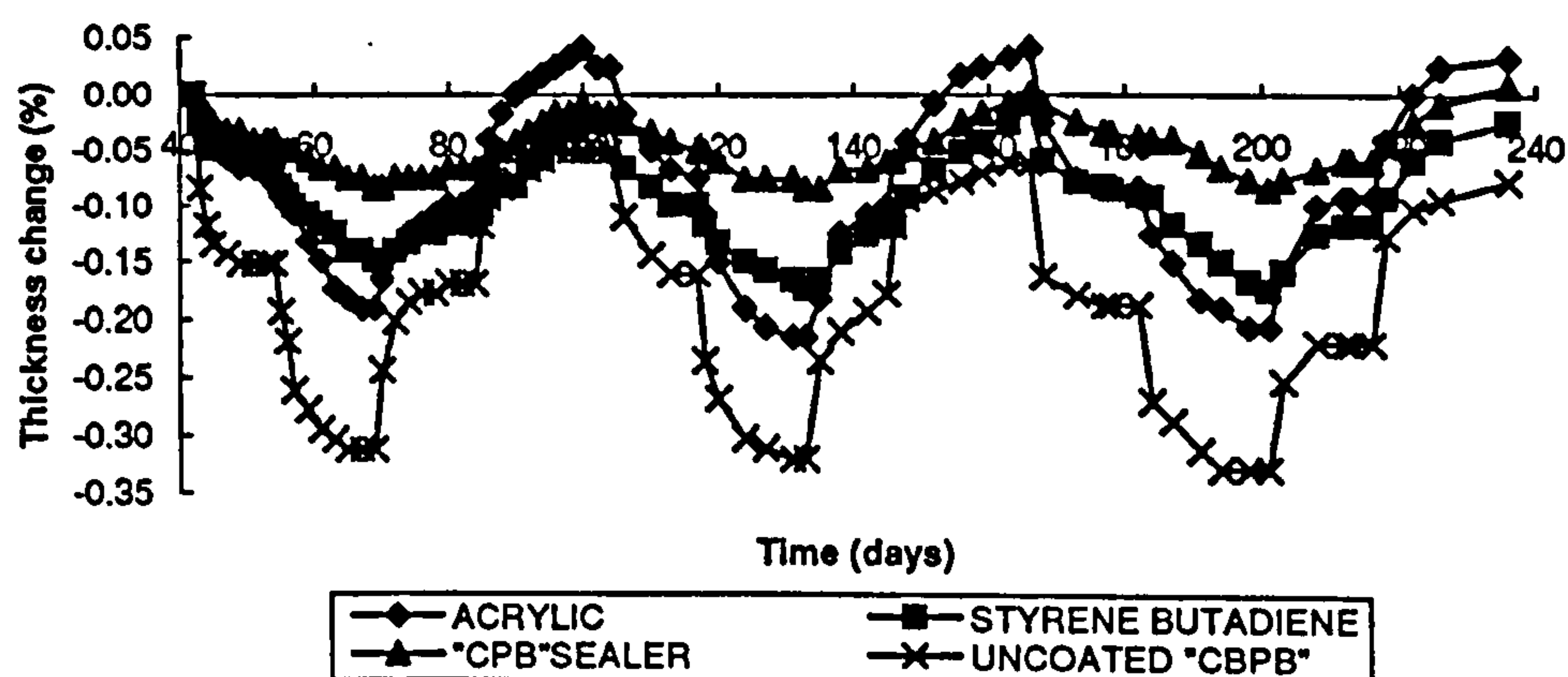


Figure 18.4 Effect of various coatings on thickness change of CBPB under cyclic RH

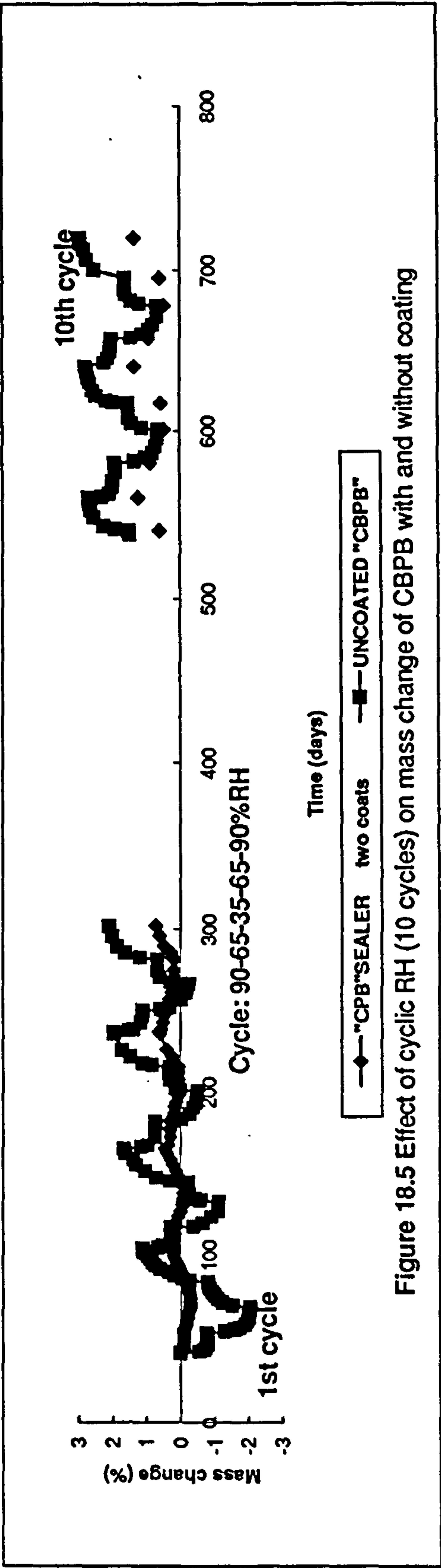


Figure 18.5 Effect of cyclic RH (10 cycles) on mass change of CBPB with and without coating

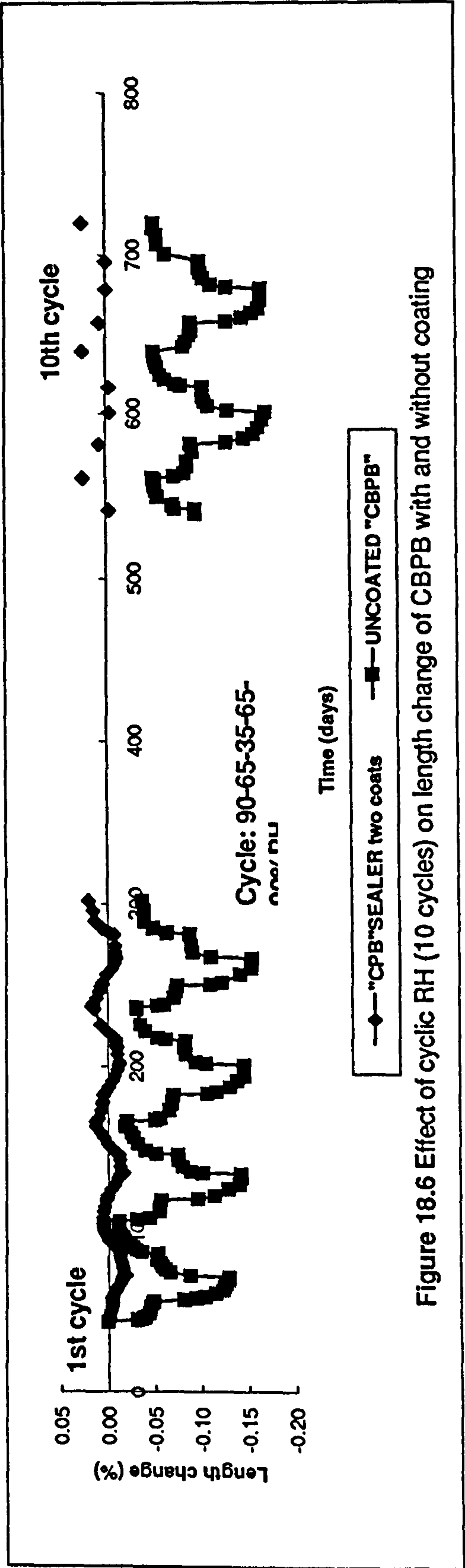


Figure 18.6 Effect of cyclic RH (10 cycles) on length change of CBPB with and without coating

