CHAPTER V

RELATIONSHIP BETWEEN THICKNESS SWELLING AND MAT STRUCTURES IN ROBOT-FORMED FLAKEBOARD MATS

Abstract

The relationship between thickness swelling and mat structures in robot-formed flakeboard mats under humid conditions with consideration of the density/overlaps in the flakeboard and the absorbed moisture has been studied. Results show a highly correlated linear relationship between thickness swelling and relative moisture content. The relationship between moisture absorption coefficient and the density/ overlaps is also linear.

5.1. Introduction

Oriented strand board (OSB), a reconstituted wood product with oriented flakes in both face and bottom layers and random flakes in the core layer, is hygroscopic and dimensionally unstable when exposed to a humid environment or immersed in water. It absorbs or releases moisture when subjected to an increase or decrease, respectively, in relative humidity at a given temperature. Thickness swelling influences composite panel performance, both visually and functionally. Johnson (1956) investigated the dimension changes in 36 types of commercial hardboard by exposing the specimens to water soaking for 24 hours and to a relative humidity of 90% for 8 months. A linear relationship between percentage of water absorption and thickness swelling was found for most panels in which the water was absorbed at approximately the same rate. Within 10 days after exposure to high relative humidity conditions, most of the boards reached approximately the same moisture content. Johnson (1964) later reported that the increase in moisture and thickness swelling for specimens of commercial particleboard exposed to 90% relative humidity were at least twice the increase obtained at exposure to 65% relative humidity in the same time period. Halligan (1970) thoroughly reviewed the effects of board density, wood species, flake geometry, resin type and content, blending efficiency, pressing conditions and special treatments on the thickness swelling in particleboard/ flakeboards produced under conventional pressing. In terms of influence of flake geometry on thickness swelling, two factors: flake slenderness ratio (ratio of length to thickness) and flake thickness have been considered (Mottet 1967). The larger the slenderness ratio, the higher dimensional stability and the smaller the flake thickness, the smaller the swelling. In higher density boards the flakes are more severely compressed resulting in potential swelling as stresses are released.

Lehmann (1972) found that thickness swelling was directly related to the amount of moisture absorbed. Under conventional press schedule, the maximum thickness increase for commercial particleboard was 9.7% under 10.29% moisture absorption, 16.2% for commercial three-layer particleboard under 11.62% moisture absorption, and 17.6% for laboratory-made particleboard under 11.08% moisture absorption. In some cases, functions of time were more highly correlated with thickness swelling than the amount of absorbed moisture. The logarithm of time, instead of square root of time stated in classical diffusion theory, provided the most highly correlated relationships with water adsorption. Gatchell *et al* (1966) related the board density to thickness swelling from exposure to high humidity environment. Suo (1991) approached a wood composite as a multilayer system and proposed an equation to predict the behavior of thickness swelling (*TS*) based on the properties of each layer,

$$TS = a_0 + a_1(MC) + a_2 \boldsymbol{r} \tag{5.1}$$

where

a_0, a_1, a_2 = constants,

MC = moisture content, and

$\boldsymbol{r}$ = board density.

Xu and Winistorfer (1995) proposed a method to determine the thickness swelling distribution across the board thickness and to relate it to the vertical density distribution. The results showed that an average of 7.82% and 15.05% thickness swelling were obtained in a 24-hour soak test for OSB and particleboard, respectively. The thickness swelling at the surface region of the OSB and particleboard was higher than that in the center. Approximately a linear relationship was found between layer density and layer thickness swelling. The layer distribution of water absorption in OSB and particleboard was also believed to be positively correlated to layer density and to layer thickness swelling (Xu *et al* 1996). An average of 16.5% and 32.1% of water absorption were measured after 24-hour water soak exposures for OSB and particleboard, respectively.

Geimer *et al* (1998) conducted research to investigate the effect of steam injection pressure and duration on the thickness swelling of resinless flake mats soaked in water and concluded that thickness swelling was greatly reduced by steam injection as compared to the thickness swelling of conventionally pressed mats.

In liquid water or in high humid environment, thickness swelling consists of three major components: natural dimensional changes of wood material, release of residual stresses imparted to the panel during pressing, and non-uniform board structure in terms of density variation (Song and Ellis 1997). Dimensional stability could be improved by decreasing board density (Vital et al 1979, 1980); therefore, the mat structure plays an important role because it controls the density/overlaps in the local area and the compression behavior during the manufacturing process. Thus the thickness swelling is not only time dependent and moisture dependent, but is also structure dependent. So far all the thickness swelling studies of OSB or particleboard are mainly based on empirical experimental data. There is a need to describe the relationship among the thickness swelling, moisture absorption and the structural properties of the panel.

The thickness changes in wood composite panels in end-use applications are usually a result of two cases: 1) due to absorption of liquid water during construction, and 2) due to absorption of moisture in service in high humidity climates. For each of these cases, specific tests can be conducted to simulate the end-use conditions. The standard 24-hour water soaking test specified in ASTM (1994) would simulate the first one. A high humidity chamber test would simulate the second one. This chapter focuses on the dimensional changes in the thickness direction, due to absorbing moisture in service.

The objectives of this study are: 1) to develop a relationship between the thickness swelling and relative moisture content; and 2) to predict the thickness swelling under high humidity test condition when the distribution of board density or overlaps is known.

5.2. Model

Thickness swelling is defined as the percentage of thickness increase over the original thickness. According to the definition of the Canadian Standard Association (CSA, 1993), the percentage of thickness swelling of a panel, *TS*, is calculated with the following formula:

$$TS = \frac{t_t - t_0}{t_0} \times 100 \tag{5.2}$$

where t_t = the thickness measured at time *t* after testing (mm), and

t_0 = the original thickness measured before testing (mm).

5.2.1. Strain and stress relationship

The orthotropic nature of wood leads to complex relations between stresses and strains, especially when time dependence and moisture dependence are considered. The understanding on the behavior of wood elements subjected to humid condition is of great value when it concerns the quality of structural flakeboard in service. Martensson (1994) proposed a general constitutive model to represent the behavior of wood. According to this model, the time derivatives of the strain are functions of stresses and moisture conditions, *i.e.*,

$$\dot{e} = \dot{e}^{e} + \dot{e}^{c} + \dot{e}^{st} + \dot{e}^{ms} \tag{5.3}$$

where

$\dot{e}^{e} = \frac{\dot{s}}{E}$ is the elastic strain rate,

$\dot{e}^{c}$ is the pure creep strain rate,

$\dot{e}^{st} = (a - \Delta a)\dot{M}$ is the shrinkage and swelling strain rate, and

$\dot{e}^{ms} = m\,s\left|\dot{M}\right|$ is the mechanosorptive strain rate.

Here, M = moisture content, s = current stress, a = absorption coefficient, E = elastic modulus and m = mechanosorptive parameter. $\Delta a = kpe^{e} + k(e^{c} + e^{ms})$ is also a function of the elastic strain, the creep strain, and the mechanosorptive strain.

