COMPRESSION BEHAVIOR OF RANDOMLY FORMED WOOD FLAKE MATS

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(Received January 1993)

ABSTRACT

A theoretical model for the prediction of compression response of a randomly formed flake mat is developed. The model rigorously relates the overall mat response to local mat structure and individual flake properties. The compression behavior of single flakes, flake columns, and random flake mats is experimentally determined. Satisfactory agreement is found between the predicted and experimentally obtained results. Equations are also derived for the calculation of the relative volumetric change of between- and inside-flake voids in a mat and the change of relative flake-to-flake bonded area during the course of mat densification. Typical predictive outputs are presented and discussed.

Keywords: Model, transverse compression, compression, Poisson distribution, flake, random flake mat, void volume, bonded area, pressing, composites.

INTRODUCTION

From a material science standpoint, significant differences exist between production of wood and non-wood composite materials. Wood composites are typically manufactured by first applying relatively small quantities of adhesive to wood elements, mechanically forming these constituents into a loose mat structure, and then consolidating the mat under heat and pressure. Development of adequate strength properties requires application of compression pressure, which densifies the loose structure and results in permanent wood deformation. In contrast, non-wood composite materials consist of reinforcing elements dispersed in large quantities of resin matrix. Effective bonding of this structure is achieved without densification. Therefore, the compression behavior of the mat structure of wood constituents, in the form of flakes, particles or fibers, is critical to wood composite manufacture.

The importance of mat compression behavior of flake mats related to wood composite processing and performance characteristics can be summarized as follows:

1. Changes in internal structure, such as void volume reduction and wood densification that occur during mat compression, strongly affect heat and mass transfer processes during hot-pressing (Humphrey and Bolton 1989; Kamke and Wolcott 1991);
2. The physical, chemical, and mechanical interactions between mat compression, heat and moisture variation, and adhesive cure can result in a nonuniform densification through the thickness of the manufactured panel, often referred to as the vertical density distribution (Suchsland 1962; Harless et al. 1987; Wolcott et al. 1990).

Wood and Fiber Science, 25(4), 1993, pp. 349–358

3. Because of a random variation in mat structure (Dai and Steiner 1994a, b), highly localized wood compression stresses and densification result from overall mat compression (Suchsland 1962; Bolton et al. 1989; Smith 1980);
4. Upon press opening the compressed wood composites can spring back and also exhibit nonreversible excessive dimensional change as a result of varying moisture conditions (Suchsland 1973; Beech 1975; Liu and McNatt 1991).

Realizing the importance of the above, it is surprising to learn of the limited published information on compression behavior of wood flake or fiber mats. Even for solid wood, little is known about transverse compression and viscoelasticity at the loading levels and over the ranges of moisture contents and temperatures that are encountered during wood composite manufacture (Humphrey and Bolton 1989).

Suchsland (1959, 1962) appears to be the only researcher to study this wood composite mat behavior. In his analysis, a random flake mat was treated as a system of independent, horizontally stacked flake columns with varying flake content, which was assumed to follow a binomial distribution. The compression stresses developed in individual flake columns within the pressed mat were shown to be very high, and were a function of transverse compression stress-strain relationships of solid wood. Although the analysis was not rigorous, it provided a valuable insight into the flakeboard manufacturing process. Kunesh (1961) experimentally investigated the inelastic behavior of solid wood under conditions of perpendicular-to-grain compression similar to the hot-pressing operation in wood composite manufacture. More recently, the transverse compression behavior and viscoelasticity of wood blocks and wood flakes have been tested and modelled by Kasal (1989) and Wolcott (1990) using theories of cellular solids.

Knowledge about the compression behavior of wood generally contributes to understanding such mat-compression-related product properties as panel density variation, springback on press opening, and thickness swelling. However, it is unsuitable for quantitative analysis of wood composite manufacturing processes unless the relationship between individual wood constituent properties, spatial arrangement of wood elements in a mat, and overall mat response is explicitly established. With the development of a random mat structure model (Dai and Steiner 1994a, b), it is now possible to derive such a relationship.

Within this context, the objectives of the present work are:

1. to develop a theoretical model that predicts the overall pressure-deformation relationship of random flake mats in compression based on solid flake compression properties and mat structure;
2. to experimentally test the compression behavior of wood flakes and flake mats, and compare these measurements with results predicted from the model; and
3. to quantitatively describe changes of mat internal structure properties, such as between-flake void volume and flake-to-flake bonded area, during compression.