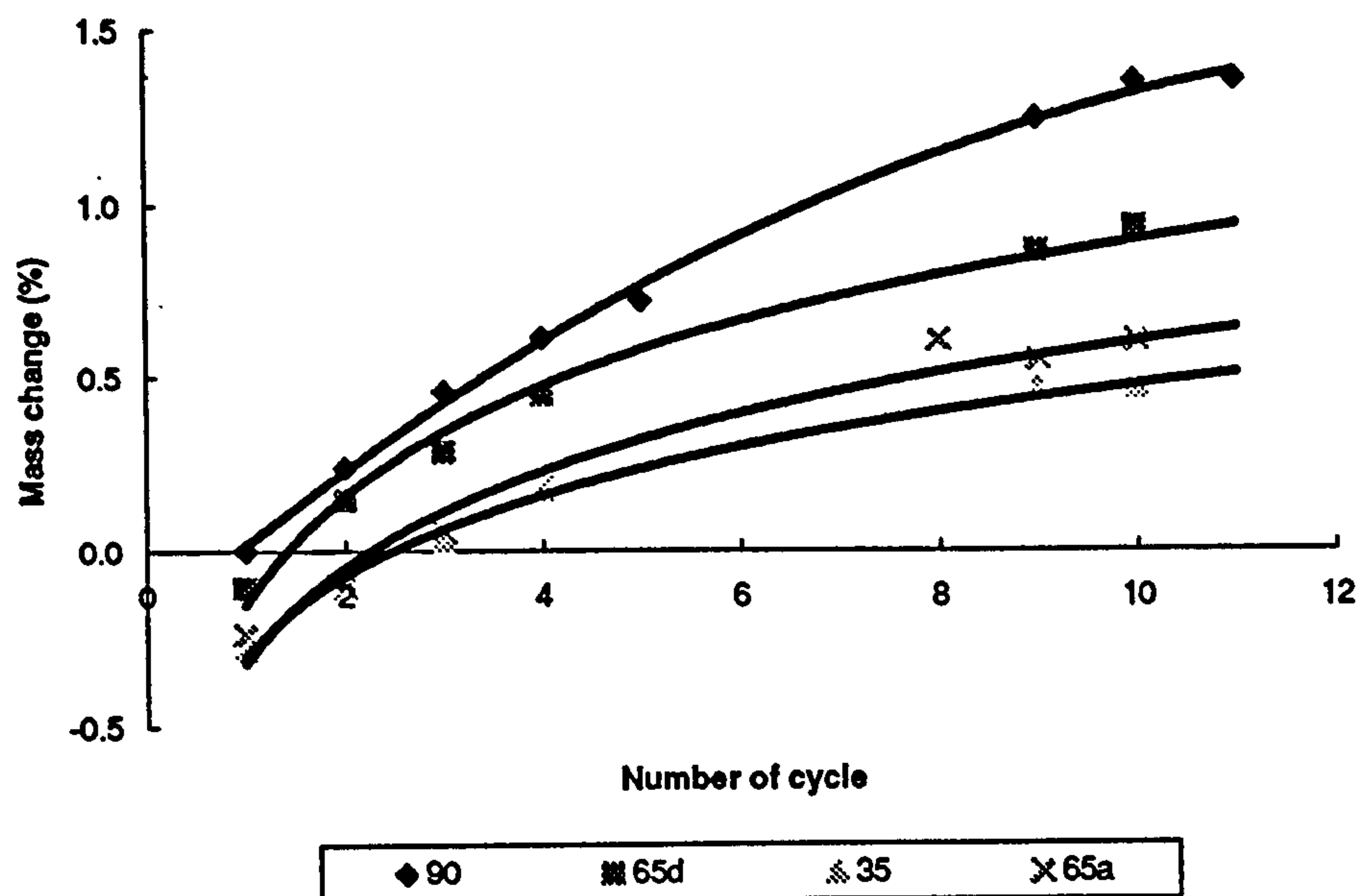


Figure 18.7 Prediction of mass change of coated CBPB with number of cycle

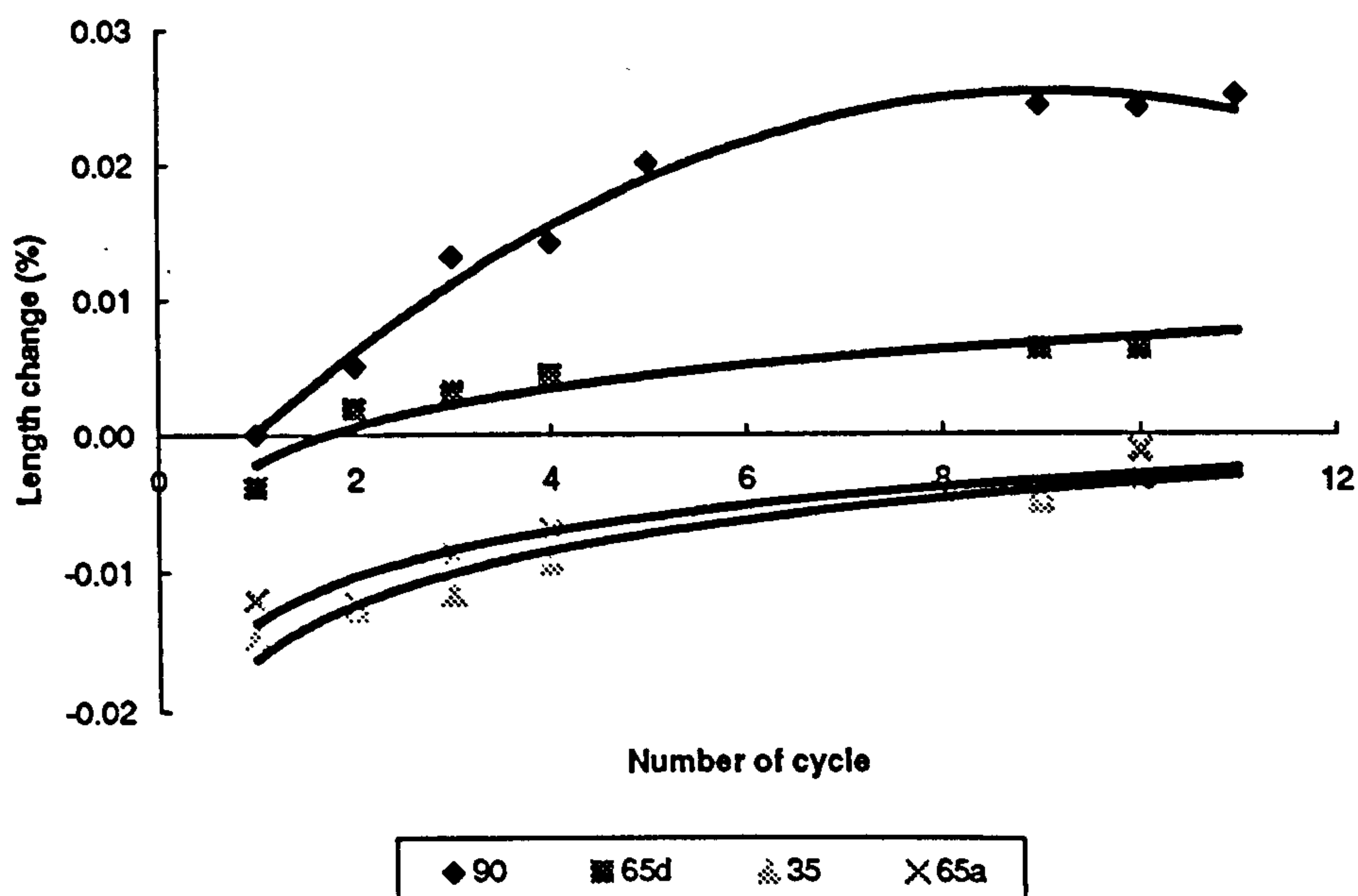


Figure 18.8 Prediction of length change of coated CBPB with number of cycle

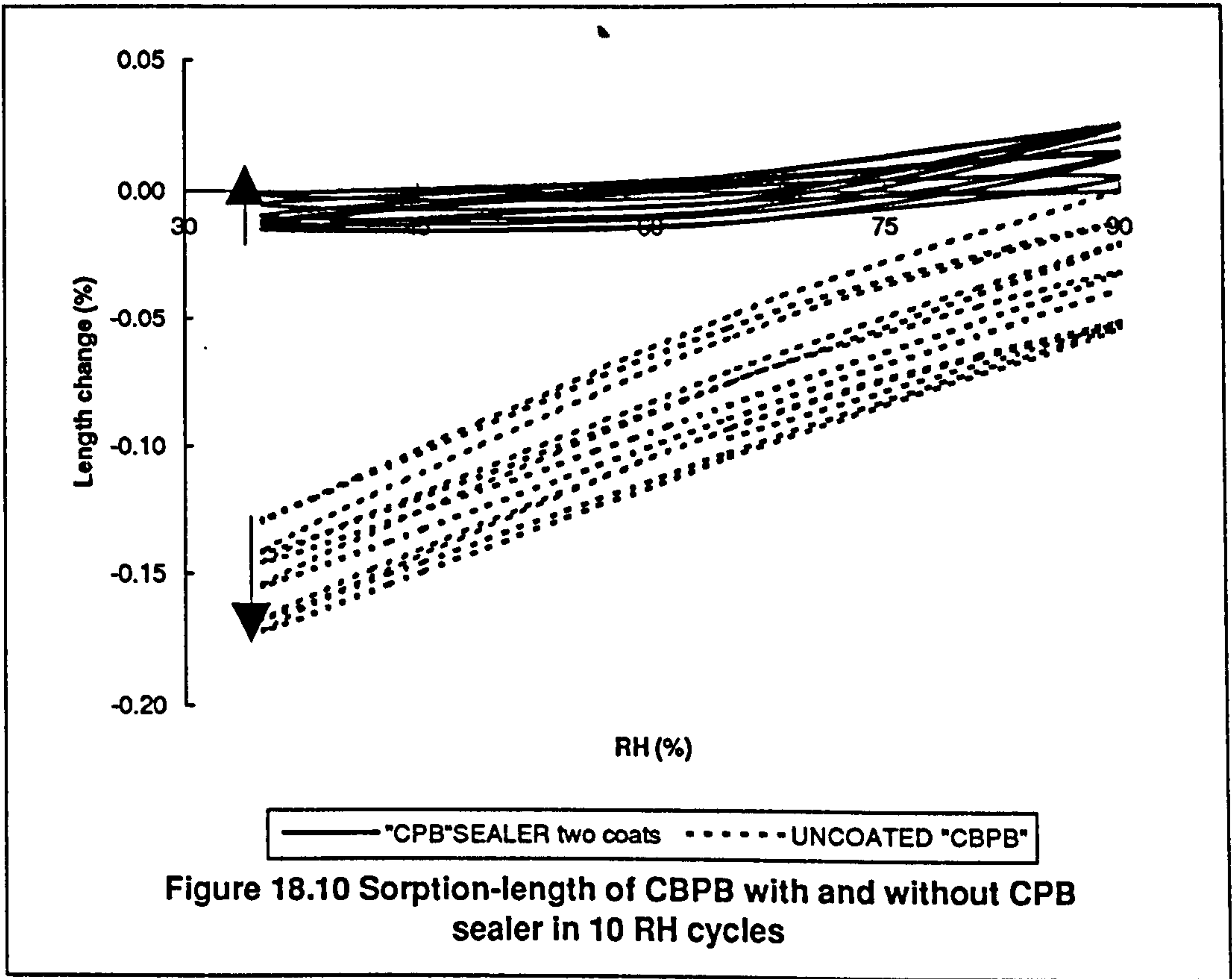
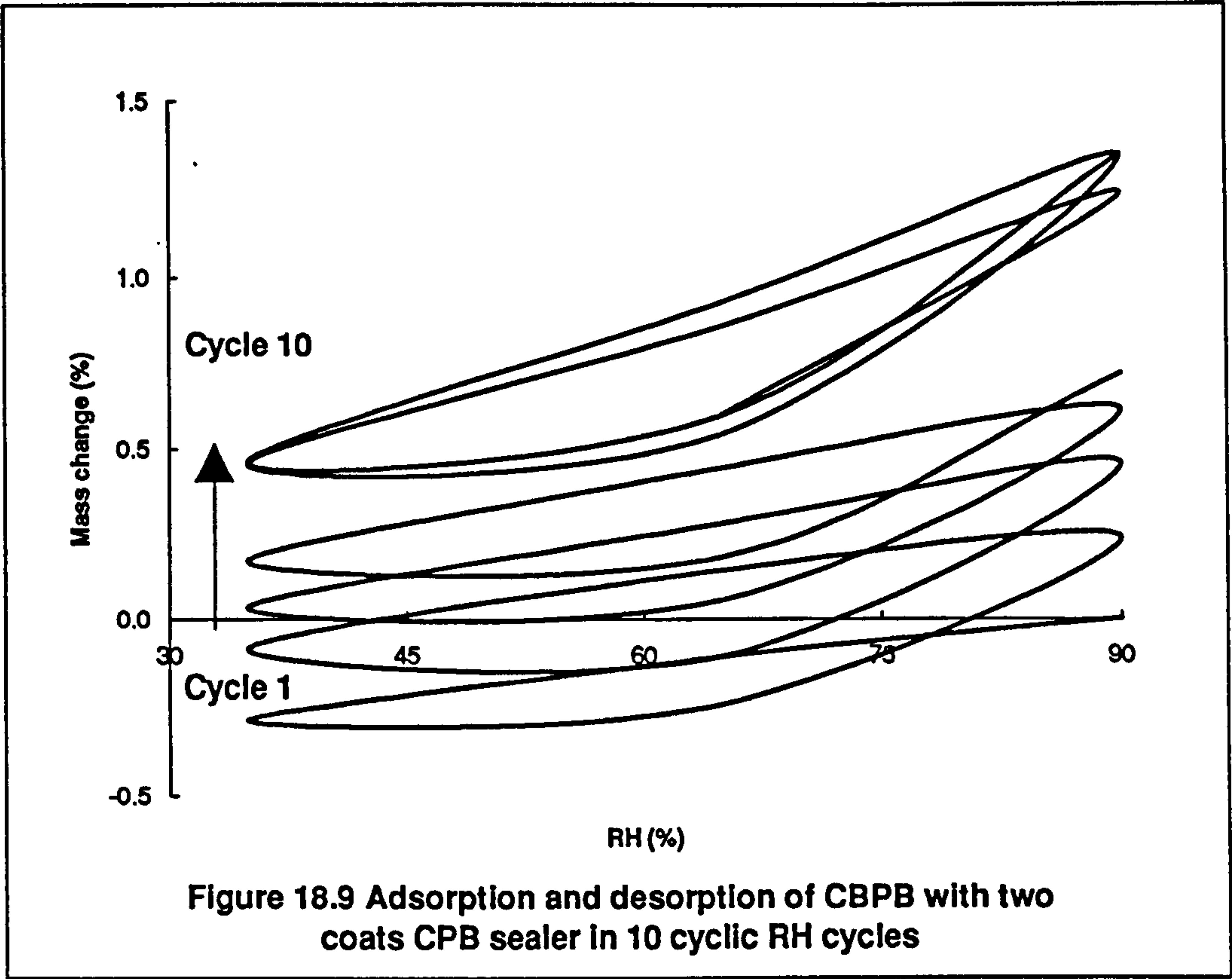


Table 18.1 Moisture uptake of coated CBPB expressed as a percentage of the control value of uncoated samples

Time (days)	7	15	30	60	295	965
Sealer type	Moisture uptake compared with that of control CBPB (%)					
<u>Model formulations</u>						
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
<u>Proprietary formulations</u>						
Acrylic	75	71	62	57	59	76
Styrene butadiene	20	28	35	42	46	58
CBPB Sealer	23	29	37	43	44	51

Table 18.2 Effect of coating numbers on behaviour of CBPB

Sealer	Uncoated CBPB		Acrylic			"CPB" sealer			
No.*	0	0	1	2	2	1	2	2	3
T (mm)*	12	18	12	12	18	12	12	18	18
RH	Mass change (%)								
90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
65	-0.778	-1.415	-0.927	-1.330	-1.559	-0.252	-0.109	-0.145	-0.104
35	-2.051	-3.093	-2.399	-2.888	-3.315	-0.624	-0.286	-0.548	-0.406
65	-0.817	-1.950	-1.344	-1.871	-2.492	-0.521	-0.244	-0.518	-0.397
90	1.119	-0.085	0.931	0.445	-0.871	0.678	0.237	-0.281	-0.223
65	0.268	-0.993	-0.469	-0.999	-1.823	0.224	0.144	-0.347	-0.260
35	-1.131	-2.450	-2.188	-2.721	-3.417	-0.342	-0.086	-0.698	-0.574
65	-0.226	-1.468	-1.305	-1.897	-2.707	-0.274	-0.106	-0.689	-0.544
90	1.652		0.773	0.171		0.834	0.453		
65	0.730		-0.562	-1.153		0.258	0.282		
35	-0.508		-2.037	-2.619		-0.317	0.031		
65	0.314		-1.217	-1.836		-0.175	0.054		
90	1.947		0.717	0.087		0.925	0.607		
	Length change (%)								
90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
65	-0.049	-0.074	-0.042	-0.044	-0.066	-0.012	-0.004	-0.010	-0.006
35	-0.130	-0.179	-0.105	-0.111	-0.150	-0.032	-0.015	-0.036	-0.030
65	-0.053	-0.098	-0.035	-0.044	-0.080	-0.022	-0.012	-0.033	-0.026
90	-0.012	-0.037	0.006	-0.001	-0.023	0.009	0.005	-0.012	-0.011
65	-0.057	-0.092	-0.034	-0.042	-0.066	-0.008	0.002	-0.019	-0.015
35	-0.142	-0.191	-0.111	-0.116	-0.154	-0.034	-0.013	-0.048	-0.038
65	-0.075	-0.120	-0.048	-0.055	-0.090	-0.026	-0.012	-0.045	-0.036
90	-0.021		0.007	0.001		0.015	0.013		
65	-0.071		-0.038	-0.044		-0.010	0.004		
35	-0.146		-0.106	-0.113		-0.039	-0.012		
65	-0.084		-0.049	-0.055		-0.025	-0.009		
90	-0.032		0.006	-0.002		0.015	0.014		
	Thickness change (%)								
90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
65	-0.152	-0.229	-0.074	-0.083	-0.226	-0.042	-0.033	-0.028	-0.011
35	-0.312	-0.486	-0.190	-0.240	-0.441	-0.084	-0.050	-0.095	-0.044
65	-0.169	-0.307	-0.091	-0.133	-0.275	-0.067	-0.041	-0.095	-0.044
90	-0.051	-0.140	0.025	0.008	-0.099	-0.017	-0.008	-0.072	-0.033
65	-0.160	-0.263	-0.074	-0.116	-0.209	-0.050	-0.008	-0.083	-0.044
35	-0.320	-0.531	-0.215	-0.249	-0.435	-0.084	-0.025	-0.156	-0.104
65	-0.177	-0.380	-0.099	-0.124	-0.292	-0.059	-0.008	-0.150	-0.104
90	-0.061		0.041	0.033		0.034	0.049		
65	-0.187		-0.083	-0.108		-0.008	0.033		
35	-0.330		-0.210	-0.240		-0.084	0.000		
65	-0.221		-0.091	-0.124		-0.059	0.008		
90	-0.076		0.033	0.008		0.008	0.033		

* NO.-number of coats; T.-thickness of substrate.