When the specimens absorb moisture in a high relative humidity condition without external load, there is no external stress applied. Therefore, all the terms related to stress vanish and **Equation** 5.3 simplifies to:

$$\dot{e} = \dot{e}^{st} = a\dot{M} \tag{5.4}$$

Since the strain, e, has the same definition as thickness swelling, TS, therefore, the following relationship also holds true:

$$\frac{d(TS)}{dt} = \frac{de}{dt} = a\frac{dM}{dt} \tag{5.5}$$

Integrating both sides of **Equation** 5.5.

$$TS(t) - TS(t_0) = a\left[M(t) - M(t_0)\right] \tag{5.6}$$

where $TS(t)$, $TS(t_0)$ = the thickness swelling at time t and t_0, respectively, and

$M(t)$, $M(t_0)$ = the moisture content at time t and t_0, respectively.

Assuming $TS(t_0)$ = 0 (no thickness swelling before the specimens were put in a humidity chamber), **Equation** 5.6 can be expressed as:

$$TS(t) = a\left[M(t) - M(t_0)\right] = a \cdot \Delta M(t) \tag{5.7}$$

where $DM(t)$ = absolute moisture absorbed from time t_0 to time t.

Equations 5.5 shows that thickness swelling rate is a linear function of the rate of moisture content and **Equation** 5.7 indicates that thickness swelling is a linear function of the moisture absorbed.

5.2.2. Effect of mat structures

The absorption coefficient, a, is a structure-related parameter. In general, it is believed that the increase of board density resulted in increase of thickness swelling (Wang and Lam 1998). Suchsland (1989) indicated that the dimensional stability of flakeboards is controlled by the higher density regions. Assuming the absorption coefficient a varies linearly with respect to the board density, a can be expressed to take on the following form:

$$a = f(r) = k_0 + k_1 r \tag{5.8}$$

where r = local board density (g/cm^3), and

k_0, k_1 = constants.

Thus the **Equations** 5.5 and 5.7 can be expressed as a function of density as follows,

$$\frac{d(TS)}{dt} = (k_0 + k_1 r)\frac{dM}{dt} \tag{5.9}$$

$$TS(t) = (k_0 + k_1 r)\Delta M(t) \tag{5.10}$$

Lu *et al* (1998) showed that the density has the following relationship with the number of flake overlaps, *O*.

$$r = \frac{O t_f r_f}{t} \tag{5.11}$$

where O = local average number of flake overlaps,

t_f = flake thickness (mm),

r_f = flake density (g/cm^3), and

t = board thickness (mm).

Substituting the **Equation** 5.11 into **Equations** 5.9 and 5.10, the thickness swelling can be expressed as a function of flake overlaps as

$$\frac{d(TS)}{dt} = (k_0 + k_1^* O)\frac{dM}{dt} \tag{5.12}$$

$$TS(t) = (k_0 + k_1^* O)\Delta M(t) \tag{5.13}$$

where

$$k_1^* = k_1 \frac{t_f\, r_f}{t} \text{ constant.}$$

5.3. Materials and Methods

Nine experimental flakeboards of size 240mm (length) by 240mm (width) by 10mm (thickness) were prepared by using a robot-forming technique. Uniform aspen flakes of size 100mm (length) by 20mm (width) by 0.8mm (thickness) with average density of 0.35g/cm^3 were used in each mat. All flakes were dried to an equilibrium moisture content of 10-12% and mixed with 6% (based on the oven-dry flake weight) powder phenol-formaldehyde resin (CASCOPHEN W91B) before the mat forming process. No wax was applied.

The flake centroid positions (x, y) and orientation angles (q) of the mat were randomly selected by a simulation program *Winmat*© (Lu *et al* 1998) assuming uniform distributions of x, y and q. Six hundred and forty six (646) flakes were used in each mat for a target board density of 0.6 g/cm^3 with an average of 19 overlaps of flakes in a column and 34 flakes in a layer. The parameters (x, y, q) of each flake were saved to a deposition data file and used for all nine mats. A robot mat-forming program ***Robot***© loaded the data file and converted the parameters of each flake into the format of robot controller commands. These commands consist of seven variables for each flake. Three of them (x_m, y_m, z_m) indicate the position of flake over the mat area. Another three (x_b, y_b, z_b) specify where the robot arm should pick up the flakes from flake holder bins and the last one for the orientation angle (q) of a flake on a mat. The whole mat-forming process was controlled by a computer, which was used to send the robot commands one by one to robot controller. Thus a loose mat was formed one flake by one flake. The nine replicated mats were made from the same database by the robot mat forming system in this way.

A laboratory hot press (300mm × 300mm) equipped with an MTS computer data acquisition system was then used to press the formed mat. Efforts were made to load the formed mat into hot press without flake movement. The origin of Cartesian coordinate was clearly identified on the pressed panels. The loose mats were hot-pressed at 180^{o}C to 10 mm stops using 0.5 min. closing time, 5 min. at stops and 0.5 min. opening time. The temperature, pressure and pressing time can be accurately recorded in a file stored in a PC during pressing. The schematic diagram of the mat structure is illustrated in **Figure** 5.1, the simulated local density averages are shown in **Figure** 5.2 and the local density measured by gravimetric method is illustrated in **Figures** 5.4a and 5.4b.

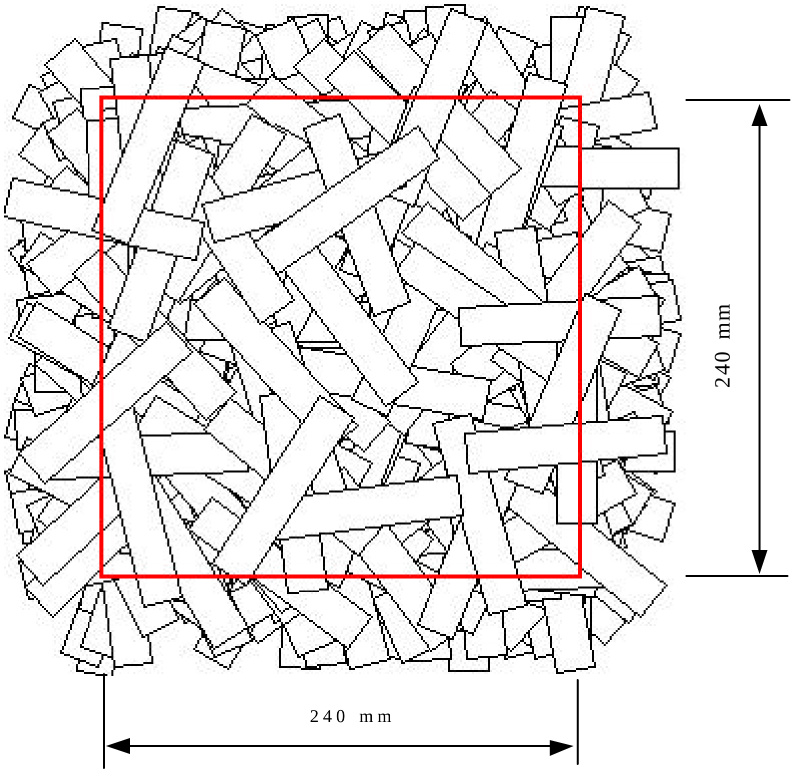

Figure 5.1 Schematic diagram of mat structures.