THEORY

A unidirectional compression of a mat of materials such as natural or synthetic fibers, particles, or flakes can simultaneously result in bending, shear, friction, and compression mechanical responses in the constituents. Among the stress modes, bending stress is the dominant component at the early stage of mat compression when low pressure is applied. At higher pressure the mat constituents are mainly subject to transverse compression (Jones 1963; Ellis et al. 1982; van Wyk 1946). The latter scenario appears to be encountered in wood composite manufacture, where the densification pressure can range as high as 4 to 7 MPa. Thus, in the following analysis, bending and other possible stresses are ignored, and the whole flake mat is treated as a system of compression units, which are the elements of flake columns. The flake mat formation is also assumed to be strictly random with regards to individual flake positions and orientations.

Compression stress-strain relationship of flakes

Wood, as a natural cellular material, exhibits a unique mechanical behavior when subjected to high compression in the perpendicular-to-grain direction. Because of the cellular structure, a typical complete deformation process goes sequentially through three stages: initial linear cell-wall bending, nonlinear cellular structure collapse, and final cell-wall densification (Gibson and Ashby 1988). The linear and nonlinear stress-strain relationship of wood can be modelled by a modified Hooke's Law (Rusch 1969; Wolcott 1990):

$$\sigma = \varphi(\epsilon)E\epsilon \tag{1}$$

where σ = stress, ϵ = strain, E = Young's modulus, and $\varphi(\epsilon)$ = nonlinear strain function.

The function $\varphi(\epsilon)$ equals unity when ϵ is in the initial linear compression range; then it starts to monotonically decrease and reaches a minimum when the cell wall totally collapses, and finally increases to infinity as the cell wall starts to densify.

For most synthetic polymer foams (Meinecke and Clark 1973) and wood (Wolcott 1990), the strain function $\varphi(\epsilon)$ is independent of the properties of matrix material or cell wall and depends only on the cellular structure. Therefore, effect of loading conditions, temperature, and moisture content should not influence the strain function $\varphi(\epsilon)$, but only Young's modulus E.

The flake compression stress σ, as defined by Eq. (1), depends on the corresponding strain ϵ. Even under the same overall mat compression, the strain ϵ of individual flakes at different locations in a mat can be substantially different. Similar strain variations can also exist within one flake of finite dimension. This unique behavior is solely a result of the nonuniform mat structure.

Random flake mat structure

Suppose a randomly packed flake mat is divided into columns of infinitely small cross-sectional area, then the number of flakes contained in each column varies (Suchsland 1962). The distribution of the flake number is described by a Poisson distribution (Dai and Steiner 1994a, b). The Poisson distribution is suitable for probabilistic characterization of a large number of events randomly occurring with a very small chance of success. An event, in the case of a flake packing process, is the deposition of a flake onto the mat area, with a success being defined here as the situation in which a specific column or point in the mat area is covered by a given flake. If the size of flakes is λ in length and ω in width, and the mat area A, the probability of success, p, is equal to flake-to-mat area ratio: $\lambda\omega/A$. In the deposition of N_f flakes, the probability of a column over A being covered by i flakes, p(i), is determined by the following Poisson distribution:

$$p(i) = \frac{a_i}{A} = \frac{e^{-n}n^i}{i!} \tag{2}$$

where a_i = total area of flake columns with i flakes, i = number of flakes in an arbitrarily chosen column, and n = mean flake number of all flake columns, which equals the probability of success p multiplied by total number of events (flakes) N_f, i.e., $n = pN_f$. In fact, the mean n is always given by the ratio of total flake coverage area $\lambda\omega N_f$ to total mat area A, no matter how flakes are distributed, or:

$$n = pN_f = \frac{\lambda\omega N_f}{A} \tag{3}$$

Pressure-thickness relationship of flake mats in compression

A force F, applied on a random flake mat, causes the mat to deform to thickness T. Because of the random distribution of flake number in columns, F can be only supported by those flake columns with flake count i greater than T/τ (τ: average flake thickness), or:

$$F = \sum_{i=T/\tau}^{\infty} \sigma_i a_i \quad (4)$$

where σ_i is the flake stress in columns with i flakes.