Table 18.3 The ratio of percentage change of 18 mm CBPB to 12 mm CBPB

Sealer	Uncoated CBPB			Acrylic			"CPB" sealer		
No.*	0	0	Ratio of	2	2	Ratio of	2	2	Ratio of
	Max. chan. (%) change of			Max. chan. (%) change of			Max. chan. (%) change of		
T (mm)*	12	18	18 to 12	12	18	18 to 12	12	18	18 to 12
RH	Mass change (%)								
90	0.000	0.000	—	0.000	0.000	—	0.000	0.000	—
65	-0.778	-1.415	1.818	-1.330	-1.559	1.172	-0.109	-0.145	1.333
35	-1.273	-1.678	1.318	-1.558	-1.757	1.128	-0.177	-0.403	2.278
65	1.234	1.143	0.926	1.017	0.823	0.809	0.042	0.030	0.721
90	1.936	1.865	0.963	2.317	1.621	0.700	0.481	0.237	0.494
65	-0.851	-0.908	1.067	-1.445	-0.952	0.659	-0.093	-0.067	0.713
35	-1.398	-1.456	1.041	-1.722	-1.594	0.926	-0.230	-0.351	1.525
65	0.905	0.981	1.085	0.824	0.709	0.861	-0.020	0.009	-0.466
	Length change (%)								
90	0.000	0.000	—	0.000	0.000	—	0.000	0.000	—
65	-0.049	-0.074	1.508	-0.044	-0.066	1.522	-0.004	-0.010	2.676
35	-0.081	-0.106	1.309	-0.067	-0.083	1.242	-0.011	-0.026	2.370
65	0.076	0.081	1.062	0.066	0.069	1.048	0.003	0.003	1.262
90	0.041	0.061	1.480	0.043	0.058	1.334	0.017	0.021	1.220
65	-0.045	-0.055	1.222	-0.041	-0.043	1.059	-0.003	-0.007	2.169
35	-0.085	-0.099	1.163	-0.074	-0.088	1.180	-0.015	-0.030	2.023
65	0.067	0.071	1.066	0.061	0.063	1.036	0.000	0.003	—
	Thickness change (%)								
90	0.000	0.000	—	0.000	0.000	—	0.000	0.000	—
65	-0.152	-0.229	1.510	-0.083	-0.226	2.725	-0.033	-0.028	0.840
35	-0.160	-0.257	1.605	-0.157	-0.215	1.364	-0.017	-0.067	4.031
65	0.143	0.179	1.248	0.108	0.165	1.534	0.008	0.000	0.000
90	0.118	0.168	1.420	0.141	0.176	1.251	0.033	0.022	0.672
65	-0.110	-0.123	1.122	-0.124	-0.110	0.886	0.000	-0.011	—
35	-0.160	-0.268	1.675	-0.133	-0.226	1.703	-0.017	-0.072	4.380
65	0.143	0.151	1.053	0.124	0.143	1.152	0.016	0.006	0.338

* NO.-number of coats; T.-thickness of substrate.

Table 18.4 A summary of t-test analysis of the change - different thickness of CBPB

Thickness	12 mm	18 mm	12 mm	18 mm	12 mm	18 mm
Treatment	Uncoated		Acrylic		CPB-sealer	
Mass change						
Mean (%)	-0.032	-0.210	-0.271	-0.387	-0.015	-0.098
Variance	1.832	2.201	2.636	1.954	0.056	0.050
df	12		12		12	
t	0.234		0.143		0.675	
p	> 0.1		> 0.1		> 0.1	
Length change						
Mean (%)	-0.011	-0.017	-0.008	-0.013	-0.002	-0.006
Variance	0.005	0.007	0.004	0.005	0.000	0.000
df	12		12		10	
t	0.154		0.138		0.603	
p	> 0.1		> 0.1		> 0.1	
Thickness change						
Mean (%)	-0.025	-0.054	-0.018	-0.042	-0.001	-0.021
Variance	0.023	0.045	0.018	0.038	0.001	0.001
df	11		11		10	
t	0.295		0.268		1.255	
p	> 0.1		> 0.1		> 0.1	

Table 18.5 Mathematical equations of mass and dimensional changes of CBPB with two coat CPB sealer subjected to a set of cycles: 90%-65%-35%-65%-90%RH

Contents	Model	a	b	c	R ²
Mass at 90%RH (a)	$Y = aX^2 + bX + c$	-0.0085	0.2374	-0.2136	1.00
Mass at 65%RH (a)	$Y = a\ln(X) + b$	0.3997	-0.3254		0.97
Mass at 65%RH (d)	$Y = a\ln(X) + b$	0.4561	-0.1596		0.99
Mass at 35%RH (d)	$Y = a\ln(X) + b$	0.3369	-0.3069		0.99
Length at 90%RH (a)	$Y = aX^2 + bX + c$	-0.0004	0.0070	-0.0064	0.98
Length at 65%RH (a)	$Y = a\ln(X) + b$	0.0047	-0.0136		0.91
Length at 65%RH (d)	$Y = a\ln(X) + b$	0.0040	-0.0022		0.90
Length at 35%RH (d)	$Y = a\ln(X) + b$	0.0056	-0.0162		0.92

* (a) adsorption from lower humidity to that; (d) desorption from higher humidity to that.

PART 5

FINAL APPRAISAL OF

TEST WORK

Chapter 19

CONCLUSIONS

19.1 Major Conclusions

The instability of commercial CBPBs has been studied and interpreted both qualitatively and quantitatively. Stabilization systems for this material have been developed.

Appraisal of the mechanisms causing dimensional and mass change in CBPBs indicates that both reaction of moisture with the constituents and carbonation of cement paste appeared to be the predominant features controlling the behaviour, though the degradation of wood chips may supplement the degree of change. Consequently: -

a) CBPB was unstable, unlike other conventional particleboards, even under constant RH, with mass and dimensional change relationships diverging with time and the contraction in the thickness being significantly greater than that in length. The profile of density and overall density changed depending on the conditions faced by individual surfaces. The changes were confirmed to be due to the effect of CO₂ (in the air environment). The findings above are of considerable importance for both manufacture and utilization in terms of relationships between the selection of processing parameters, storage duration after manufacture and before site construction, and size requirement.

b) The behaviour of CBPBs reflected the change in RH. Unique behaviour has been discovered when subjecting CBPBs to a single and cyclic changes in RH. The changes in mass and dimensions with time of exposure consisted of two distinct stages: a significant rate of change during the early stage (as for other wood materials) and a reduced rate of change in the later stage (unique nature), with a

distinct "inflection point" in the relationship between dimensional and mass change. The effect on CBPBs before the "inflection point" was dominated by the moisture reaction and that after it was attributable to the carbonation of, or moisture condensation on, CBPBs. Such were these distinct characteristics that two completely different slopes appeared in the lines of the relationship before and after the "inflection point".

Sensitivity of dimensions and mass to the level of RH was very different, with length change being more sensitive to the change in RH at the lower end of the range, but mass change being more sensitive over the upper end of the range. The different reaction of CBPBs with liquid water and moisture vapour was also very clear. Over the whole range of moisture loss deformation of CBPBs was comprised of at least five distinct stages: low shrinkage rate associated with high mass decrease; linear shrinkage with mass decrease; linear shrinkage with higher slope due to the contribution of carbonation; linearity between deformation and mass decrease in further drying, and a final stage of drying with high shrinkage rate accompanied by small amount of mass decrease.

c) Cycling CBPBs through a set of different RHs resulted in especially interesting and practical information - a consistent decrease in dimensions, but increase in mass, with increasing number of cycles. The accumulated changes could amount, after a number of cycles, to equal to or greater than the maximum sorption changes. This has helped explain the reason for cracks and splits when CBPBs are eventually installed in a rigid framework.

d) The hysteresis effects of both mass and dimensional changes were very significant. All hysteresis loops were very dissimilar to those of other wood based materials, including:

- Loop shapes. Mass loops were closed with ad - and de - sorption curves intersecting at between 65 and 90 %RH, and dimension loops were open.

- loop nature. Successive loops for mass change moved upward and those for dimensions moved downward. The degree of movement between the successive cycles reduced with increasing number of cycles.

A mathematical model, which has been combined with moisture diffusion theory and carbonation or condensation rules by introducing Fickian and non - Fickian terms, has been developed:

$$\Delta M_{cp} (\Delta L_{cp}, \Delta T_{cp}) = 100 \left[\frac{M_f(L_f, T_f)}{M_i(L_i, T_i)} - 1 \right] [A + Bt - A \exp(-Ct)]_{\Delta m(d)}$$

The equations can successfully predict changes in mass and dimensions of CBPBs, cement paste and dissected wood chips. Moreover, combination of accumulated and sorption changes allowed behaviour prediction for CBPBs under a set of cyclic RH exposure.

Techniques for the preparation of wood chips removed from the furnished and pressed board, the manufacture of cement paste and their measurement have been developed. It was found that the behaviour of CBPBs reflected that of wood chips and of cement paste. The trend of the behaviour of the constituents was very similar to that of CBPBs in all the results obtained, but the magnitude of the changes at various conditions was different. Bearing in mind the inclusion of cement paste could bring about a significant increase in the mass of dissected chips subjecting to high RH (90 %) and stress relief of wood chips would increase the measured values of dimensional changes.

A technique for quantifying the structure of CBPBs has been developed using SEM and image analysis methods to provide numerical basis for quantitative modelling of CBPBs. This has also very valuable implications for other areas of wood composite research. Analysis concluded:

- the area of the CBPBs was comprised of about 40 % wood chips, 59 % cement paste and less than 1 % detectable voids; compared with a calculated volume fraction

for chips of 0.74, this indicating that the wood chips in CBPBs were highly compressed.

- all wood chips lay nearly flat but were randomly distributed in the horizontal surface, the effective angle between the wood chips and the horizontal surface was about 11.1° and between the wood chips and the edges of CBPBs about 45° , thereby confirming that the effect of wood chips on the length and width change of CBPBs was very similar.

- the percent area occupied by the cement paste was higher in the outer surfaces than in the core, whilst the size of wood chips increased from surface to core. Unlike the mechanism of density profile in other wood particleboards it was this that resulted in a density profile for CBPBs showing higher density in the surface layers and lower in the core.

From numerical results the behaviour prediction for CBPBs was derived by applying the theory of mixtures. This is a novel application of these ideas in light of internal swelling or shrinkage rather than external stresses, showing physical rather than mechanical behaviour and different structure of CBPBs compared to conventional composite analysis. Results not only confirmed the physical interpretation and percentage contributions of constituents but also established a simplified method for predicting idealised mass and dimensional change of CBPBs. It was found that in using the rule of mixtures, the most closely related fraction should be chosen, that is, the mass change of CBPBs being a sum of change in cement paste and wood chip weighted according to the mass fraction:

$$\Delta M_{cpj} = 100[m_{pf}(\frac{M_{pjf}}{M_{pji}} - 1)E_{pj} + 100[m_{wf}(\frac{M_{wjf}}{M_{wji}} - 1)E_{wj}]$$

and the dimensional change of CBPBs summed by the dimensional change of cement paste and wood chip weighted according to the volume fraction:

$$\Delta L(T)_{cp\alpha} = [V_p e_p \Delta L(T)_p + V_w e_{w\alpha} \Delta L(T)_{w\alpha}] \left[\frac{1 - \sqrt{V_{wf}}}{e_p} + \frac{1}{\left(\frac{1}{\sqrt{V_{wf}}} - 1 \right) e_p + e_{w\alpha}} \right]$$

Stabilization of CBPBs has been achieved using the following systems which could be very useful in practice if it is important to avoid or reduce the continual deformation:

- the application of surface coatings was not only able to remarkably reduce both mass and dimensional changes but also to strongly resist carbonation of CBPBs. The effectiveness depended on the types of sealers (proprietary systems > model systems; solvent - borne sealers > water - borne sealers) and the thickness of film. However, there was a consistent deterioration after long term / multicycles;
- the duration of time after mixing and the pressure exerted during pressing both had favourable influences on the behaviour of wood chips due to increased penetration of cement paste;
- the behaviour of CBPBs were influenced by the immediate history of exposure. The full or wider range ad- and de- sorption isotherm defined a loop that enclosed a hysteresis region;
- prolonged storage will reduce the magnitude of mass and dimensional changes of CBPBs on subsequent exposure;
- predrying was very efficacious in stabilizing CBPBs, depending on schedules. However, the mass change of CBPBs was independent of the pre - drying schedules after exposing in a high RH (90 %) rather than a permanent shrinkage in dimensions;
- edge sealing had an influence on the change of both mass and dimensions due to increased flow through the edge than through the top or bottom faces;

- significant difference in the behaviour of CBPBs occurred between water - soaking and oven drying treatments, and between liquid and vapour water exposure. The carbonation of CBPBs did not take place under water soaking.

An all - embracing statement summarised the work and conclusions. From a vast amount of experimental data and analysis one now knows much more about the behaviour of CBPBs in terms of their basic constituents and one is now in a position where behaviour can be modelled and predicted and products can be stabilized thereby giving the user more confidence in its performance.

19.2 Recommendations for Future Work

- 1) Further study should involve investigating the effect of the concentration of CO₂, more intermediate levels of RH and their combined effects on the behaviour of CBPB, and establishing more intermediate curves, especially on full adsorption and desorption and mathematical modelling of the sorption phenomenon.
- 2) Due to the favourable influence of temperature on the stabilization of CBPB, it would be very valuable to study in detail the effect of temperature and hence the combined effects of temperature, RH and CO₂ on CBPB.
- 3) Further work should also extended to investigate the relationship between the behaviour and structure of CBPB, including the size of particleboard (which may change the nature of internal stresses).
- 4) It is of great worth to investigate the relationship between the changes of physical and mechanical properties.
- 5) In terms of behaviour in compliance with the theory of mixtures, future work is required to examine methods of changing the surface chemistry of the wood chip to reduce its hygroscopicity, without reducing the internal bond strength of the composite; and to examine ways of reducing the permeability of the cement paste

without reducing the internal bond strength of the composite.

Chapter 21

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Appendix I

TECHNOLOGY AND PROCESSING OF CBPB

CBPB's manufacturing technology is based on the early ERI patents (Elmendorf Research Inc.). The production process can be summarised by the following flow diagram:

Raw material store ---> Flaking (Chipping) ---> (Milling) ---> Mixing ---> Forming ---> Pressing ---> Hardening (Sizing) ---> Curing ---> Conditioning ---> Finishing ---> Storage (Packaging, Shipment)

Material store Normally debarked wood is stored for about 2 months in order to decompose components (such as sugar) that may delay or hinder cement setting, and evenly distribute the moisture. During storing the possibility of decay and mould attack should be excluded.

Flaking (Chipping) Knife shaft disintegrators or knife ring disintegrators are used in the preparation of chips depending on the form of wood supplied. The flakes are normally produced in the size: 0.35 x 35 x 35 mm.