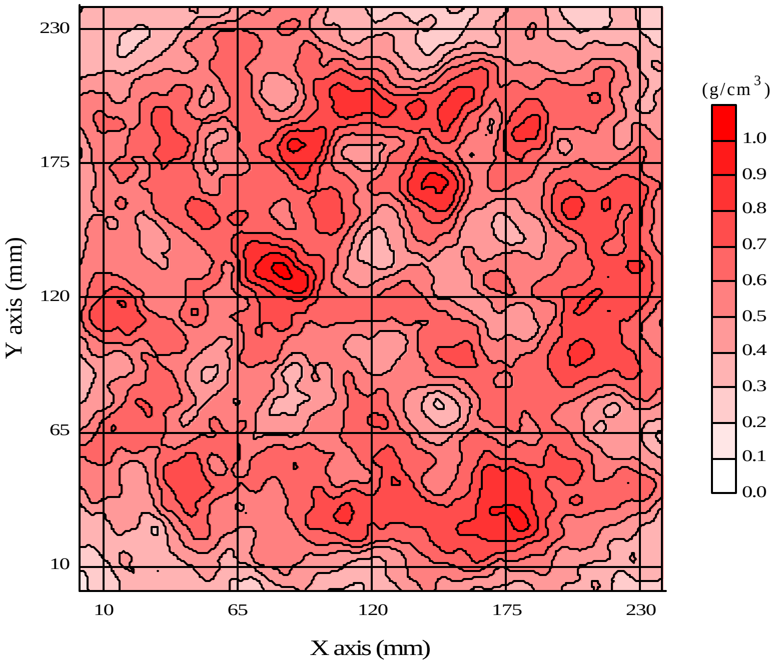

Figure 5.2 Contour map of simulated horizontal density distribution.

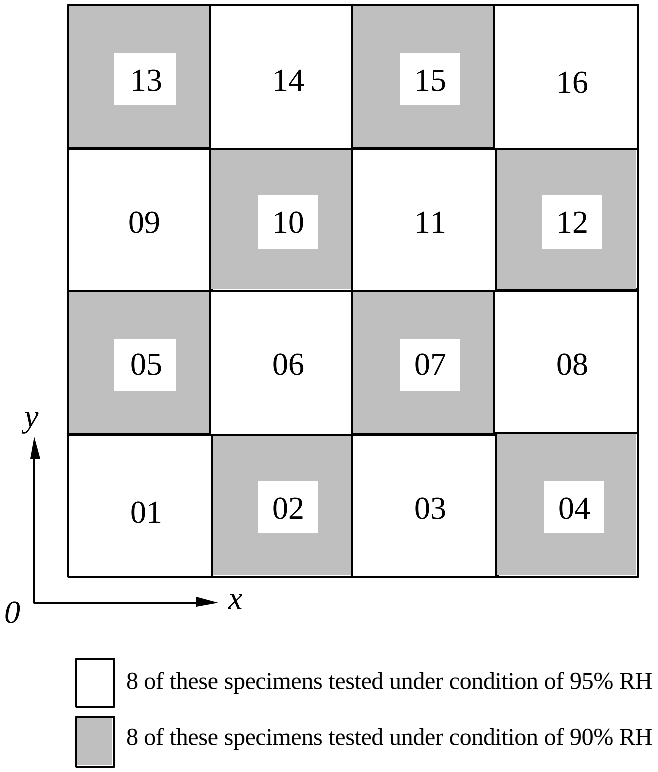

Figure 5.3. Specimen cutting pattern corresponding to each square in **Figure** 5.2.

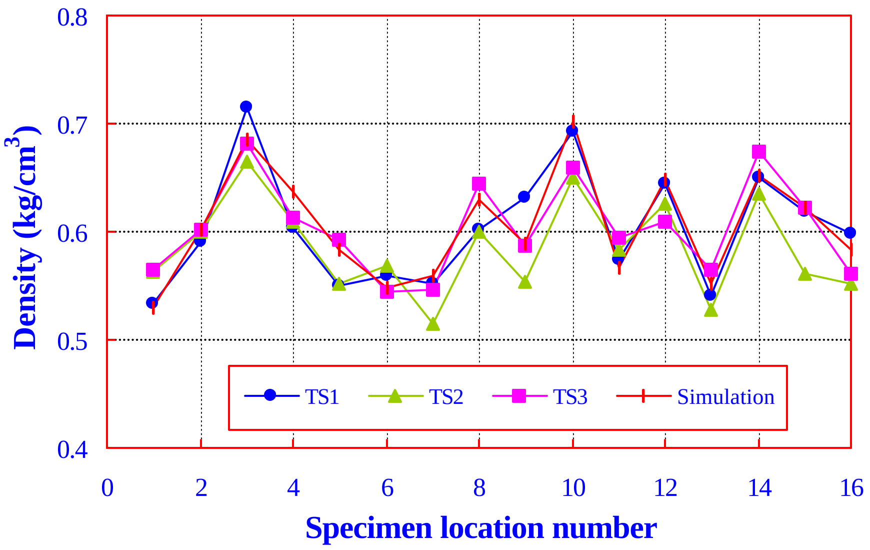

Figure 5.4a Local density averages of robot-formed flakeboard mats (TS1, TS2, TS3) as compared to the simulated mat (density for robot-formed mats were measured from 50mm × 50mm specimens and density for simulation was predicted by ***Winmat***© at 50mm × 50mm sampling zone).

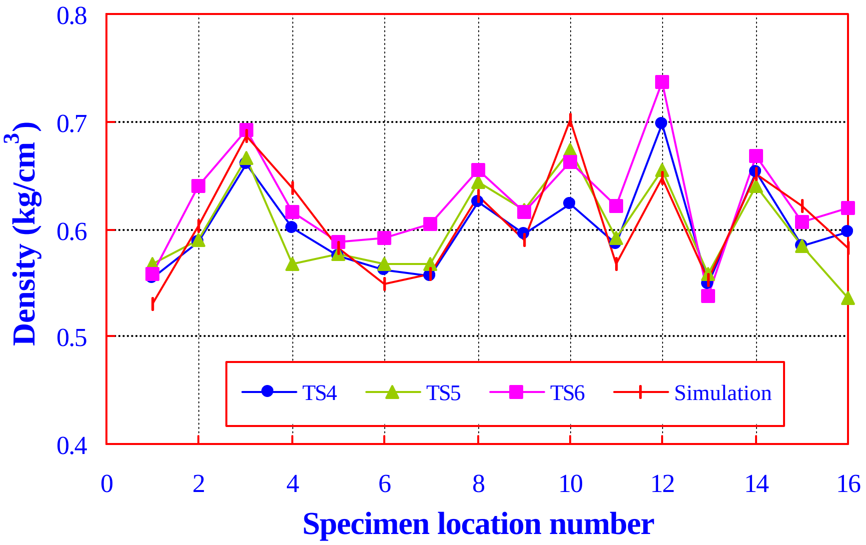

Figure 5.4b Local density averages of robot-formed flakeboard mats (TS4, TS5, TS6) as compared to the simulated mat (density for robot-formed mats were measured from 50mm × 50mm specimens and density for simulation was predicted by ***Winmat***© at 50mm × 50mm sampling zone).