Combining Eqs. (1) and (2) with Eq. (4), the nominal overall compression stress, σ_n, which equals the applied pressure, can be obtained by:

$$\sigma_n = \frac{F}{A} = \sum_{i=T/\tau}^{\infty} \sigma_i \frac{a_i}{A} = Ee^{-n} \sum_{i=T/\tau}^{\infty} \varphi(\epsilon_i)\epsilon_i \frac{n^i}{i!} \quad (5)$$

where ϵ_i is the flake strain in columns with i flakes, and is determined by:

$$\epsilon_i = \frac{\tau - T/i}{\tau} = \frac{i\tau - T}{i\tau} \quad (6)$$

So far, a theoretical model for predicting the mat pressure-deformation relationship is developed using fundamental mathematical and mechanical concepts. This theory can further be applied to calculate relative void volume and flake-to-flake bonded area changes with mat thickness during the course of densification.

Relative void volume

Assuming wood cell-wall density D_0 (typically 1.5 g/cm^3), the total relative void volume RV_t is readily given by:

$$RV_t = 1 - \frac{D}{D_0} = 1 - \frac{W}{TAD_0} \quad (7)$$

where D and W are the overall mat density and weight, respectively.

Considering wood as a porous material, the total void volume in a loose flake mat may be classified into two components: between-flake voids and inside-flake voids. Differentiation between the two types of void appears to be necessary since the environmental conditions inside flakes may not always be equilibrated with conditions between flakes during hot-pressing (Kamke and Wolcott 1991). This may not be achieved without taking into account the horizontal flake number variation as defined by Eqs. (2) and (3). At any mat thickness T, between-flake voids can only occur in the columns with flake count less than T/τ. Thus, neglecting the lateral expansion in compressed flakes, the relative between-flake void volume RV_{bf} is obtained by:

$$RV_{bf} = \frac{1}{TA} \sum_{i=0}^{T/\tau} (T - i\tau)a_i = \sum_{i=0}^{T/\tau} \left(1 - \frac{i\tau}{T}\right)\frac{a_i}{A} = e^{-n} \sum_{i=0}^{T/\tau} \left(1 - \frac{i\tau}{T}\right)\frac{n^i}{i!} \quad (8)$$

since a_i/A is known by Eq. (2)

The relative inside-flake void volume RV_{if} is merely given by subtracting the between-flake void volume from the total void volume, or:

$$RV_{if} = RV_t - RV_{bf} \quad (9)$$

Relative flake-to-flake bonded area

It seems clear that the only purpose of highly compacting flake mats during the manufacture of wood composites is to increase flake-to-flake contact and promote bonding. Thus, it is of great importance to predict how the inter-flake contact area relates to the mat compaction. For an i-flake column in a mat, there are (i − 1) potential flake-to-flake interfaces or bonded areas. The maximum inter-flake bonded area BA_{max} of a flake mat results from an ideal complete mat compaction. Since the total area of i-flake columns in a random mat, a_i, is known from Eq. (2), BA_{max} is given by (Dai and Steiner 1994b):

$$BA_{max} = \sum_{i=2}^{\infty} (i - 1)a_i = A(n - 1 + e^{-n}) = A(n - 1) \quad \text{as } n \to \infty \quad (10)$$

Note that a one-flake "column" cannot from any bonds.

For a partially compacted mat thickness T, the actual bonded area is always less than BA_{max} because effective flake-to-flake contact can only occur in columns with total solid-flake thickness greater than T. As such, the relative bonded area RBA can be defined by:

$$RBA = \frac{1}{BA_{max}} \sum_{i=T/\tau}^{\infty} (i - 1)a_i = \frac{e^{-n}}{n - 1} \sum_{i=T/\tau}^{\infty} (i - 1)\frac{n^i}{i!} \qquad (11)$$

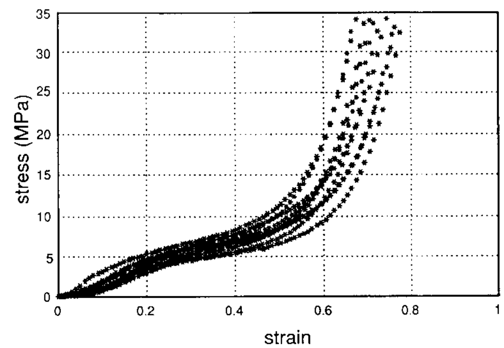

FIG. 1. Experimentally measured stress-strain relationships for single aspen flakes under transverse compression. Flake size: 25 mm × 25 mm × 0.79 mm, 9.1% MC, 20 C, and 0.5 mm/min loading rate.