Milling After chipping the flakes are homogenized in a hammer mill. An adjustable portion of the chips is milled to a certain percentage and dimension. It normally defined the width:

Width (mm)	Content (%)
< 0.5	10
0.5 - 1.0	25
1.0 - 3.35	55
> 3.35	5

Mixing In the mixing section wood and cement are mixed with additional mineralizing agents and water. [In large plants ($\geq 100 \text{ m}^3 / \text{day}$), top and middle layers are mixed apart in separate metering and mixing sections]. Individual components are metered in relation to the weight of absolutely dry wood. The moisture in the wood is continuously monitored and all the ingredients are metered by weight. A board of a basic formula is about 65 % cement, 35 % wood chips (or other plant materials) by weight depending on the required properties.

Currently in manufacture, about 3 % of aluminium sulphate and 3 % sodium silicate are added to the furnish. The former is known to be an accelerator but reasons for addition of sodium silicate are still unknown. It does however appear to produce sticky "gel" around the wood chips.

The order of adding the additional aggregates is:

water (1) + aluminium sulphate (2) + sodium silicate (3)

+

cement (4)

For wood chips with a certain moisture content, the water required for manufacture of cement bonded particleboard can be calculated from the equation:

$$Z = 0.35X + (0.30 - MC)Y$$

where

Z is the water requirement.

X is the weight of cement.

MC is the (oven dry) moisture content of wood chip.

Y is the weight of absolutely dry chip.

Forming The accuracy of the thickness of finished boards is dependent on the quality of forming, and this makes it indispensable to keep the spreading accurate and constant within narrow limits. Mechanical or air spreading systems can be used for this purpose. In general, the material is continuously spread onto a conveyor caul. The weight is controlled once more by a special area - weight determination device. Faulty mouldings are eliminated and the material returned to the spreading machine. After the spreading machine, the endless formed mat on the caul is stretched by a

fast extraction belt and cut to the size of the raw board by an edging saw. The offcuts are again returned to the spreading machine. The thickness of formed boards is about 3 - 3.3 times of final product.

Pressing After forming, the board "blanks" are composed by a means of a stacker into stacks in holding frames. The stacks are compacted to the predetermined thickness in a press and fixed by a cover in the holding frame. A pressure of 2.5 - 3.0 N / mm² is used for pressing.

Hardening The stacks of boards fixed in the mounting carriage are pre-hardened ("boosting") in a hardening tunnel with heating (about 70 °C) for about (6 - 8 hours), and then boards are de - stacked and trimmed.

Curing After de - stacking, the boards are kept in the curing store for about 7 - 8 days in which the hydration takes place.

Conditioning In order to achieve the required properties and moisture content, the boards are converted to the oven with a temperature of about 115 °C for about 3.5 hours depending on the thickness, normally a moisture content from about 22 to 9 %.

Finishing Depending on application or customer demand, the boards can be polished on one or two sides.

Appendix II

BONDING BETWEEN WOOD CHIPS AND HYDRAULIC CEMENT PASTE

1) Mechanical Interaction Between Wood and Cement Paste

The filling or partial filling of adherent surface irregularities with a liquid phase adhesive will form plugs on solidification of the adhesive. Such mechanical forces play a direct role in bond formation. The extent and strength of the mechanical bonds, which is small in most cases (Marian and Stumbo, 1962), depends on a number of physical and chemical properties of both the adhesive and adherent. The roughness of the wood [due to the mechanical machining of the substrate, cellulosic nature of the material-part cells (cell lumen), pit apertures, subcellular pores and microscopic apertures within the cell wall], in addition to increasing the surface area of the interface for specific adhesion to occur, also produces a greater opportunity for the development of adhesive plugs, hence increasing the mechanical bonding.

The physical and chemical dissimilarities of the wood surface and the cement matrix limit both the extent to which the surfaces can be brought and kept in close proximity during the hydration and possible bonding stages, and the nature, and hence the strength, of the wood cement bonding. The purely organic surface of wood is unlikely to be compatible with the ionic inorganic polymers present in the cement matrix, for the formation of specific bonds (Coutts, 1979); cement is not a good adhesive, allowing only a limited capacity for direct contact (Coutts and Campbell, 1979). Bonding between wood and cement is primarily due to mechanical interlocking on a macro-and micro-scale (Ahn, 1978; Ahn and Moslemi, 1980), with macro-interlocking being regarded as the filling of the cell cavities (lumens) and micro-interlocking being caused by crystal growth, generated by hydration of the cement into the cavities (particularly that of the tri-calcium silicate and tri-aluminate). Systematical tests concluded (Steward, 1986) that mechanical bonding plays a major part in the total bonding between wood and cement paste and physio-chemical and

chemical bonding probably accounts for less than 17% of the total bond strength.

2) Wood-Cement Chemical Relationship

Wood-cement composites are unique structural materials. A major technological problem with these inorganic bonded materials is that the bonding strength is dependent on the wood species (Hachmi and Campbell, 1988 in Moslemi, 1988). The physical interaction has been reviewed above. The following section will discuss the chemical part although it is thought to be of secondary importance in contributing to the strength of CBPB.

It is well known that the composition and hydration characteristics of CBPB, which determine the properties, can vary depending on cement type, the manufacturing raw materials and cement manufacturing variables. Normally the hydration of cement and wood can be divided into five stages:

- 1) initial rapid hydration (15-30 minutes);
- 2) dormant period (2-4 hours);
- 3) acceleration period-setting phase (several hours);
- 4) hardening phase (within 24 hours);
- 5) continuing hardening (Jennings, 1983 cited Hachmi and Campbell in Moslemi, 1988).

Correspondingly, the bonding development between wood chips and cement can be divided into three stages: a chemical stage (early wood-cement hydration), a chemical and physical phase (cement crystallizing and building a matrix around the wood chips), and a physical phase (may continue several years). The possible chemical reactions can be summarised as follows:

A) Physio-chemical interaction (Hachmi and Campbell, 1988) During an early stage of hydration: - solution diffusion, wood swelling and dissolution. There are most likely two interactions existing in the wood cement matrix (Figure II 1).

At later stages of hydration: - water and dissolved wood components are probably pulled out of the wood chips and migrate into the interfacial layer, hence inhibiting later stages of the hydration and hardening process. This causes shrinkage

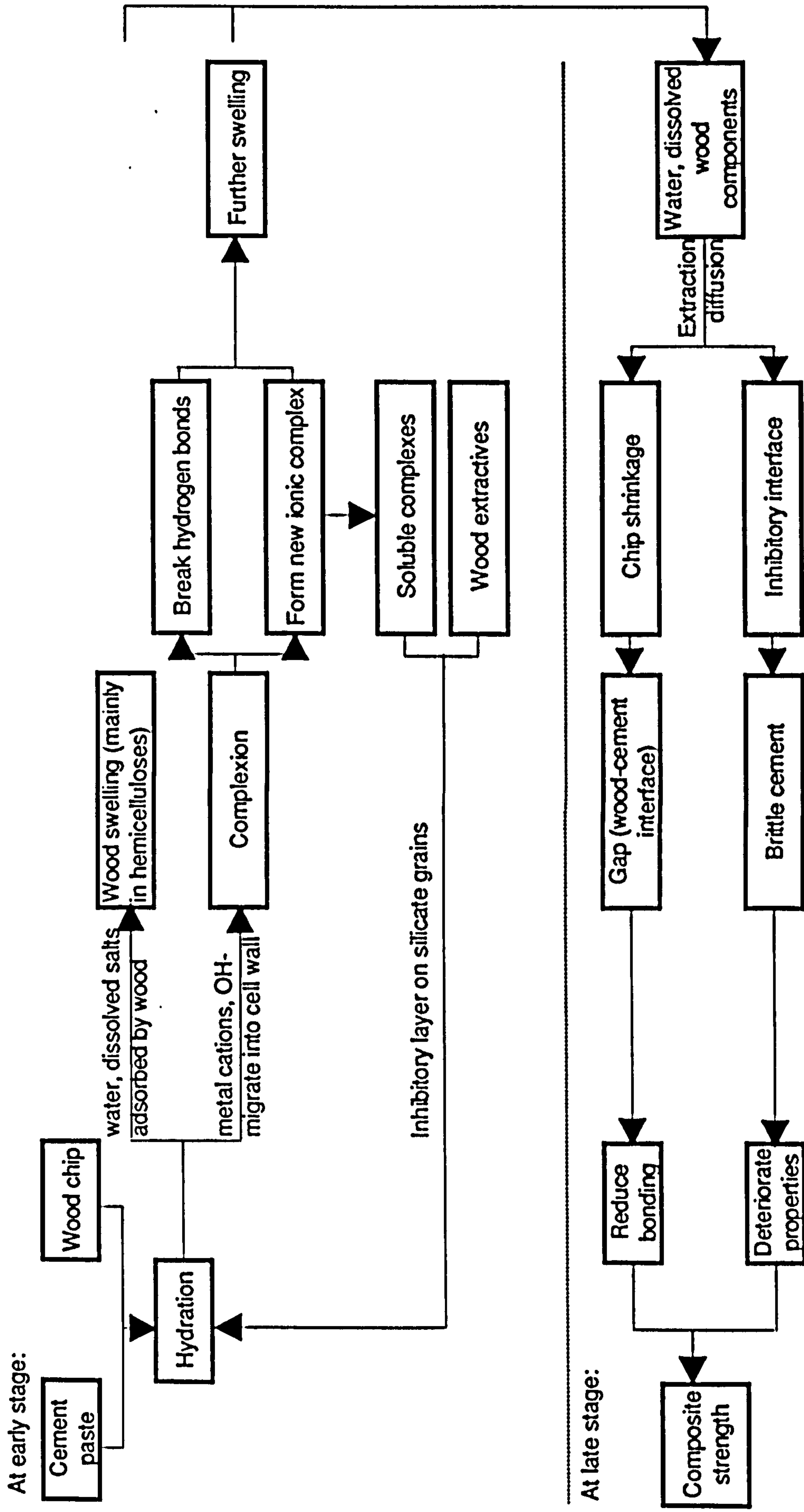


Figure II 1 A schematical diagram of physio-chemical processes between wood and cement during hydration

of the wood chips and reducing the bonding strength (brittle wood & cement).

B) *Chemical interactions* The chemical and physical interactions between wood and wet cement are poorly understood. However, there is no lack of information on the effect of wood species, extractives or other factors on the hydration of CBPB (Fan *et al*, 1989, 1992; Lee, 1984; Moslemi, 1987, 1989). A summary of possible chemical interactions between the wood and cement paste is given below based on Hachmi and Campbell (1988 in Moslemi, 1988) or others mentioned.

a) Carbohydrates intrude into the crystal structure, decreasing the cement crystallinity and then strength.

b) Carbohydrates sorb onto the cement grains and complex with the metal ions, forming insoluble products (Scandermann *et al*, 1960; 1964).

c) Carbohydrates react via the alkaline-catalyzed peeling and stopping reactions (common in alkaline pulping processes).

d) Alkaline cement paste neutralizes the carboxylic acid groups (glucuronic acids) on the hemicelluloses (glucuronoxylans), forming calcium gluconates (Singh, 1976).

e) Acetyl groups (on the hemicelluloses, particularly the xylans) cleave in the presence of alkali, forming calcium acetate.

f) Nonpolar extractives (terpenes and resins) reduce hydrogen bonding due to their nonpolar nature.

g) Alkalis saponify the fats, yielding calcium salts of the fatty acids.

h) Phenolic hydroxyl groups (in tannin, flavonoids, lignin or related phenolic compounds) react with calcium hydroxide to form calcium phenolates.

i) Complex reacts with metal ions to form calcium phenolates.

AN EXAMPLE OF ORIGINAL IMAGE ANALYSIS DATA (HORIZONTAL SURFACE 2)

Class name	Area mm ²	Length mm	Breadth mm	Orientat ion rad	Perimet er mm	Area no hole	Number of holes	Ellipse minor m
Pore size 0	0.05	0.44	0.26	0.50	1.26	0.05	0	0.15
Pore size 0	0.07	0.49	0.28	0.58	1.46	0.07	0	0.18
Pore size 0	0.08	0.70	0.25	0.59	1.80	0.08	0	0.14
Pore size 0	0.07	0.53	0.43	1.00	2.06	0.07	0	0.18
Pore size 0	0.04	0.43	0.17	0.30	1.08	0.04	0	0.11
Pore size 0	0.06	0.51	0.30	0.64	2.35	0.06	1	0.14
Pore size 0	0.05	0.37	0.25	2.01	1.07	0.05	0	0.17
Pore size 0	0.04	0.35	0.25	2.10	1.31	0.05	1	0.16
Pore size 0	0.03	0.51	0.11	1.36	1.16	0.03	0	0.08
Pore size 0	0.03	0.39	0.18	1.05	1.21	0.03	0	0.11
Pore size 0	0.09	0.72	0.30	2.79	2.25	0.09	1	0.16
Pore size 0	0.04	0.43	0.24	0.43	1.68	0.04	1	0.10
Pore size 0	0.07	0.52	0.30	3.00	1.47	0.07	0	0.17
Pore size 0	0.12	1.02	0.30	2.75	2.82	0.12	0	0.15
Pore size 0	0.04	0.44	0.22	0.64	1.20	0.04	0	0.12
Pore size 0	0.11	0.64	0.28	1.52	1.70	0.11	0	0.21
Pore size 0	0.03	0.34	0.17	0.60	0.88	0.03	0	0.13
Pore size 0	0.12	0.64	0.28	2.00	1.86	0.12	0	0.23
Pore size 0	0.04	0.45	0.32	2.16	1.70	0.04	0	0.10
Pore size 0	0.04	0.37	0.18	2.19	0.97	0.04	0	0.13
Pore size 0	0.05	0.48	0.21	0.30	1.31	0.05	0	0.13
Pore size 0	0.07	0.52	0.34	0.49	1.82	0.07	0	0.16