The formed panels were placed in ambient conditions for more than 6 months before testing specimens were cut. Specimens cut from six panels were tested under 95% and 90% relative humidity conditions in which half of the specimens was used for model setup and the other half was used for the model verification. Specimens cut from the remaining three panels were tested under 24-hour water soaking. The 50mm × 50mm specimen size was chosen in this study because the sample board size is limited. Sixteen specimens from each board were prepared and 8 of them tested under condition of 95% relative humidity and the other 8 tested under condition of 90% relative humidity (**Figure** 5.3). For water soaking test, 16 specimens from each panel were divided into two groups of 8 each, which were tested separately. The initial thickness values of each specimen were measured at four corners 5 mm away from each edge using a micrometer (0.01 mm) and the initial weight was recorded by an electronic balance (0.0001 g). The initial moisture content of the specimen was 5.2% on average.

A humidity chamber was used to condition the specimens during humidity conditioning. The absorbing moisture tests were carried out under 95% and 90% relative humidity conditions at 60^{o}C, and thickness measurements were taken at 2, 6, 12, 24, 48, 72, 96, 120, 144 and 168 hours at the same location of a specimen. The absorbing water tests were done by emerging specimens in water at temperature of 20 ± 1^{o}C and the thickness measurements were taken at 0.5, 1.5, 3, 5.5, 8, 14.5, 19.5, and 24 hours. Determination of thickness swelling was obtained from each measuring point and the average thickness swelling for a specimen was calculated by taking the average from four thickness measurements. Determination of the absorbed moisture was obtained from weight measurements taken at the same intervals as the measurement for thickness. The relative thickness swelling (the increase of thickness swelling between two adjacent measurements) and relative moisture (the increase of moisture absorbed between two adjacent measurements) were also calculated for each time interval during the tests.

5.4. Results and Discussions

5.4.1. Relationship between moisture content and time

Flake based wood composites, such as flakeboard and OSB, contain both between-flake voids and within-flake micro-pores. Water absorbed into the between-flake voids does not directly contribute to the dimensional changes in the flake network; therefore, the volume changes are the results of expansion in the cell walls of the flakes. In order to simulate this situation, a humidity chamber was chosen to investigate this particular case. After measuring thickness changes and weight changes with time, the thickness swelling and the moisture absorbed were obtained. The results show that the absorbed moisture of the flakeboard samples increased rapidly in the first 24 hours of test (**Figure** 5.5). Then it gradually leveled as testing time increased and reached a relative moisture content of 11.8% (5.2% initial moisture content excluded) under 95% relative humidity (**Figure** 5.5a) and of 9.8% (5.2% initial moisture content excluded) under 90% relative humidity (**Figure** 5.5b). According to the classical diffusion theory, absorbed moisture is expected to vary linearly with the square root of time. **Figure** 5.6 shows that the classical diffusion theory can be used to approximate the absorbed moisture versus time relationship at the initial absorption stage within the first 24 hours in flake-based wood composites.

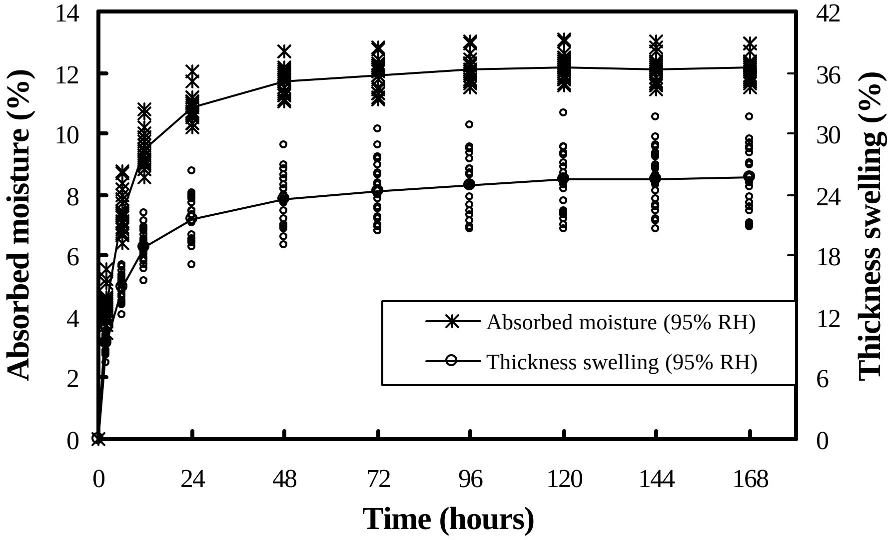

Figure 5.5a Absorbed moisture and thickness swelling in relation to test time under 95% relative humidity test condition.

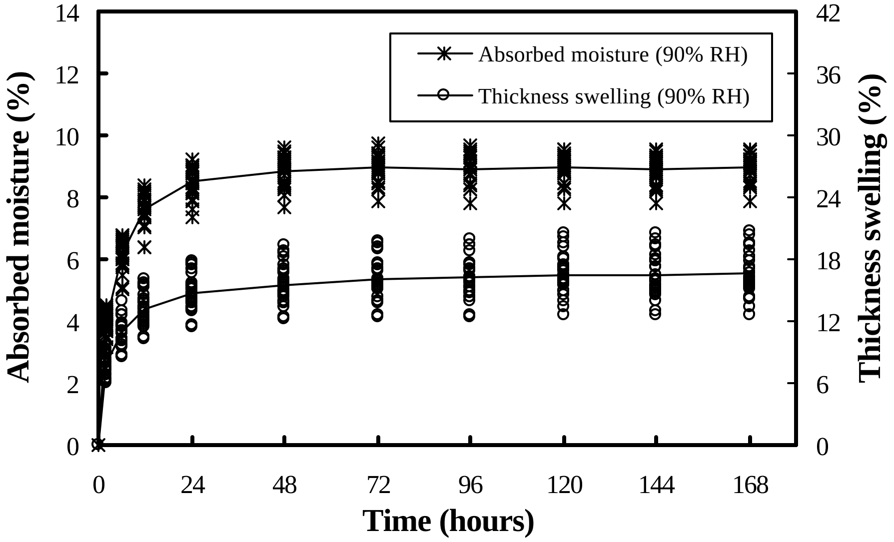

Figure 5.5b Absorbed moisture and thickness swelling in relation to test time under 90% relative humidity test condition.