EXPERIMENT

The following experiment was designed to provide a data base for estimating the parameters of model input and to verify the proposed model. It consists of determining: perpendicular-to-grain compression stress-strain relationship of single flakes and flake columns, and pressure-deformation relationship of random flake mats.

Materials

Aspen (*Populus tremuloides*) veneers of thickness 0.79 mm were prepared by slicing along the grain direction. The veneers were cut into 25- × 25-mm^2 square flakes and rectangular flakes with average length 37.51 mm and width 6.09 mm. The flakes were then conditioned to a 9.1% moisture content at 20 C. Square flakes were used for single flake compression tests and also randomly selected to form 6-, 10-, 14-, and 18-flake columns for column compression tests.

All flake mats were prepared by hand felting 72 g of rectangular flakes into a forming box with inside area 152 × 152 mm^2. A highly compressible foam wall was placed around the mat perimeter to contain the flakes during testing. Efforts were made to ensure the randomness of mat formation during each packing process.

To compare compression responses of mats constructed from different sizes of flakes, the 37.51-mm × 6.09-mm flakes were further cut in half along length and width to give two different sizes: 37.51 mm × 3.05 mm and 18.76 mm × 6.09 mm.

Method

All tests were conducted on a computerized, hydraulic press interfaced with an MTS controller at an ambient temperature of about 20 C. The computer control and monitoring system allowed the complete testing procedure to be programmed and compression pressure and deformation data to be acquired in real time.

Prior to testing the samples, the machine compliance was measured and the pressure-deformation of platens was found to be linear. This deformation was subtracted from the overall gross displacement to obtain the real compression of samples. Samples of single and multi-flake columns were compressed at a loading rate of 0.5 mm/min, while 25 mm/min was used for flake mats.

RESULTS AND DISCUSSION

Flake compression modulus and strain function

Considerable variation is found among the compression responses of individual flakes (Fig. 1). This may result from wood heterogeneity and the variance induced by the flake preparation process, namely, the effects of the principal material orientation (tangential and radial) (Bodig 1963), sapwood-to-heartwood and

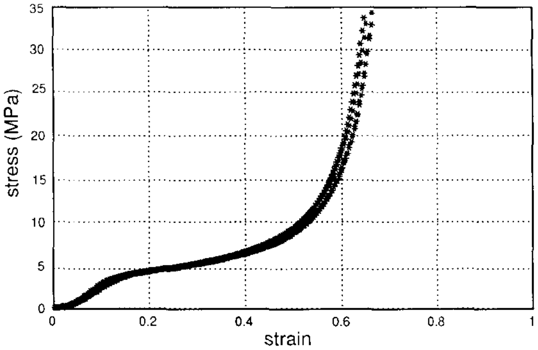

FIG. 2. Experimentally measured compression stress-strain relationships for aspen flake columns (10-flake). Other conditions as in Fig. 1.

TABLE 1. *The regression results for strain function $\varphi(\epsilon)$.*

Strain (ϵ)	Strain function ($\varphi(\epsilon)$)
0–0.16	1
>0.16	Eq. 12
i	b_i
0	−18.41
1	455.24
2	−4,361.09
3	21,797.65
4	−57,902.60
5	54,472.87
6	131,405.66
7	−512,553.08
8	748,850.68
9	−541,248.47
10	160,504.47

earlywood-to-latewood ratio (Kennedy 1968) and thickness variation and surface roughness (Wolcott et al. 1989). However, such effects are dramatically reduced when flake columns are compressed (Fig. 2). The exact reason for such variation reduction is unknown. A universal statistical law relevant to this phenomenon is that the variance of an average value of several independent variables is always smaller than that of individual variables. In this regard, the stress-strain relationship of a flake column is indeed an average response of all flake elements of which the column is made, and should accordingly vary less.