Elongati on 1	Elongati on 2	Aspect ratio	Convex circ.	Circulari ty	Form factor	Hole area mm ²	Convexi ty	Number detected
3.76	2.95	1.69	1.37	1.55	0.41	0	0.88	68
3.47	2.73	1.73	1.33	1.58	0.40	0	0.84	68
6.61	5.19	2.80	1.61	1.86	0.29	0	0.87	68
3.73	2.93	1.24	1.54	2.13	0.22	0	0.72	68
5.07	3.98	2.44	1.42	1.61	0.39	0	0.88	68
4.62	3.63	1.68	1.56	2.81	0.13	0	0.56	109
2.80	2.20	1.50	1.23	1.35	0.55	0	0.91	68
2.86	2.25	1.41	1.31	1.78	0.32	0	0.74	68
7.88	6.19	4.77	1.70	1.80	0.31	0	0.94	109
4.50	3.54	2.16	1.38	1.85	0.29	0	0.75	109
5.88	4.62	2.43	1.58	2.14	0.22	0	0.74	68
5.21	4.10	1.81	1.58	2.52	0.16	0	0.63	68
3.88	3.05	1.71	1.35	1.57	0.41	0	0.86	68
8.90	6.99	3.38	1.85	2.33	0.18	0	0.80	68
4.84	3.81	2.05	1.49	1.68	0.36	0	0.89	68
3.87	3.04	2.25	1.37	1.47	0.46	0	0.93	109
3.49	2.74	2.04	1.29	1.34	0.55	0	0.96	68
3.58	2.81	2.29	1.31	1.55	0.42	0	0.85	109
5.64	4.43	1.40	1.81	2.53	0.16	0	0.71	109
3.61	2.83	2.08	1.32	1.41	0.50	0	0.93	109
4.60	3.61	2.30	1.42	1.64	0.37	0	0.87	109
4.19	3.29	1.55	1.48	2.00	0.25	0	0.74	109

Pore size 0	0.12	0.61	0.40	0.39	1.94	0.12	1	0.25
Pore size 0	0.04	0.41	0.22	1.03	1.42	0.04	1	0.12
Pore size 0	0.03	0.44	0.14	1.82	1.19	0.03	1	0.10
Pore size 0	0.11	0.92	0.31	2.89	3.87	0.11	1	0.15
Pore size 0	0.04	0.33	0.24	2.01	1.02	0.04	0	0.15
Pore size 0	0.07	0.56	0.32	2.95	3.41	0.07	1	0.15
Pore size 0	0.03	0.38	0.21	1.34	1.14	0.03	0	0.11
Pore size 0	0.17	0.69	0.53	2.83	3.19	0.17	0	0.31
Pore size 0	0.04	0.37	0.23	2.19	1.21	0.04	0	0.13
Pore size 0	0.04	0.43	0.19	0.96	1.20	0.04	0	0.12
Pore size 0	0.03	0.44	0.21	3.14	1.61	0.03	0	0.09
Pore size 0	0.03	0.40	0.25	1.30	1.61	0.03	0	0.10
Pore size 0	0.05	0.31	0.26	1.03	0.95	0.05	0	0.21
Pore size 0	0.04	0.60	0.24	2.50	1.91	0.04	0	0.08
Pore size 0	0.20	1.11	0.47	1.47	3.49	0.20	0	0.23
Pore size 0	0.06	0.50	0.25	0.56	1.69	0.06	0	0.15
Pore size 0	0.07	0.48	0.26	2.12	1.54	0.07	0	0.19
Pore size 0	0.08	0.57	0.45	1.01	2.71	0.08	1	0.18
Pore size 0	0.07	0.55	0.36	0.58	1.79	0.07	0	0.17
Pore size 0	0.05	0.54	0.18	0.97	1.52	0.05	1	0.11
Pore size 0	0.05	0.48	0.32	2.88	1.94	0.05	1	0.13
Pore size 0	0.03	0.45	0.32	0.59	1.91	0.04	1	0.10
Pore size 0	0.09	0.52	0.38	1.88	2.11	0.09	0	0.23
Pore size 0	0.04	0.43	0.18	0.04	1.13	0.04	0	0.13
Pore size 0	0.05	0.55	0.27	1.83	2.25	0.05	1	0.12
Dark wood 0	0.31	0.93	0.74	0.15	3.60	0.31	2	0.42
Dark wood 0	0.12	0.71	0.28	0.46	2.91	0.12	5	0.21

3.14	2.47	1.54	1.30	1.58	0.40	0	0.82	109
4.25	3.34	1.89	1.46	2.00	0.25	0	0.73	109
5.88	4.62	3.09	1.55	1.85	0.29	0	0.84	109
7.74	6.08	2.92	1.73	3.31	0.09	0	0.52	109
2.89	2.27	1.41	1.35	1.46	0.47	0	0.92	109
4.73	3.71	1.75	1.58	3.73	0.07	0	0.42	109
4.61	3.62	1.80	1.50	1.80	0.31	0	0.83	109
2.83	2.22	1.31	1.31	2.19	0.21	0	0.60	109
3.70	2.91	1.58	1.39	1.78	0.31	0	0.78	109
4.48	3.52	2.33	1.45	1.66	0.36	0	0.88	56
6.19	4.86	2.14	1.71	2.55	0.15	0	0.67	109
4.95	3.89	1.65	1.61	2.50	0.16	0	0.64	109
1.87	1.47	1.19	1.12	1.18	0.72	0	0.95	109
9.41	7.39	2.52	2.08	2.77	0.13	0	0.75	109
6.08	4.78	2.35	1.62	2.19	0.21	0	0.74	109
4.26	3.35	2.00	1.43	1.95	0.26	0	0.73	109
3.22	2.53	1.82	1.35	1.64	0.37	0	0.82	109
3.92	3.08	1.25	1.59	2.67	0.14	0	0.60	56
4.09	3.21	1.55	1.41	1.85	0.29	0	0.76	109
6.05	4.75	3.02	1.56	1.97	0.26	0	0.79	109
4.68	3.67	1.48	1.60	2.47	0.16	0	0.65	109
5.79	4.55	1.39	1.84	2.90	0.12	0	0.63	109
2.89	2.27	1.39	1.29	1.93	0.27	0	0.67	109
4.15	3.26	2.40	1.37	1.52	0.43	0	0.90	56
6.06	4.76	2.05	1.66	2.83	0.12	0	0.58	109
2.82	2.21	1.26	1.32	1.83	0.30	0	0.72	68
4.35	3.42	2.57	1.45	2.40	0.17	0.01	0.60	109

Dark wood 0	0.06	0.65	0.18	2.86	2.12	0.06	5	0.11
Dark wood 0	0.12	0.85	0.44	3.14	4.24	0.13	5	0.18
Dark wood 0	0.03	0.47	0.20	2.83	1.60	0.03	2	0.09
Dark wood 0	0.09	0.50	0.38	1.01	1.86	0.09	2	0.22
Dark wood 0	0.15	0.71	0.49	2.53	4.01	0.16	12	0.27
Dark wood 0	0.13	1.42	0.32	3.08	5.48	0.13	3	0.12
Dark wood 0	0.05	0.45	0.27	1.16	2.12	0.05	2	0.15
Dark wood 0	0.20	0.97	0.48	1.16	5.33	0.22	16	0.26
Dark wood 0	0.18	0.63	0.45	1.86	2.15	0.18	3	0.36
Dark wood 0	0.87	3.41	0.99	2.81	20.68	1.05	47	0.32
Dark wood 0	0.08	0.67	0.32	2.01	3.04	0.09	4	0.15
Dark wood 0	0.23	1.07	0.64	1.96	5.01	0.28	13	0.28
Dark wood 0	0.22	1.54	0.44	1.36	6.47	0.25	14	0.18
Dark wood 0	0.18	1.39	0.35	0.18	5.56	0.20	11	0.17
Dark wood 0	0.06	0.72	0.28	1.37	2.40	0.06	2	0.10
Dark wood 0	0.14	1.07	0.43	1.47	4.84	0.15	3	0.16
Dark wood 0	0.06	0.49	0.34	2.92	2.44	0.07	3	0.17
Dark wood 0	0.06	0.89	0.17	2.86	2.22	0.06	2	0.08
Dark wood 0	0.04	0.57	0.20	3.11	1.81	0.04	2	0.09
Dark wood 0	0.16	1.25	0.28	1.49	5.82	0.16	8	0.16
Dark wood 0	0.35	1.03	0.64	2.77	3.97	0.37	13	0.44
Dark wood 0	0.08	0.91	0.30	2.72	3.66	0.09	4	0.11
Dark wood 0	0.10	1.04	0.26	2.21	3.34	0.11	3	0.12
Dark wood 0	0.04	0.52	0.19	2.03	1.39	0.05	3	0.11
Dark wood 0	0.15	0.66	0.44	1.84	2.22	0.15	2	0.28
Dark wood 0	0.10	0.76	0.26	1.05	2.39	0.10	4	0.16
Dark wood 0	0.21	1.10	0.50	1.06	6.45	0.22	9	0.24

7.44	5.85	3.58	1.73	2.52	0.16	0.01	0.68	109
5.94	4.66	1.92	1.66	3.42	0.09	0.01	0.48	109
6.89	5.41	2.39	1.70	2.54	0.15	0	0.67	109
2.88	2.26	1.31	1.37	1.77	0.32	0	0.78	68
3.33	2.61	1.47	1.38	2.89	0.12	0.01	0.48	109
15.63	12.28	4.45	2.38	4.29	0.05	0	0.56	109
3.88	3.05	1.67	1.45	2.64	0.14	0	0.55	109
4.70	3.69	2.02	1.54	3.36	0.09	0.01	0.46	68
2.25	1.77	1.40	1.18	1.45	0.48	0.01	0.81	68
13.45	10.57	3.43	2.25	6.27	0.03	0.19	0.36	109
5.52	4.33	2.11	1.58	3.02	0.11	0.01	0.52	109
4.93	3.87	1.68	1.59	2.92	0.12	0.04	0.54	109
10.99	8.63	3.48	2.01	3.92	0.07	0.03	0.51	109
10.63	8.35	4.01	1.97	3.68	0.07	0.01	0.54	109
9.40	7.38	2.58	1.92	2.87	0.12	0	0.67	109
8.42	6.61	2.51	1.87	3.70	0.07	0.01	0.51	109
3.71	2.92	1.46	1.47	2.70	0.14	0.01	0.54	109
14.29	11.22	5.17	2.23	2.66	0.14	0	0.84	109
7.77	6.10	2.91	1.81	2.50	0.16	0	0.72	109
10.03	7.88	4.39	2.03	4.17	0.06	0.01	0.49	109
3.00	2.36	1.61	1.27	1.89	0.28	0.01	0.67	109
10.15	7.97	3.03	2.00	3.60	0.08	0.01	0.56	109
10.90	8.56	4.04	2.01	2.99	0.11	0.01	0.67	109
5.95	4.67	2.68	1.53	1.85	0.29	0	0.83	109
3.03	2.38	1.49	1.28	1.65	0.37	0	0.78	109
5.90	4.63	2.93	1.52	2.17	0.21	0	0.70	109
5.78	4.54	2.19	1.64	3.99	0.06	0.01	0.41	109

Dark wood 0	0.10	0.64	0.45	1.80	2.36	0.11	7	0.20
Dark wood 0	0.14	1.17	0.33	2.85	4.30	0.15	4	0.15
Dark wood 0	0.06	0.45	0.34	2.47	2.37	0.07	2	0.18
Dark wood 0	0.85	1.78	1.00	0.52	13.04	1.02	63	0.61
Dark wood 0	0.10	0.61	0.34	1.93	2.40	0.11	7	0.21
Dark wood 0	0.04	0.31	0.21	1.98	0.95	0.04	2	0.16
Dark wood 0	0.16	0.94	0.50	2.40	3.46	0.17	8	0.21
Dark wood 0	0.04	0.40	0.32	2.29	1.71	0.05	2	0.13
Dark wood 0	0.09	0.60	0.37	2.74	3.54	0.10	2	0.20
Wood size 0	0.04	0.87	0.15	0.35	2.07	0.04	2	0.06
Wood size 0	0.04	0.63	0.24	2.32	2.05	0.04	1	0.08
Wood size 0	0.06	0.65	0.20	2.32	1.92	0.06	0	0.12
Wood size 0	0.05	0.70	0.20	0.42	2.08	0.05	0	0.09
Wood size 0	0.30	1.20	0.46	2.78	3.57	0.31	13	0.31
Wood size 0	0.70	1.82	0.84	0.59	6.29	0.75	29	0.49
Wood size 0	0.03	0.34	0.27	2.98	1.64	0.04	2	0.13
Wood size 0	0.51	1.62	0.67	2.81	8.13	0.54	24	0.40
Wood size 0	0.04	0.56	0.17	0.22	1.63	0.04	0	0.09
Wood size 0	0.79	1.72	0.94	2.46	6.54	0.85	46	0.59
Wood size 0	0.03	0.39	0.17	1.89	1.44	0.03	0	0.11
Wood size 0	0.06	0.85	0.12	1.57	1.97	0.06	0	0.08
Wood size 0	0.13	0.78	0.28	1.27	2.32	0.13	2	0.21
Wood size 0	0.05	0.43	0.22	0.67	1.27	0.05	0	0.14
Wood size 0	0.17	0.94	0.33	0.83	2.28	0.17	1	0.23
Wood size 0	0.04	0.51	0.25	1.22	1.54	0.04	0	0.11
Wood size 0	0.41	1.25	0.51	0.21	3.76	0.42	18	0.41
Wood size 0	0.15	0.68	0.46	0.71	2.63	0.15	8	0.27