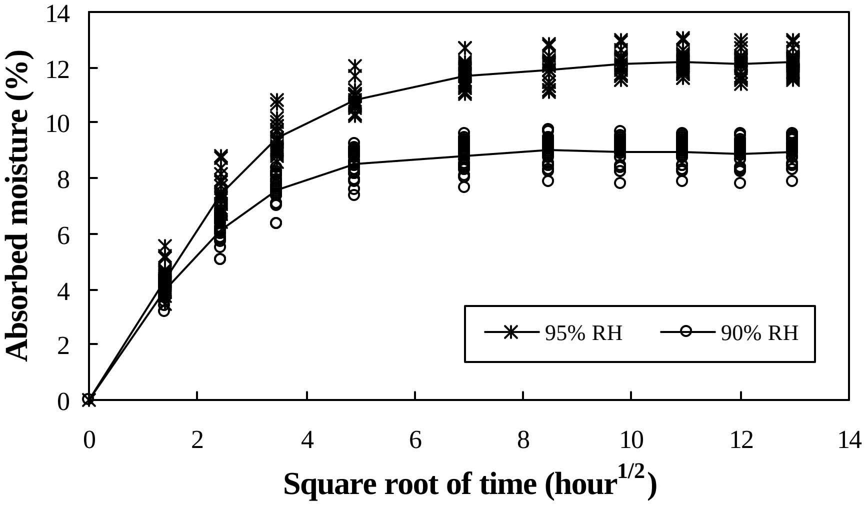

Figure 5.6 Absorbed moisture of flakeboard in relation to square root of time under 95% and 90% relative humidity test conditions.

In the 24-hour water soaking test, approximately two-thirds (69.24%) of the total amount of water (99.18%) absorbed in 24 hours was taken up during the first half-hour (**Figure** 5.7), resulting in 24.56% (79% of total) thickness swelling. However, this fast-absorbed water does not necessarily saturate the fiber completely because most of the water stays as free water inside the specimen. The thickness continues to expand to an approximately constant level of 31% thickness swelling after 5 hours soaking. At this point, the fibers are fully saturated, and the thickness swelling keeps approximately constant no matter how much water is absorbed thereafter.

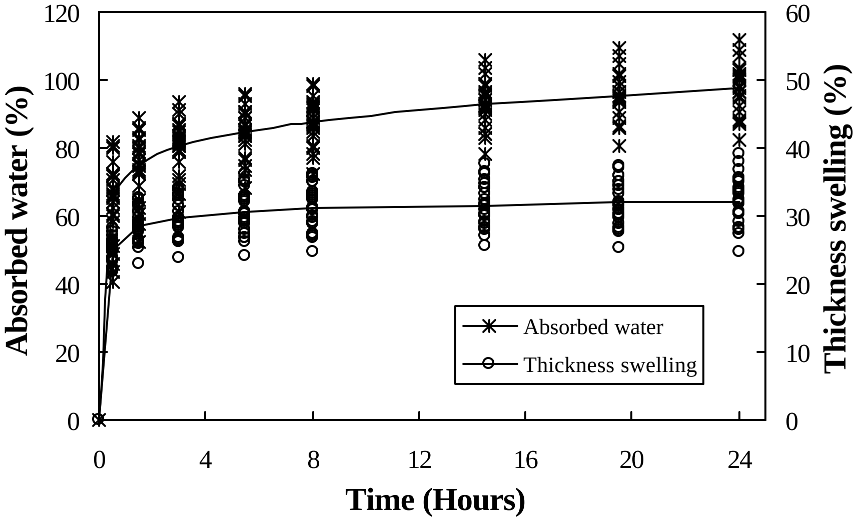

Figure 5.7 Water absorption and thickness swelling in relation to soaking time during 24-hour water soaking test.

5.4.2. Relationship between thickness swelling and moisture absorbed

It is known that the thickness swelling and moisture absorption of flakeboard is time-dependent both in high relative humidity conditions (**Figure** 5.5) and water soaking test conditions (**Figure** 5.7). The thickness swelling and absorbed moisture are correlated in both 95% and 90% relative humidity conditions (**Figures** 5.8a and 5.8b). Similarly the relationship between the relative thickness swelling and relative moisture absorbed in each time interval is well correlated (**Figures** 5.9a and 5.9b). However, in water soaking test, the above relations are poorly correlated (**Figures** 5.8c, 5.9c, and 5.10c). This is because in the humidity chamber almost all the absorbed moisture contributed to thickness swelling. In water soaking test, a large amount of water absorbed by the specimens entered into the voids between flakes and pores inside the flakes as free water. Only partial absorption contributed to thickness swelling. When the fiber saturation point is reached, no further dimension changes occur. From the slope of the regression lines in **Figures** 5.8a and 5.9a, one can estimate that on average, a 1% moisture change of the flakeboard would result in a 2% change in thickness swelling. This phenomenon is further demonstrated in **Figures** 5.10a in terms of the rate of thickness swelling changes and the rate of moisture changes. A similar relationship was found in **Figures** 5.8b, 5.9b and 5.10b.

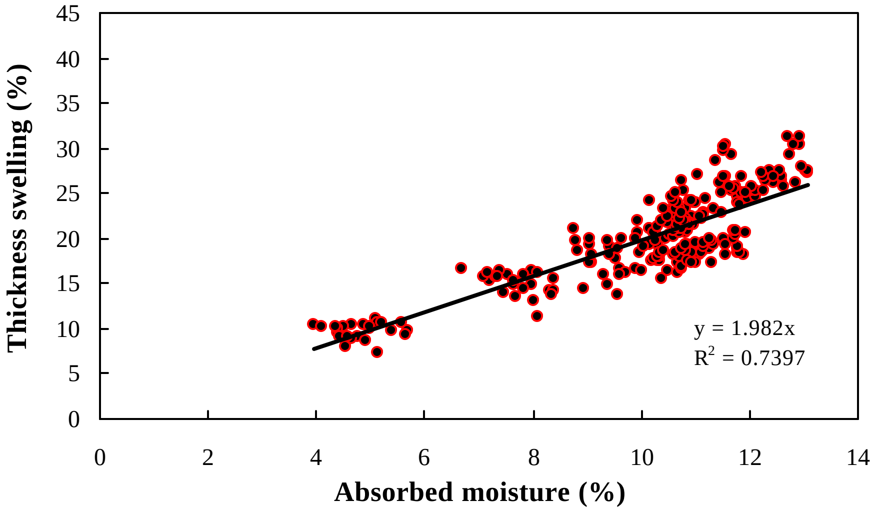

Figure 5.8a The correlation between thickness swelling and absorbed moisture under 95% relative humidity condition.