In evaluating the average compression modulus E and the nonlinear strain function $\varphi(\epsilon)$ of flakes, 10-flake column data are used. E is estimated at approximately 25 MPa, which is much less than the corresponding modulus of a wood block. This seems to be a result of the dominance of surface roughness effect as the specimen thickness becomes very small (Wolcott et al. 1989). However, this deviation may not invalidate the use of the modified Hooke's Law (Eq. 1) for this application. $\varphi(\epsilon)$ can be obtained by determining the constants in the following equation through a computer program:

$$\varphi(\epsilon) = \sum_{i=0}^{10} b_i \epsilon^i \qquad (12)$$

The results of b_i are listed in Table 1. It should be noted that this estimation involves an approximation in designating $\varphi(\epsilon)$ equal to unity in the linear range, as both Fig. 1 and Fig. 2 show slight nonlinearity of the stress-strain curves at the beginning. It appears that this discrepancy has little impact on the prediction accuracy, especially for higher mat compression regions where the induced error accounts for a negligible portion of total predicted stresses.

Compression response of flake mats

Validation of the model.—Based on the estimated flake compression modulus and strain function, the mat compression response can be predicted using Eqs. (3), (5) and (6). As shown in Fig. 3, a close agreement is found between the predicted response and experimental measurement, except at pressure less than 1.5 MPa. This discrepancy seems to relate to the fact that the pressure against a flake mat during the initial compression stage is mainly resisted through flake bending, not transverse compression. A prediction of initial flake bending stresses could be made by treating the whole mat as a system of bending units with the span of each unit being determined by the distribution of free flake length, i.e., the distance along a flake between adjacent contacts with other flakes (Dai and Steiner 1994a). This calculation is not considered here since our

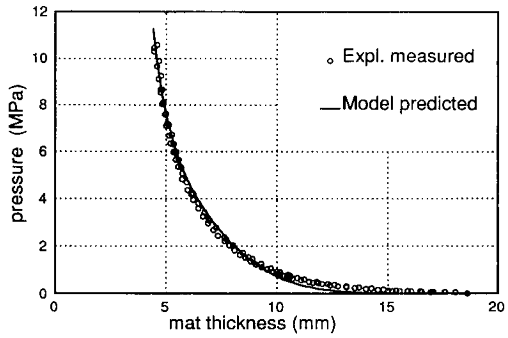

FIG. 3. Comparison between experimental measurements and model prediction of pressure-mat thickness relationship of a randomly formed flake mat in compression. Flake size: 37.51 mm × 6.09 mm × 0.79 mm, total flakes: 72 g. 9.1% MC, 20 C and 25 mm/min loading rate.

present interest lies in mat compression ranges of greater than 2 MPa, which is normally seen in the hot-pressing of wood composites.

According to Eq. (3), for a randomly formed flake mat, compression response as defined by Eq. (5) depends on the flake size only through the total coverage area content $\lambda\omega N_f$. Thus, it is not affected by any change of flake length λ or width ω as long as the total flake coverage area is kept constant. This has been demonstrated experimentally by determining compression pressure-deformation relationship of mats of flakes with different sizes (Fig. 4). Again the region of initial discrepancy arises because the early compression pressure on a mat is dominated by flake bending resistance, not

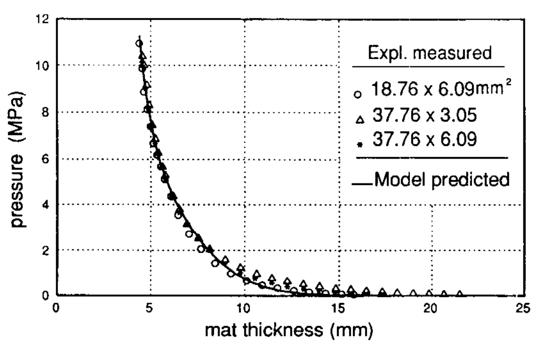

FIG. 4. Experimentally measured pressure-mat thickness relationships for flake mats of different flake sizes compared to model prediction. All flake thickness: 0.79 mm and other conditions as in Fig. 3.