3.97	3.11	1.42	1.51	2.08	0.23	0.01	0.73	109
9.60	7.54	3.49	1.91	3.21	0.10	0.01	0.59	109
3.25	2.55	1.35	1.41	2.65	0.14	0	0.53	109
3.72	2.92	1.78	1.44	3.98	0.06	0.17	0.36	109
3.62	2.84	1.77	1.32	2.12	0.22	0.01	0.62	56
2.44	1.92	1.50	1.22	1.35	0.55	0	0.90	56
5.71	4.49	1.88	1.66	2.47	0.16	0.02	0.67	56
3.86	3.04	1.27	1.53	2.36	0.18	0	0.65	56
3.83	3.01	1.60	1.48	3.27	0.09	0	0.45	109
18.64	14.64	5.77	2.53	2.90	0.12	0	0.87	68
10.02	7.87	2.59	2.03	2.92	0.12	0	0.70	109
6.70	5.26	3.30	1.62	2.14	0.22	0	0.76	68
9.95	7.81	3.48	1.97	2.65	0.14	0	0.74	68
4.85	3.81	2.59	1.40	1.85	0.29	0.01	0.76	68
4.72	3.71	2.15	1.41	2.12	0.22	0.05	0.67	68
3.36	2.64	1.28	1.51	2.49	0.16	0	0.61	68
5.15	4.05	2.41	1.47	3.22	0.10	0.03	0.46	68
8.02	6.30	3.29	1.80	2.31	0.19	0	0.78	68
3.73	2.93	1.83	1.32	2.08	0.23	0.06	0.63	68
4.67	3.67	2.25	1.43	2.23	0.20	0	0.64	68
13.09	10.28	6.86	2.19	2.36	0.18	0	0.93	68
4.76	3.74	2.75	1.42	1.83	0.30	0	0.77	68
3.86	3.03	1.91	1.39	1.63	0.38	0	0.85	68
5.15	4.04	2.87	1.42	1.55	0.42	0	0.92	68
6.01	4.72	2.08	1.65	2.08	0.23	0	0.79	68
3.87	3.04	2.43	1.29	1.66	0.36	0.01	0.77	68
3.16	2.48	1.49	1.32	1.94	0.27	0.01	0.68	68

Wood size 0	0.51	1.68	0.92	1.74	10.64	0.63	32	0.39
Wood size 0	0.29	0.97	0.62	2.51	4.29	0.30	18	0.38
Wood size 0	0.10	0.96	0.31	2.92	2.92	0.10	1	0.13
Wood size 0	0.34	1.05	0.83	2.20	5.27	0.40	21	0.41
Wood size 0	0.04	0.48	0.18	2.73	1.26	0.04	2	0.11
Wood size 0	0.08	0.70	0.24	0.66	2.45	0.09	4	0.14
Wood size 0	0.12	0.80	0.30	1.96	2.59	0.12	6	0.18
Wood size 0	0.16	1.00	0.30	0.27	2.60	0.16	1	0.21
Wood size 0	0.10	0.78	0.25	0.30	1.89	0.11	3	0.17
Wood size 0	0.40	1.90	0.39	3.10	5.53	0.44	24	0.27
Wood size 0	0.18	0.77	0.49	0.09	2.89	0.20	11	0.30
Wood size 0	0.31	1.54	0.78	1.86	5.40	0.33	16	0.25
Wood size 0	0.05	0.34	0.27	0.49	1.47	0.05	1	0.17
Wood size 0	0.04	0.54	0.17	1.09	1.32	0.04	3	0.09
Wood size 0	0.08	0.85	0.21	1.63	2.28	0.08	1	0.12
Wood size 0	0.41	1.42	0.48	2.35	3.90	0.43	16	0.37
Wood size 0	0.04	0.75	0.18	1.89	2.02	0.04	1	0.07
Wood size 0	0.04	0.48	0.18	2.36	1.14	0.04	0	0.11
Wood size 0	0.35	1.63	0.41	0.87	4.23	0.37	22	0.27
Wood size 0	0.06	1.07	0.21	2.50	2.57	0.06	1	0.07
Wood size 0	0.03	0.38	0.26	1.34	1.44	0.04	1	0.11
Wood size 0	0.89	1.63	1.23	1.78	8.21	1.06	57	0.69
Wood size 0	0.89	2.32	1.02	1.66	8.29	0.98	56	0.49
Wood size 0	0.48	1.73	0.79	1.40	8.51	0.56	34	0.35
Wood size 0	0.06	0.50	0.22	1.97	1.34	0.06	1	0.15
Wood size 0	0.25	0.83	0.59	0.46	2.97	0.27	18	0.39
Wood size 0	0.35	1.85	0.44	1.57	7.32	0.41	22	0.24

5.47	4.30	1.81	1.71	4.19	0.06	0.12	0.41	68
3.25	2.55	1.57	1.28	2.26	0.20	0.02	0.57	68
9.29	7.29	3.14	1.91	2.60	0.15	0	0.73	68
3.29	2.58	1.27	1.43	2.55	0.15	0.06	0.56	68
5.78	4.54	2.64	1.53	1.76	0.32	0	0.87	68
6.20	4.87	2.94	1.64	2.47	0.16	0.01	0.66	68
5.62	4.42	2.69	1.50	2.15	0.22	0.01	0.70	68
6.17	4.85	3.36	1.55	1.83	0.30	0	0.85	68
5.84	4.59	3.14	1.49	1.65	0.37	0	0.90	68
9.12	7.16	4.87	1.83	2.48	0.16	0.04	0.74	68
3.22	2.53	1.56	1.34	1.91	0.28	0.02	0.70	68
7.69	6.04	1.96	1.88	2.74	0.13	0.02	0.69	68
2.52	1.98	1.27	1.25	1.93	0.27	0	0.65	68
7.40	5.81	3.15	1.73	1.88	0.28	0	0.92	68
9.22	7.24	4.01	1.84	2.29	0.19	0	0.80	109
4.87	3.83	2.96	1.42	1.71	0.34	0.01	0.83	68
12.91	10.14	4.21	2.16	2.75	0.13	0	0.79	68
5.47	4.30	2.69	1.48	1.58	0.40	0	0.94	68
7.54	5.92	3.92	1.69	2.02	0.25	0.02	0.84	109
18.37	14.43	5.14	2.50	2.92	0.12	0	0.86	68
4.28	3.36	1.46	1.60	2.19	0.21	0	0.73	68
3.01	2.36	1.33	1.36	2.46	0.17	0.17	0.55	56
6.04	4.74	2.28	1.62	2.48	0.16	0.09	0.65	109
6.26	4.92	2.20	1.66	3.47	0.08	0.08	0.48	68
4.13	3.24	2.29	1.34	1.53	0.43	0	0.88	68
2.75	2.16	1.40	1.22	1.66	0.36	0.02	0.73	68
9.74	7.65	4.16	1.98	3.49	0.08	0.06	0.57	109

Wood size 0	0.16	0.85	0.50	0.21	2.88	0.17	3	0.24
Wood size 0	0.27	0.90	0.73	0.94	4.09	0.28	8	0.39
Wood size 0	0.08	0.84	0.37	2.40	2.95	0.08	2	0.12
Wood size 0	0.03	0.54	0.17	0.90	1.55	0.03	0	0.08
Wood size 0	0.58	1.75	0.74	0.66	6.60	0.62	19	0.42
Wood size 0	0.05	0.72	0.17	1.00	1.78	0.05	2	0.08
Wood size 0	0.08	0.52	0.38	2.86	2.07	0.09	4	0.21
Wood size 0	0.11	0.66	0.37	0.42	1.79	0.11	0	0.21
Wood size 0	0.08	0.53	0.36	0.83	1.88	0.09	8	0.18
Wood size 0	0.18	1.21	0.28	1.76	2.96	0.19	1	0.19
Wood size 0	0.09	1.09	0.26	0.84	3.41	0.09	0	0.10
Wood size 0	0.04	0.38	0.20	1.34	1.00	0.04	2	0.12
Wood size 0	0.64	2.22	0.55	3.12	6.89	0.73	47	0.37
Wood size 0	0.05	0.86	0.15	1.24	2.07	0.05	0	0.08
Wood size 0	0.28	1.07	0.54	1.11	3.55	0.30	13	0.33
Wood size 0	0.33	1.24	0.79	2.31	5.84	0.37	15	0.33
Wood size 0	0.52	1.65	0.73	1.37	10.54	0.61	26	0.40
Wood size 0	0.33	2.06	0.50	1.54	9.18	0.35	13	0.21
Wood size 0	0.15	0.93	0.34	3.06	2.43	0.15	3	0.20
Wood size 0	0.74	3.20	0.55	2.21	9.64	0.79	23	0.29
Wood size 0	0.09	0.54	0.31	2.43	1.61	0.09	3	0.20
Wood size 0	0.36	1.77	0.61	1.79	8.53	0.44	22	0.26
Wood size 0	0.57	1.66	0.67	0.19	4.83	0.59	7	0.44
Wood size 0	0.81	2.41	0.70	2.65	6.79	0.82	13	0.43
Wood size 0	0.75	1.93	1.10	0.33	11.08	0.84	54	0.50
Wood size 0	0.04	0.43	0.24	2.62	1.30	0.06	2	0.13
Wood size 0	0.11	0.74	0.30	0.19	2.11	0.12	8	0.18

4.45	3.49	1.72	1.53	2.01	0.25	0.01	0.76	109
2.96	2.33	1.24	1.35	2.20	0.21	0.01	0.61	109
9.22	7.24	2.26	2.05	3.00	0.11	0	0.68	109
9.10	7.14	3.28	1.88	2.43	0.17	0	0.77	109
5.26	4.13	2.37	1.48	2.44	0.17	0.04	0.61	109
11.01	8.64	4.34	2.01	2.31	0.19	0	0.87	109
3.15	2.48	1.34	1.39	2.00	0.25	0.01	0.69	109
3.91	3.07	1.77	1.34	1.51	0.44	0	0.88	56
3.65	2.87	1.47	1.40	1.92	0.27	0.01	0.73	109
7.95	6.24	4.31	1.69	1.94	0.26	0	0.87	109
13.96	10.96	4.15	2.21	3.28	0.09	0	0.67	109
3.95	3.10	1.96	1.37	1.46	0.47	0	0.93	109
7.68	6.03	4.03	1.68	2.43	0.17	0.09	0.69	109
14.55	11.43	5.84	2.28	2.58	0.15	0	0.88	109
4.17	3.28	1.98	1.46	1.91	0.28	0.03	0.76	109
4.73	3.72	1.58	1.62	2.88	0.12	0.05	0.56	109
5.28	4.15	2.27	1.62	4.14	0.06	0.09	0.39	109
12.74	10.01	4.14	2.20	4.49	0.05	0.01	0.49	109
5.87	4.61	2.74	1.50	1.80	0.31	0	0.84	56
13.84	10.87	5.84	2.22	3.17	0.10	0.05	0.70	56
3.38	2.65	1.74	1.30	1.54	0.42	0.01	0.85	56
8.75	6.88	2.91	1.88	4.03	0.06	0.08	0.47	109
4.84	3.80	2.47	1.40	1.80	0.31	0.02	0.78	63
7.23	5.68	3.47	1.69	2.13	0.22	0.01	0.79	56
4.95	3.89	1.75	1.57	3.60	0.08	0.08	0.44	109
4.18	3.28	1.77	1.44	1.75	0.33	0.01	0.83	109
5.22	4.10	2.46	1.48	1.84	0.30	0.02	0.81	109

Wood size 0	0.04	0.49	0.12	0.18	1.23	0.04	3	0.10
Wood size 0	0.05	0.49	0.21	1.79	1.40	0.05	0	0.13
Wood size 0	0.38	1.13	0.63	1.79	3.72	0.42	18	0.42
Wood size 0	0.50	1.66	0.68	2.16	5.26	0.54	26	0.38
Wood size 0	0.15	0.92	0.46	2.45	3.33	0.15	12	0.20
Wood size 0	0.17	0.95	0.47	2.54	3.26	0.18	5	0.23
Wood size 0	0.27	1.14	0.48	2.67	4.50	0.31	14	0.30
Wood size 0	0.40	2.22	0.54	2.02	6.76	0.44	20	0.23
Wood size 0	0.19	0.80	0.41	2.10	2.40	0.22	19	0.29
Wood size 0	0.20	1.03	0.54	2.20	3.75	0.22	12	0.25
Wood size 0	0.09	0.63	0.29	1.74	1.93	0.09	2	0.19
Wood size 0	0.07	0.66	0.31	1.84	3.04	0.07	2	0.13
Wood size 0	0.23	1.33	0.30	2.34	3.49	0.24	11	0.22
Wood size 0	0.05	0.54	0.24	2.33	1.69	0.05	1	0.11
Wood size 0	0.36	1.62	0.57	2.19	7.05	0.40	26	0.28
Wood size 0	0.06	0.65	0.29	2.02	2.09	0.07	2	0.12
Wood size 0	0.03	0.62	0.15	1.25	1.77	0.04	2	0.07
Wood size 0	0.03	0.39	0.20	2.62	1.08	0.03	0	0.11
Wood size 0	0.07	0.55	0.26	1.34	1.63	0.07	0	0.16
Wood size 0	0.35	1.46	0.45	1.97	3.91	0.38	30	0.31
Wood size 0	0.11	0.71	0.27	0.64	1.87	0.11	2	0.20
Wood size 0	0.25	0.91	0.71	1.59	4.30	0.28	8	0.36
Wood size 0	0.32	1.03	0.65	1.40	4.00	0.35	12	0.40
Wood size 0	0.04	0.38	0.19	2.42	1.21	0.04	1	0.12
Wood size 0	0.09	0.57	0.32	0.67	1.83	0.09	2	0.21
Wood size 0	0.27	0.82	0.56	1.55	2.82	0.27	8	0.42
Wood size 0	0.67	1.41	1.13	2.09	6.04	0.70	19	0.61

6.39	5.02	3.92	1.62	1.80	0.31	0	0.90	109
4.66	3.66	2.34	1.52	1.73	0.33	0	0.88	56
3.39	2.66	1.79	1.31	1.71	0.34	0.04	0.77	109
5.53	4.34	2.43	1.50	2.10	0.23	0.04	0.71	68
5.77	4.53	1.99	1.59	2.45	0.17	0.01	0.65	68
5.14	4.04	2.02	1.49	2.21	0.21	0.01	0.67	68
4.86	3.82	2.35	1.50	2.46	0.16	0.04	0.61	56
12.34	9.69	4.13	2.09	3.01	0.11	0.03	0.69	68
3.47	2.73	1.94	1.34	1.57	0.41	0.03	0.85	68
5.20	4.08	1.92	1.58	2.34	0.18	0.02	0.67	68
4.26	3.35	2.17	1.38	1.78	0.31	0	0.77	109
6.43	5.05	2.16	1.73	3.27	0.09	0	0.53	109
7.69	6.04	4.41	1.65	2.05	0.24	0.01	0.81	109
6.25	4.91	2.28	1.69	2.21	0.20	0	0.77	109
7.27	5.71	2.84	1.71	3.32	0.09	0.04	0.52	109
6.86	5.39	2.27	1.79	2.38	0.18	0	0.75	109
11.75	9.23	4.01	2.05	2.77	0.13	0	0.74	109
4.63	3.64	2.00	1.51	1.68	0.35	0	0.90	109
4.33	3.40	2.10	1.41	1.75	0.33	0	0.80	49
6.10	4.79	3.23	1.52	1.86	0.29	0.03	0.82	109
4.44	3.49	2.67	1.36	1.56	0.41	0	0.87	63
3.23	2.54	1.28	1.41	2.41	0.17	0.03	0.58	63
3.30	2.59	1.59	1.40	2.00	0.25	0.03	0.70	63
4.00	3.14	2.02	1.35	1.82	0.30	0	0.75	63
3.52	2.77	1.76	1.34	1.71	0.34	0	0.79	63
2.50	1.96	1.45	1.21	1.54	0.42	0.01	0.78	63
2.95	2.32	1.24	1.37	2.08	0.23	0.03	0.66	63