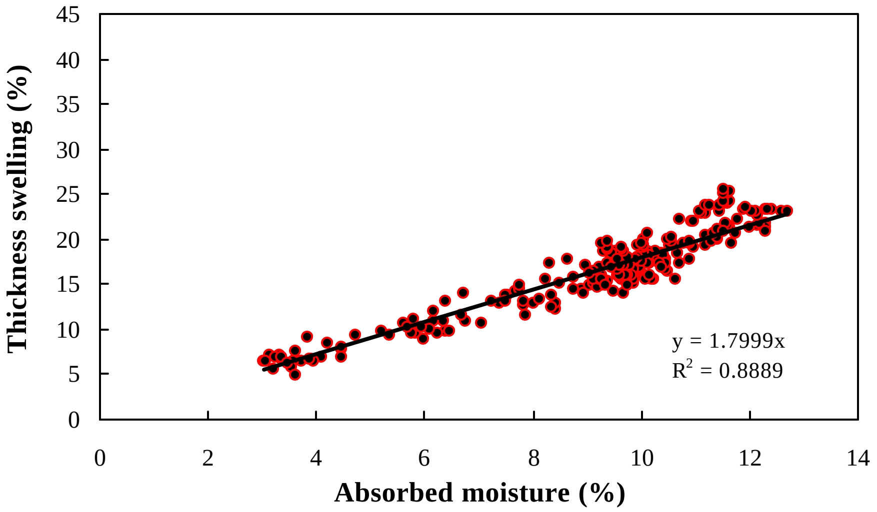

Figure 5.8b The correlation between thickness swelling and absorbed moisture under 90% relative humidity condition.

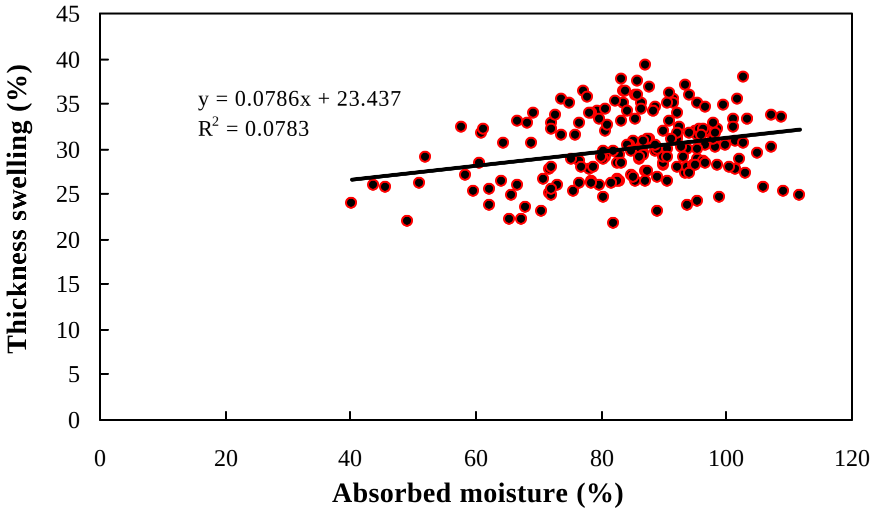

Figure 5.8c The correlation between thickness swelling and absorbed moisture under 24-hour water soaking test.

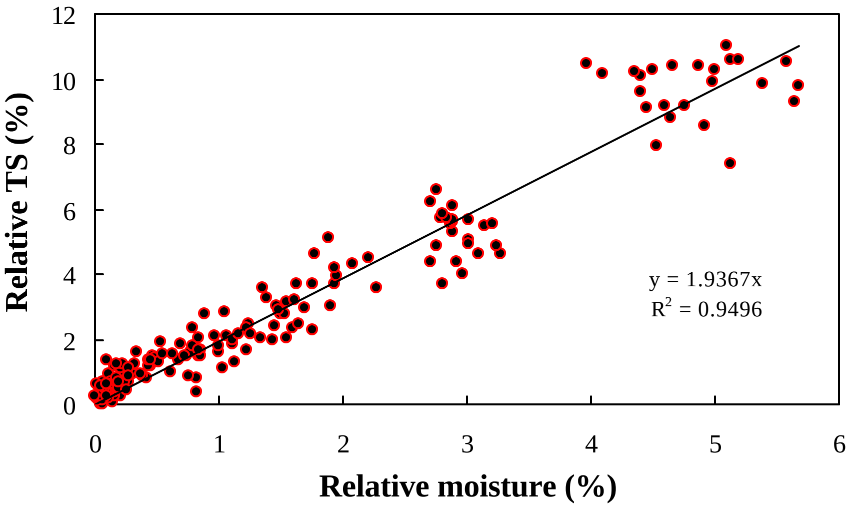

Figure 5.9a The correlation between the relative thickness swelling and relative moisture absorbed at each time interval under 95% relative humidity condition.

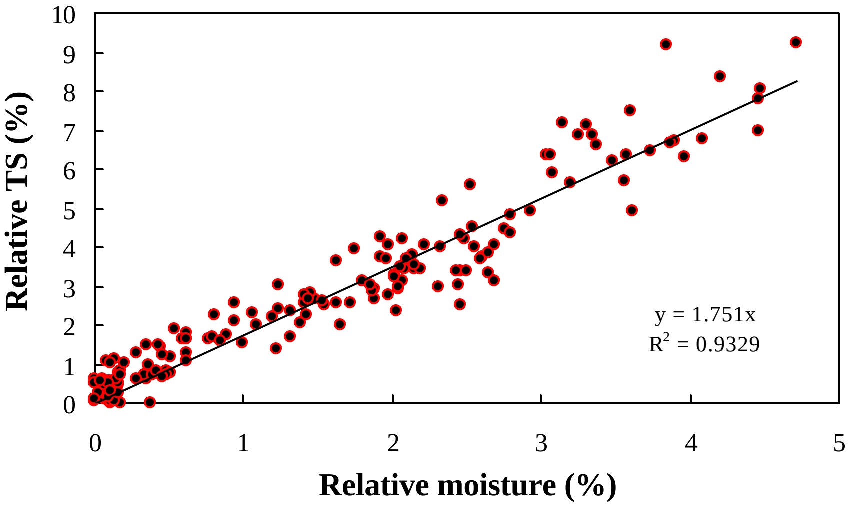

Figure 5.9b The correlation between the relative thickness swelling and relative moisture absorbed at each time interval under 90% relative humidity condition.