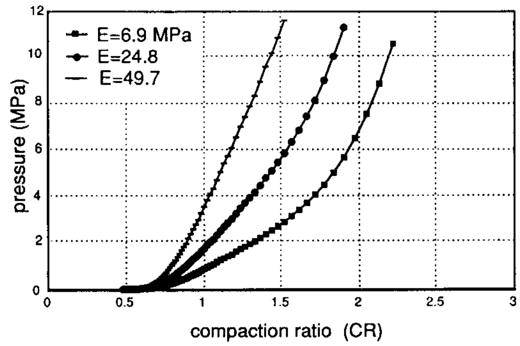

FIG. 5. Predicted compression response of a random flake mat as affected by flake compression modulus. Flake size and other conditions as in Fig. 3.

flake compression. The bending response is strongly affected by the flake slenderness ratio (ratio of length to width) (Jones 1963).

Effect of flake properties.—An important feature of the proposed model is that it establishes an explicit relationship between individual flake compression properties and overall mat response, as well as a relationship between local compression strain and stress and overall mat densification. According to Eq. (5), the mat densification response is a linear function of flake compression modulus E, as presented in Fig. 5, which indicates the relationship between the applied pressure and compaction ratio (ratio of mat density to flake density). For a given species and flake thickness in a mat, the modulus E, during hot-pressing, is a temporal and spatial function of temperature and moisture content inside the mat. Therefore, with the development of this model, the success of predicting the vertical density profile of flakeboard may be achieved by incorporating a heat and mass transfer model (e.g., Humphrey and Bolton 1989) and the compressive viscoelasticity of flakes (Wolcott 1990) into Eq. (5).

Local stress distribution.—At any given mat densification (or mat thickness T), the distribution of local compression stresses can be obtained by incorporating the compression stress-strain relationship of flakes in Eq. (1) into the Poisson distribution of flake counts in individual columns (Eqs. 2, 3). As shown in

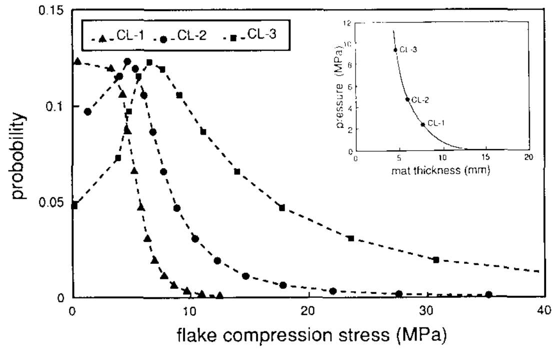

FIG. 6. Predicted local stress distribution of a flake mat under three different compression levels. Conditions as in Fig. 3.

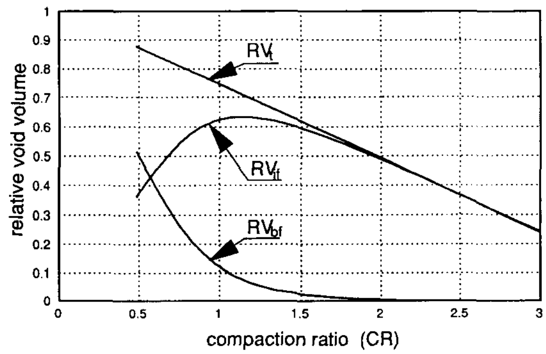

FIG. 7. Predicted relative volumetric change of total (RV_t), between (RV_{bf})- and inside-flake (RV_{if}) voids in an aspen flake mat under compression. Flake density: 0.38 g/cm^3 and other conditions as in Fig. 3.

Fig. 6, local stresses can vary markedly from as small as zero to as high as more than 40 MPa, with the variances increasing as applied pressure on the mat increases. This is a characteristic stemming from the parentage of the Poisson distribution.

The level and variability of local stresses will directly relate to the severity of residual stresses in the compressed panel. The residual stresses, in turn, determine the minimum pressing time needed to give the panel an acceptable internal bond strength, and affect the springback and thickness swelling (Bolton et al. 1989). Furthermore, since such a wide distribution of local stresses is transferred to flake interfaces during pressing, the flake-resin bond development within the composite varies (Humphrey and Ren 1989). As a result, a distribution of localized bonding strength in the final board is expected. Therefore, a quantitative characterization of the local stresses in the pressed mat may lead to the prediction of optimum pressing time and variability of board properties.