Wood size 0	0.08	0.55	0.25	1.51	1.69	0.08	3	0.18
Wood size 0	0.04	0.72	0.15	2.20	1.60	0.04	0	0.08
Wood size 0	0.05	0.45	0.25	0.59	1.20	0.05	0	0.13
Wood size 0	0.05	0.60	0.20	2.27	1.60	0.06	4	0.11
Wood size 0	0.04	0.31	0.19	2.91	0.90	0.04	0	0.15
Wood size 0	0.08	0.51	0.25	2.90	1.66	0.08	0	0.19
Wood size 0	0.11	0.62	0.37	0.58	2.16	0.11	2	0.22
Wood size 0	0.12	0.58	0.35	0.79	2.25	0.12	1	0.27
Wood size 0	0.79	1.92	1.10	0.36	15.68	0.94	27	0.52
Wood size 0	0.14	0.68	0.32	2.90	2.08	0.14	1	0.25
Wood size 0	0.06	0.76	0.23	1.00	1.77	0.06	0	0.10
Wood size 0	0.71	1.70	1.14	2.00	6.84	0.75	37	0.53
Wood size 0	0.04	0.47	0.18	1.23	1.17	0.04	2	0.11
Wood size 0	0.09	0.60	0.28	0.87	2.24	0.09	0	0.18
Wood size 0	0.91	3.31	0.63	0.24	9.27	0.92	10	0.35
Wood size 0	0.04	0.43	0.20	2.18	1.43	0.04	2	0.12
Wood size 0	0.11	0.98	0.23	1.59	2.43	0.11	6	0.14
Wood size 0	0.07	0.69	0.30	2.14	2.90	0.08	3	0.13
Wood size 0	0.04	0.53	0.18	1.57	1.81	0.04	1	0.09
Wood size 0	0.03	0.33	0.25	0.44	1.48	0.04	3	0.12
Wood size 0	0.07	0.44	0.31	2.33	1.63	0.08	1	0.22
Wood size 0	0.04	0.56	0.20	2.65	1.67	0.04	1	0.09
Wood size 0	0.57	1.72	0.96	2.62	7.05	0.63	35	0.42
Wood size 0	0.05	0.58	0.20	0.34	1.67	0.05	1	0.10
Wood size 0	0.06	0.48	0.29	1.19	1.50	0.06	1	0.15
Wood size 0	0.10	0.81	0.23	1.72	1.88	0.10	0	0.15
Wood size 0	0.10	0.69	0.32	2.75	2.76	0.12	8	0.19

3.97	3.12	2.22	1.33	1.72	0.34	0	0.77	63
11.73	9.21	4.90	2.01	2.14	0.22	0	0.94	63
4.28	3.36	1.82	1.41	1.56	0.41	0	0.90	63
6.99	5.49	3.01	1.65	1.97	0.26	0	0.84	63
2.70	2.12	1.66	1.22	1.35	0.55	0	0.90	63
3.40	2.67	2.01	1.30	1.68	0.35	0	0.77	63
3.50	2.75	1.65	1.36	1.85	0.29	0	0.73	63
2.77	2.18	1.65	1.25	1.83	0.30	0	0.68	63
4.65	3.65	1.74	1.57	4.98	0.04	0.15	0.31	63
3.38	2.65	2.12	1.34	1.60	0.39	0	0.84	63
9.51	7.47	3.33	1.85	2.03	0.24	0	0.91	63
4.06	3.19	1.50	1.45	2.29	0.19	0.04	0.63	63
5.27	4.14	2.66	1.51	1.60	0.39	0	0.94	63
4.20	3.30	2.17	1.40	2.14	0.22	0	0.66	63
12.02	9.44	5.25	2.07	2.74	0.13	0.01	0.76	63
4.77	3.74	2.22	1.47	2.03	0.24	0	0.73	63
9.01	7.07	4.23	1.82	2.11	0.23	0.01	0.87	56
6.83	5.36	2.28	1.76	3.08	0.11	0.01	0.57	109
7.14	5.61	3.00	1.74	2.56	0.15	0	0.68	109
3.53	2.77	1.36	1.46	2.36	0.18	0.01	0.62	109
2.59	2.03	1.43	1.26	1.68	0.35	0	0.75	49
8.20	6.44	2.80	1.85	2.39	0.17	0	0.77	109
5.19	4.08	1.79	1.58	2.64	0.14	0.07	0.60	109
7.41	5.82	2.99	1.70	2.20	0.21	0	0.77	63
4.07	3.20	1.65	1.48	1.79	0.31	0	0.83	63
6.82	5.36	3.50	1.57	1.71	0.34	0	0.92	63
4.75	3.73	2.15	1.47	2.46	0.17	0.02	0.60	49

Wood size 0	0.04	0.47	0.21	0.97	1.35	0.04	2	0.11
Wood size 0	0.46	1.67	0.74	1.71	7.32	0.49	17	0.35
Wood size 0	0.07	0.82	0.18	1.53	2.64	0.08	5	0.11
Wood size 0	0.55	1.45	1.00	0.63	5.84	0.57	16	0.49
Wood size 0	0.07	0.61	0.21	0.95	1.61	0.07	0	0.14
Wood size 0	0.05	0.45	0.20	2.02	1.33	0.05	0	0.13
Wood size 0	0.04	0.35	0.25	1.04	1.35	0.04	1	0.15
Wood size 0	0.16	1.18	0.26	0.50	3.12	0.17	7	0.17
Wood size 0	0.14	0.91	0.47	0.30	3.41	0.17	5	0.19
Wood size 0	0.39	1.47	0.59	2.80	6.27	0.41	20	0.34
Wood size 0	0.05	0.43	0.20	0.96	1.22	0.05	0	0.14
Wood size 0	0.17	0.87	0.44	1.13	4.15	0.20	11	0.25
Wood size 0	0.06	0.52	0.19	1.11	1.29	0.06	0	0.15
Wood size 0	0.08	0.74	0.30	0.99	2.09	0.08	3	0.13
Wood size 0	0.06	0.45	0.29	2.30	1.75	0.06	1	0.16
Wood size 0	0.04	0.32	0.22	1.68	0.99	0.04	1	0.15
Wood size 0	0.04	0.46	0.16	1.34	1.10	0.04	0	0.10
Wood size 0	0.32	1.51	0.47	0.06	4.51	0.34	11	0.27
Wood size 0	0.13	0.75	0.37	2.70	2.60	0.14	7	0.22
Wood size 0	0.04	0.44	0.18	0.24	1.20	0.04	0	0.12
Wood size 0	0.20	0.87	0.48	1.11	3.24	0.21	9	0.29
Wood size 0	0.33	1.98	0.36	2.16	4.79	0.33	4	0.21
Wood size 0	0.85	2.00	0.87	0.32	11.14	0.94	51	0.54
Wood size 0	0.17	0.80	0.64	0.64	4.37	0.19	12	0.27
Wood size 0	0.04	0.48	0.22	0.63	1.41	0.04	1	0.12
Wood size 0	0.06	0.46	0.29	2.52	1.44	0.06	1	0.18
Wood size 0	0.05	0.58	0.16	0.16	1.34	0.05	1	0.11

5.54	4.35	2.22	1.50	1.90	0.28	0	0.79	63
6.03	4.73	2.26	1.68	3.04	0.11	0.02	0.55	63
9.30	7.30	4.60	1.88	2.78	0.13	0.01	0.68	63
3.79	2.97	1.44	1.48	2.21	0.20	0.02	0.67	63
5.38	4.23	2.87	1.46	1.72	0.34	0	0.84	63
4.33	3.40	2.28	1.39	1.72	0.34	0	0.81	63
2.99	2.35	1.41	1.33	1.88	0.28	0	0.71	63
8.59	6.74	4.52	1.77	2.19	0.21	0.01	0.80	63
6.02	4.73	1.95	1.71	2.59	0.15	0.03	0.66	63
5.51	4.33	2.50	1.50	2.82	0.13	0.02	0.53	63
3.85	3.02	2.12	1.33	1.56	0.41	0	0.85	63
4.35	3.41	1.99	1.43	2.82	0.13	0.02	0.51	63
4.52	3.55	2.68	1.39	1.50	0.45	0	0.93	56
7.10	5.58	2.46	1.67	2.12	0.22	0	0.79	63
3.55	2.79	1.55	1.37	2.06	0.24	0	0.67	63
2.65	2.08	1.49	1.23	1.41	0.50	0	0.87	63
5.60	4.40	2.91	1.52	1.61	0.39	0	0.94	63
7.20	5.65	3.21	1.66	2.26	0.20	0.02	0.73	63
4.42	3.47	2.03	1.46	2.06	0.23	0.01	0.71	63
4.78	3.76	2.47	1.45	1.69	0.35	0	0.86	63
3.84	3.01	1.81	1.38	2.05	0.24	0.01	0.67	49
11.92	9.36	5.54	2.02	2.35	0.18	0	0.86	56
4.75	3.73	2.30	1.54	3.42	0.09	0.09	0.45	63
3.70	2.91	1.26	1.54	2.97	0.11	0.02	0.52	63
5.25	4.12	2.18	1.49	1.88	0.28	0	0.79	63
3.26	2.56	1.58	1.31	1.60	0.39	0	0.81	63
6.68	5.25	3.67	1.59	1.70	0.35	0	0.94	63

Wood size 0	0.40	1.09	0.78	2.06	5.53	0.47	21	0.47
Wood size 0	0.09	0.83	0.44	0.66	3.72	0.10	5	0.14
Wood size 0	0.03	0.30	0.19	1.21	0.86	0.03	0	0.13
Wood size 0	0.17	0.95	0.57	1.12	4.05	0.20	12	0.24
Wood size 0	0.04	0.55	0.18	2.88	1.81	0.04	0	0.08
Wood size 0	0.22	1.07	0.69	2.07	5.53	0.24	14	0.27
Wood size 0	0.14	1.13	0.34	1.81	3.12	0.14	3	0.16
Wood size 0	0.10	0.87	0.29	2.87	2.76	0.10	2	0.14
Wood size 0	0.26	1.07	0.58	0.60	3.85	0.27	5	0.31
Wood size 0	0.06	0.59	0.16	1.66	1.51	0.06	1	0.14
Wood size 0	0.10	0.85	0.23	1.85	2.69	0.10	3	0.15
Wood size 0	0.13	0.71	0.41	2.18	2.18	0.14	5	0.23
Wood size 0	0.13	0.58	0.43	1.79	1.75	0.13	0	0.29
Wood size 0	0.33	1.38	0.60	1.12	4.72	0.35	17	0.31
Wood size 0	0.31	0.91	0.50	0.42	2.75	0.31	4	0.43
Wood size 0	0.98	3.76	0.89	1.67	16.24	1.03	20	0.33
Wood size 0	0.10	0.79	0.34	1.91	2.85	0.11	5	0.16
Wood size 0	0.20	0.98	0.41	1.14	3.30	0.21	4	0.26
Wood size 0	0.03	0.50	0.17	0.74	1.19	0.03	0	0.08
Wood size 0	0.05	0.35	0.28	2.88	1.19	0.05	0	0.16
Wood size 0	0.03	0.44	0.14	1.94	1.26	0.03	0	0.09
Wood size 0	0.12	0.95	0.29	1.34	2.43	0.12	3	0.16
Wood size 0	0.05	0.35	0.25	0.53	1.16	0.05	0	0.17
Wood size 0	0.03	0.52	0.12	2.11	1.13	0.04	1	0.09
Wood size 0	0.06	0.49	0.19	0.86	1.22	0.06	0	0.16
Wood size 0	0.04	0.52	0.18	0.54	1.38	0.04	0	0.09
Wood size 0	0.05	0.60	0.20	2.40	1.54	0.05	1	0.10

2.96	2.32	1.39	1.29	2.47	0.16	0.07	0.52	63
7.59	5.96	1.91	1.86	3.47	0.08	0	0.54	63
2.89	2.27	1.60	1.22	1.36	0.54	0	0.89	63
5.11	4.02	1.67	1.56	2.74	0.13	0.02	0.57	63
8.46	6.64	3.00	1.84	2.70	0.14	0	0.68	63
5.12	4.02	1.55	1.67	3.29	0.09	0.01	0.51	63
9.29	7.30	3.30	1.92	2.37	0.18	0	0.81	56
7.70	6.04	2.96	1.74	2.49	0.16	0	0.70	63
4.36	3.43	1.86	1.45	2.11	0.22	0.01	0.69	63
5.55	4.36	3.68	1.50	1.70	0.35	0	0.88	56
7.21	5.66	3.68	1.69	2.40	0.17	0	0.70	56
3.87	3.04	1.76	1.36	1.70	0.35	0	0.80	56
2.57	2.02	1.36	1.26	1.36	0.54	0	0.93	56
5.72	4.50	2.29	1.53	2.31	0.19	0.02	0.67	56
2.72	2.14	1.84	1.24	1.40	0.51	0	0.88	56
14.51	11.40	4.24	2.31	4.64	0.05	0.06	0.50	56
6.14	4.82	2.31	1.62	2.52	0.16	0	0.64	56
4.83	3.79	2.36	1.46	2.09	0.23	0.01	0.70	56
7.86	6.18	3.03	1.75	1.87	0.29	0	0.93	56
2.70	2.12	1.27	1.28	1.58	0.40	0	0.81	56
5.92	4.65	3.15	1.57	1.97	0.26	0	0.80	49
7.48	5.87	3.23	1.70	1.98	0.26	0	0.86	56
2.59	2.04	1.38	1.25	1.51	0.44	0	0.83	56
7.73	6.07	4.49	1.66	1.71	0.34	0	0.97	56
3.96	3.11	2.55	1.31	1.39	0.51	0	0.94	56
7.26	5.71	2.92	1.76	2.02	0.24	0	0.87	49
7.74	6.08	3.00	1.77	2.01	0.25	0	0.88	56