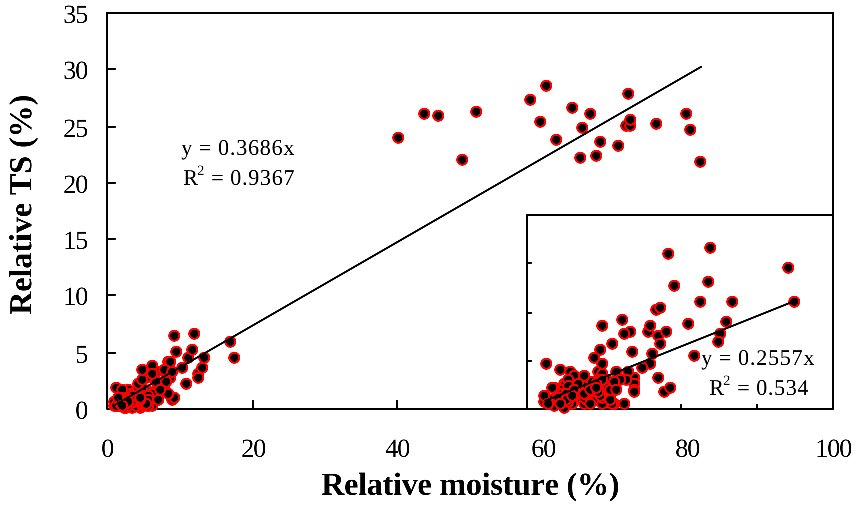

Figure 5.9c The correlation between the relative thickness swelling and relative moisture absorbed at each time interval under 24-hour water soaking test (the bottom right chart is obtained without the first measurement).

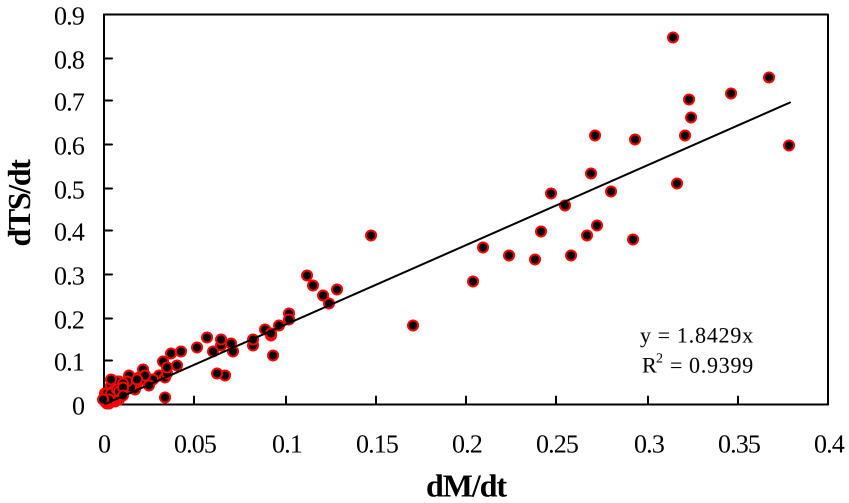

Figure 5.10a The correlation between the rate of thickness swelling and the rate of moisture changes under 95% relative humidity condition.

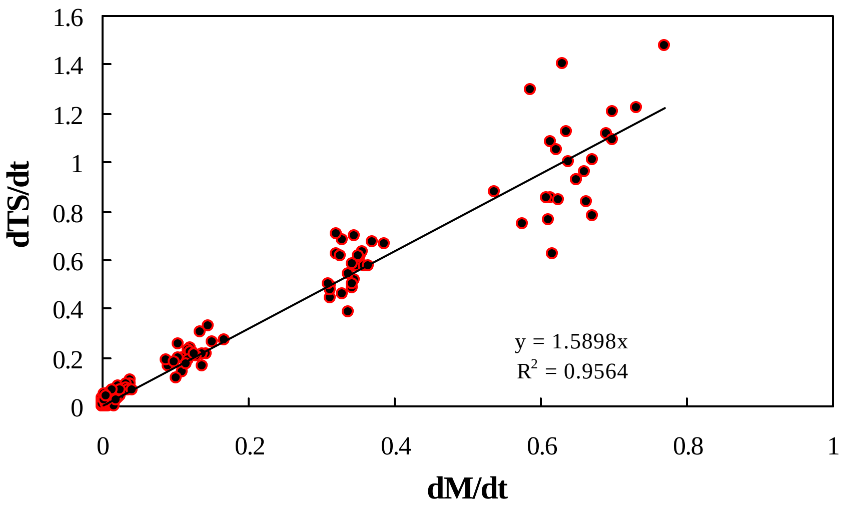

Figure 5.10b The correlation between the rate of thickness swelling and the rate of moisture changes under 90% relative humidity condition.

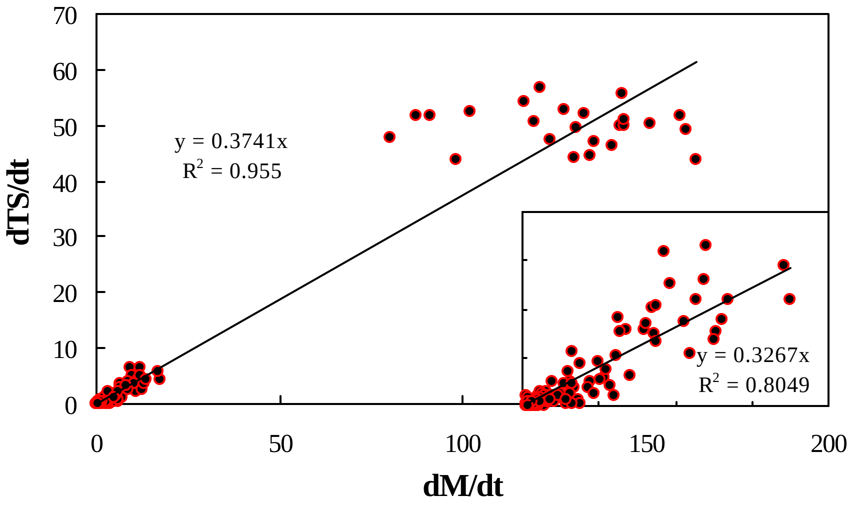

Figure 5.10c The correlation between the rate of thickness swelling and the rate of moisture changes under 24-hour water soaking test (the bottom right chart is obtained wihtout the first measurement).

5.4.3. Relationship between density and absorption coefficient

By nature of the random deposition process of the flakeboards, the density varies in different locations in the mat area. Along with the normal swelling of wood cell wall in solid wood, the residual compression stress is another factor to be considered in the strain release process during moisture absorption. This factor is handled by considering the absorption coefficient as panel density dependent in the model. It is common sense that wood swells only when moisture content is below fiber saturation point. More absorbed free water does not further contribute to swelling. Therefore, the development of a relationship between density and absorption coefficient is essential and critical in defining dimensional stability at high relative humidity conditions.

Figure 5.11 shows the linear relationship between moisture absorption coefficient and panel density. Both higher density and higher relative humidity conditions result in a higher a. From **Figure** 5.11, the two regression lines for 95% and 90% relative humidity conditions are statistically parallel (slopes are 4.1839 and 4.2193) to each other. If the average slope of these two lines is taken for consideration, the resulting error is less than 0.5%. This means that the relative a changes are the same in both test conditions at the same density changes.

5.4.4. Verification of the model

The model verification was carried out using the other half of the specimens. Tests follow the same procedures under 95% and 90% relative humidity conditions as described before. **Figures** 5.12a and 5.12b show that the measured thickness swelling agrees well with that of model predictions at three different density levels (0.66, 0.62 and 0.56 g/cm^3). From **Figure** 5.13, the measured and predicted absorption coefficients versus density also agree well.