Predicted results of internal mat structure change

Void volume.—Figure 7 shows a typical result of predicted (Eqs. 7, 8, 9) total relative void volume RV_t, relative between-flake void volume RV_{bf} and inside-flake void volume RV_{if} during the course of mat densification. While RV_t linearly decreases with the compaction ratio CR, the two components RV_{bf} and RV_{if} exhibit markedly different patterns. Without doubt, the absolute volume of both between- and inside-flake voids always decreases with an increase in CR. The initial rapid increase in RV_{if} is merely a result that rate of decrease in inside-flake void volume with CR is much less than that of total mat volume. According to this prediction, less than 10% of between-flake void volume likely exits in random flakeboards, where the core CR is usually greater than 1.

Flake bonded area.—As discussed previously, mat compression response is independent of flake length and width. For the same reason, any change in flake length and width should not affect the relative flake bonded area for a randomly formed flake mat.

The predicted relative flake-to-flake bonded area, RBA, with mat densification with respect to flake thickness is displayed in Fig. 8. It is interesting to note that an increase in flake thickness results in higher RBA at lower CR, while a less important role is played by flake thickness at higher CR. This result may shed some light on how flake thickness affects the development of internal bond strength in flakeboard. Increasing the flake thickness appears beneficial for enhancing panel bond strength, not only by increasing areal resin concentration but also by promoting flake-to-flake contact, especially for low density products (Suda et al. 1987).

According to Eq. (10), the maximum flake bonding condition could be achieved by at least two approaches. One way, as commonly seen in wood composite manufacture, is to randomly form flake mats and then completely densify the loose mat structure. An alternative could be to perfectly pack flakes into an ideal, non-void interspersed mat, as one would imagine that the total flake bonded area in such a mat structure, even without densification, does equal (n − 1)A as given by Eq. (10). With present technology, such ideal mat structures may not be practical to manufacture. Nevertheless, the result here certainly suggests opportunities to achieve good flake bonding condition without over-densifying wood composite products.

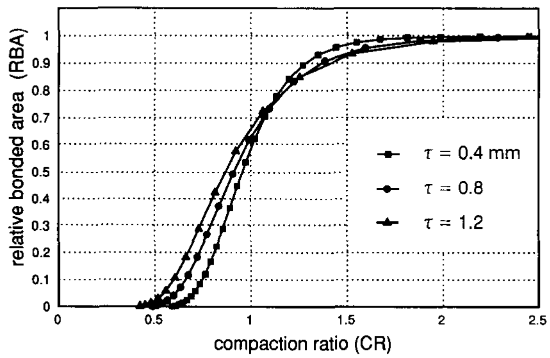

FIG. 8. Predicted relative change of flake-to-flake bonded area in a flake mat under compression as affected by flake thickness. Other conditions as in Fig. 3.

SUMMARY AND CONCLUSIONS

In modelling compression behavior of a randomly formed flake mat, the mat structure is viewed as a system of horizontally arranged flake columns with infinitely small cross-sectional area. Pressure applied on the mat is primarily resisted solely through transverse compression of flakes in those columns with total solid-flake thickness greater than current mat thickness. With prior knowledge of the Poisson distribution of column flake count, a model has been developed to predict the mat compression response based on the compression characteristics of flakes.

Because variations in single flakes are much greater than flake columns, a more accurate estimation of flake compression stress-strain relationship as model input parameters is provided by the flake column data. The model prediction is in good agreement with experimental results except at pressure less than 1.5 MPa. The predicted mat compression response is not affected by flake length and width.

With the development of this model, a quantitative relationship between individual flake compression properties and overall mat response, as well as the relationship between local compression and stresses and overall mat densification, is established. This essentially provides a new approach to investigating the role played by individual flakes in defining overall flakeboard properties and how localized material properties affect overall panel behavior.

Equations are also derived for the calculation of relative volumetric changes of total, between- and inside-flake voids, and relative flake-to-flake bonded area during mat densification. A quantitative description of internal mat structure change is necessary to fully understand the mechanism of heat and mass transfer and the development of internal bond strength during the hot-pressing operation. The establishment of the present model may also provide a basis for predicting such flakeboard properties as vertical density distribution, springback on press opening, and even thickness swelling. To achieve this, further work is needed to extend the present model to incorporate viscoelasticity of the mat under compression at loading levels and over ranges of temperature and moisture content experienced during hot-pressing.

ACKNOWLEDGMENTS

Financial support for this work from NSERC/Canada through a strategic research grant is gratefully acknowledged. The authors would like to thank Dr. J. David Barrett for his critical review of this paper.

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