Wood size 0	0.04	0.35	0.17	2.43	0.86	0.04	0	0.14
Wood size 0	0.06	0.62	0.24	0.58	1.78	0.06	1	0.13
Wood size 0	0.42	1.09	0.61	2.41	3.68	0.46	17	0.49
Wood size 0	0.12	1.00	0.34	0.34	2.93	0.12	2	0.15
Wood size 0	0.27	0.94	0.64	2.86	4.64	0.30	22	0.36
Wood size 0	0.04	0.42	0.26	2.57	1.82	0.04	0	0.12
Wood size 0	0.19	0.89	0.49	1.29	4.55	0.22	21	0.27
Wood size 0	0.20	1.35	0.40	2.29	4.73	0.20	3	0.19
Wood size 0	0.44	1.49	1.12	0.96	8.40	0.46	5	0.38
Wood size 0	0.05	0.46	0.25	1.30	2.06	0.05	1	0.13
Wood size 0	0.03	0.30	0.23	1.21	0.97	0.03	1	0.13
Wood size 0	0.10	0.58	0.36	2.31	1.76	0.10	4	0.22
Wood size 0	0.85	1.55	1.10	2.70	9.86	0.93	46	0.70
Wood size 0	0.03	0.37	0.17	1.13	1.11	0.03	0	0.11
Wood size 0	0.03	0.46	0.17	1.18	1.30	0.04	2	0.09
Wood size 0	0.68	1.87	1.12	0.10	7.13	0.71	17	0.46
Wood size 0	0.45	2.28	0.61	1.19	15.33	0.50	23	0.25
Wood size 0	0.13	0.89	0.39	1.27	4.67	0.14	5	0.19
Wood size 0	0.03	0.41	0.20	1.17	1.22	0.04	4	0.10
Wood size 0	0.04	0.37	0.26	2.01	1.52	0.04	0	0.13
Wood size 0	0.04	0.49	0.26	2.28	1.74	0.04	1	0.11
Wood size 0	0.04	0.43	0.25	0.79	1.30	0.04	0	0.11
Wood size 0	0.03	0.57	0.14	1.82	1.33	0.03	0	0.07
Wood size 0	0.18	1.02	0.29	0.80	2.54	0.18	2	0.23
Wood size 0	0.19	0.96	0.33	0.84	2.79	0.19	3	0.25
Wood size 0	0.22	0.92	0.48	0.19	2.71	0.22	4	0.31
Wood size 0	0.21	0.71	0.59	0.61	3.22	0.21	1	0.38

3.31	2.60	2.13	1.23	1.25	0.64	0	0.99	56
6.26	4.92	2.60	1.58	2.04	0.24	0	0.78	56
2.83	2.22	1.79	1.22	1.59	0.39	0.03	0.76	56
8.39	6.59	2.91	1.86	2.39	0.17	0	0.77	56
3.36	2.64	1.48	1.42	2.54	0.16	0.03	0.56	49
4.63	3.63	1.63	1.60	2.61	0.15	0	0.61	49
4.13	3.25	1.82	1.43	2.94	0.12	0.03	0.49	49
9.15	7.19	3.35	1.90	3.00	0.11	0	0.63	49
5.03	3.95	1.34	1.70	3.56	0.08	0.02	0.48	49
4.49	3.53	1.85	1.49	2.67	0.14	0	0.56	49
2.92	2.29	1.31	1.35	1.54	0.42	0	0.88	56
3.39	2.66	1.59	1.28	1.58	0.40	0	0.81	56
2.83	2.22	1.41	1.28	3.02	0.11	0.08	0.42	56
4.29	3.37	2.25	1.38	1.73	0.33	0	0.79	49
6.26	4.92	2.64	1.62	1.98	0.25	0	0.82	49
5.17	4.06	1.67	1.67	2.44	0.17	0.03	0.69	56
11.51	9.04	3.76	2.14	6.44	0.02	0.05	0.33	49
6.02	4.73	2.30	1.63	3.62	0.08	0.01	0.45	49
5.02	3.94	2.05	1.50	1.90	0.28	0.01	0.79	49
3.68	2.89	1.43	1.47	2.20	0.21	0	0.67	49
5.46	4.29	1.89	1.61	2.33	0.18	0	0.69	49
5.07	3.98	1.74	1.60	1.93	0.27	0	0.83	56
9.95	7.82	4.00	1.95	2.08	0.23	0	0.94	56
5.75	4.51	3.51	1.53	1.69	0.35	0	0.90	56
4.78	3.75	2.86	1.42	1.80	0.31	0	0.79	56
3.85	3.02	1.92	1.35	1.63	0.38	0	0.83	56
2.40	1.89	1.22	1.28	1.97	0.26	0	0.65	56

Wood size 0	0.50	1.36	0.75	0.86	5.14	0.53	25	0.47
Wood size 0	0.23	0.97	0.44	0.90	2.53	0.24	2	0.31
Wood size 0	0.05	0.61	0.15	2.63	1.42	0.05	0	0.11
Wood size 0	0.07	0.49	0.35	0.76	1.34	0.08	3	0.19
Wood size 0	0.07	0.53	0.28	1.91	1.48	0.07	0	0.17
Wood size 0	0.25	1.23	0.65	0.58	7.06	0.27	12	0.26
Wood size 0	0.07	0.58	0.27	2.55	2.10	0.07	2	0.16
Wood size 0	0.10	0.52	0.44	0.54	3.30	0.12	3	0.24
Wood size 0	0.12	0.93	0.26	1.98	3.04	0.13	4	0.17
Wood size 0	0.96	2.34	1.01	2.43	9.72	1.06	46	0.52
Wood size 0	0.74	1.59	1.16	2.51	7.99	0.86	42	0.60
Wood size 0	0.04	0.48	0.22	2.25	1.42	0.04	0	0.11
Wood size 0	0.04	0.39	0.25	0.63	1.85	0.04	1	0.12
Wood size 0	0.04	0.58	0.20	2.23	1.45	0.05	2	0.10
Wood size 0	0.78	2.31	0.73	0.01	10.59	0.84	35	0.43
Wood size 0	0.05	0.46	0.31	1.84	1.81	0.05	1	0.13
Wood size 0	0.18	1.39	0.25	2.62	3.58	0.18	4	0.16
Wood size 0	0.05	0.43	0.27	2.18	1.52	0.06	3	0.14
Wood size 0	0.30	1.40	0.76	1.79	7.99	0.34	7	0.27
Wood size 0	0.03	0.43	0.19	2.41	1.33	0.03	1	0.10
Wood size 0	0.17	0.80	0.59	2.39	3.71	0.22	6	0.28
Wood size 0	0.20	1.01	0.55	1.08	6.60	0.22	9	0.25
Wood size 0	0.03	0.38	0.18	2.66	1.20	0.03	1	0.11
Wood size 0	0.16	0.71	0.41	0.23	2.22	0.16	0	0.28
Wood size 0	0.08	0.67	0.24	1.73	1.91	0.08	0	0.15
Wood size 0	0.31	1.13	0.65	2.61	5.69	0.42	9	0.34
Wood size 0	0.07	0.70	0.26	2.52	2.48	0.08	3	0.13

3.69	2.89	1.82	1.30	2.05	0.24	0.03	0.64	56
4.04	3.17	2.19	1.32	1.47	0.46	0	0.90	56
7.25	5.69	4.22	1.64	1.77	0.32	0	0.93	56
3.24	2.54	1.41	1.32	1.39	0.52	0.01	0.95	56
3.88	3.05	1.92	1.35	1.56	0.41	0	0.86	49
5.96	4.68	1.91	1.65	3.95	0.06	0.01	0.42	49
4.58	3.60	2.12	1.43	2.20	0.21	0	0.65	49
2.78	2.18	1.17	1.39	2.99	0.11	0.02	0.46	49
7.06	5.54	3.57	1.65	2.45	0.17	0.01	0.67	49
5.71	4.49	2.33	1.65	2.80	0.13	0.1	0.59	49
3.39	2.66	1.37	1.40	2.61	0.15	0.12	0.54	49
5.41	4.25	2.22	1.52	1.94	0.27	0	0.78	49
4.14	3.25	1.57	1.53	2.70	0.14	0	0.57	49
7.63	5.99	2.89	1.71	1.94	0.27	0	0.88	49
6.84	5.37	3.17	1.68	3.39	0.09	0.07	0.50	49
4.41	3.46	1.50	1.56	2.33	0.18	0	0.67	49
10.99	8.63	5.67	1.95	2.41	0.17	0	0.81	49
3.90	3.06	1.63	1.44	1.95	0.26	0.01	0.74	49
6.55	5.15	1.83	1.72	4.12	0.06	0.04	0.42	49
5.52	4.34	2.26	1.54	2.07	0.23	0	0.75	49
3.70	2.91	1.37	1.45	2.51	0.16	0.05	0.58	49
5.08	3.99	1.84	1.57	4.16	0.06	0.02	0.38	49
4.31	3.38	2.15	1.42	1.84	0.29	0	0.77	49
3.18	2.50	1.75	1.28	1.57	0.40	0	0.81	49
5.81	4.56	2.78	1.56	1.95	0.26	0	0.80	49
4.18	3.28	1.75	1.47	2.91	0.12	0.11	0.51	49
6.96	5.47	2.72	1.65	2.64	0.14	0	0.62	49

Wood size 0	0.07	0.47	0.30	2.83	1.67	0.07	1	0.20
Wood size 0	0.09	0.65	0.29	1.85	2.21	0.09	1	0.18
Wood size 1	1.58	3.34	0.94	0.73	9.74	1.72	91	0.60
Wood size 1	2.00	4.98	1.26	1.53	18.31	2.41	132	0.51
Wood size 1	1.94	3.87	0.98	2.80	14.00	2.01	66	0.64
Wood size 1	1.89	3.38	1.08	2.95	10.16	2.16	125	0.71
Wood size 1	1.07	3.85	0.78	0.17	12.43	1.16	35	0.35
Wood size 1	1.10	2.40	1.14	1.55	11.36	1.33	81	0.58
Wood size 1	1.03	2.35	0.95	0.81	8.30	1.21	48	0.56
Wood size 1	1.37	4.70	0.89	0.30	14.20	1.46	91	0.37
Wood size 1	1.12	2.19	1.31	0.52	12.43	1.29	59	0.65
Wood size 1	1.15	2.34	1.09	2.66	11.12	1.41	103	0.63
Wood size 1	1.05	2.64	0.82	2.56	11.64	1.14	45	0.51
Wood size 1	1.67	2.41	1.37	1.07	11.61	1.87	128	0.88
Wood size 1	1.11	3.67	0.91	1.08	18.21	1.28	77	0.38
Wood size 1	1.47	3.53	0.87	0.03	11.49	1.55	50	0.53
Wood size 2	2.48	3.09	1.49	0.33	16.26	2.91	137	1.02
Wood size 2	2.05	2.78	1.44	2.94	14.09	2.17	86	0.94
Wood size 2	2.65	3.51	1.78	2.12	20.86	3.16	219	0.96
Wood size 2	2.01	3.26	1.49	0.34	12.30	2.15	90	0.79
Wood size 2	2.95	3.61	1.70	1.39	22.87	3.45	171	1.04
Wood size 3	4.00	6.75	1.26	0.02	27.79	4.91	184	0.75
Wood size 3	3.17	5.12	1.59	2.79	24.05	3.82	181	0.79
Wood size 4	4.43	5.09	2.22	1.51	21.42	5.10	319	1.11
Wood size 5	5.14	5.69	1.94	0.05	27.32	6.05	274	1.15
Wood size 6	6.89	6.49	2.97	2.94	36.49	8.05	412	1.35

2.93	2.30	1.56	1.24	1.74	0.33	0	0.72	49
4.51	3.54	2.21	1.45	2.05	0.24	0	0.71	49
7.08	5.56	3.55	1.61	2.19	0.21	0.14	0.73	68
12.39	9.73	3.95	2.14	3.65	0.07	0.41	0.59	109
7.72	6.06	3.95	1.69	2.84	0.12	0.07	0.60	56
6.03	4.74	3.12	1.55	2.08	0.23	0.27	0.74	109
13.88	10.90	4.95	2.19	3.39	0.09	0.09	0.65	63
5.24	4.11	2.11	1.59	3.06	0.11	0.23	0.52	49
5.37	4.22	2.47	1.56	2.31	0.19	0.18	0.68	68
16.05	12.60	5.27	2.38	3.42	0.09	0.09	0.70	68
4.26	3.35	1.67	1.47	3.31	0.09	0.17	0.44	63
4.76	3.74	2.14	1.49	2.92	0.12	0.26	0.51	109
6.64	5.21	3.23	1.65	3.20	0.10	0.09	0.51	49
3.47	2.73	1.76	1.32	2.53	0.16	0.2	0.52	68
12.15	9.54	4.03	2.13	4.88	0.04	0.17	0.44	109
8.51	6.69	4.06	1.77	2.68	0.14	0.08	0.66	63
3.86	3.03	2.08	1.41	2.91	0.12	0.43	0.49	68
3.76	2.95	1.93	1.31	2.78	0.13	0.12	0.47	63
4.64	3.65	1.97	1.44	3.61	0.08	0.51	0.40	49
5.28	4.15	2.19	1.49	2.45	0.17	0.14	0.61	68
4.42	3.47	2.12	1.49	3.76	0.07	0.5	0.40	49
11.40	8.95	5.35	2.05	3.92	0.07	0.91	0.52	49
8.28	6.50	3.22	1.76	3.81	0.07	0.65	0.46	109
5.84	4.59	2.29	1.63	2.87	0.12	0.67	0.57	56
6.30	4.94	2.94	1.58	3.40	0.09	0.91	0.46	109
6.11	4.80	2.18	1.60	3.92	0.07	1.16	0.41	56