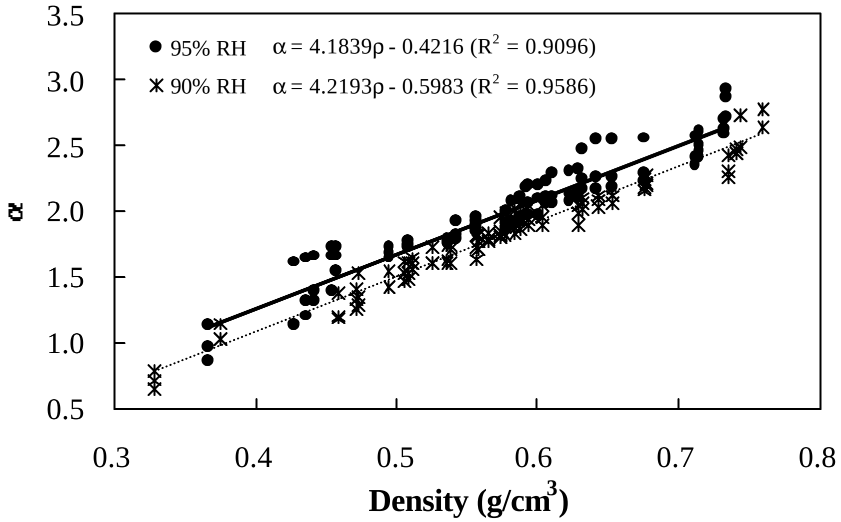

Figure 5.11 The relationship between absorption coefficient and density of flakeboard under 95% and 90% relative humidity test conditions.

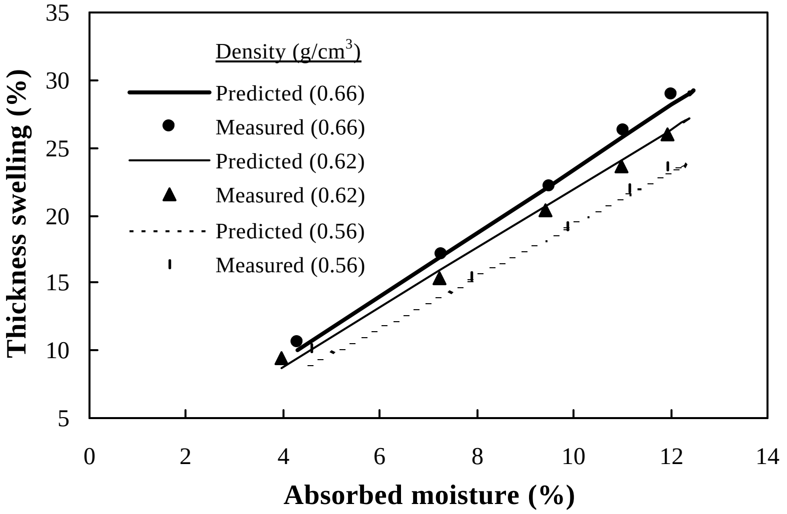

Figure 5.12a The predicted and measured thickness swelling in relation to absorbed moisture for three density levels (TS404 - 0.66, TS408 - 0.62 and TS406 - 0.56 g/cm^3) under 95% relative humidity test condition.

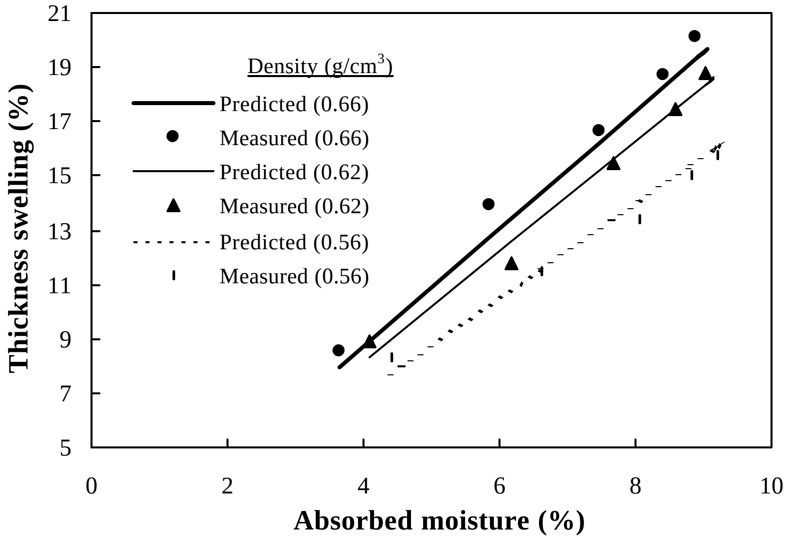

Figure 5.12b The predicted and measured thickness swelling in relation to absorbed moisture for three density levels (TS512 - 0.66, TS410 - 0.62 and TS407 - 0.56 g/cm^3) under 90% relative humidity test condition.

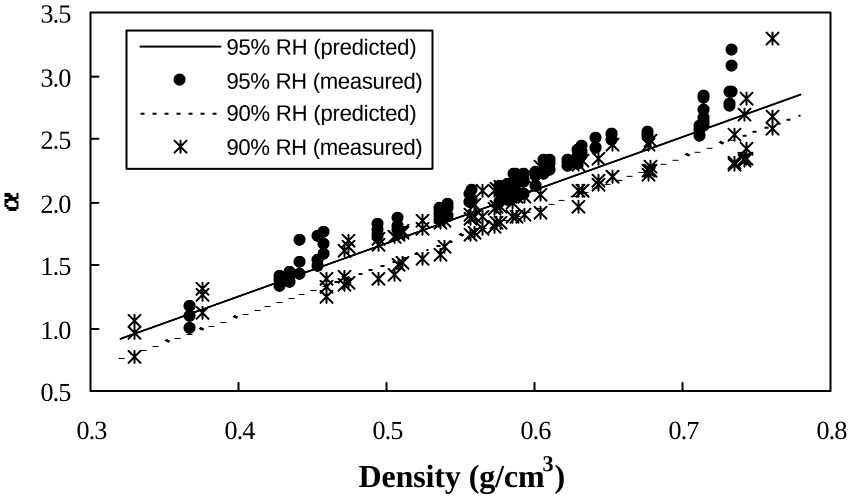

Figure 5.13 The predicted and measured absorption coefficients in relation to density under 95% and 90% relative humidity test conditions.

5.5. Conclusions

From this study, the following conclusions can be drawn:

The thickness swelling was found to be time-dependent, moisture-dependent and density-dependent during moisture absorption test under high relative humidity conditions. The relationship between moisture absorption and time conforms to the classical diffusion theory.

A linear relationship was obtained between the relative thickness swelling and relative moisture absorbed and between the rate of thickness swelling changes and the rate of relative moisture changes.

The moisture absorption coefficient is a linear function of the board density and the localized panel density plays an important role in absorption since the moisture is mostly absorbed by wood cell wall components.

5.6. References

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