VISCOELASTICITY OF WOOD COMPOSITE MATS DURING CONSOLIDATION

Chunping Dai

Group Leader
Wood Composites Group, Forintek Canada Corp
2665 East Mall
Vancouver, B.C.
Canada V6T 1W5

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ABSTRACT

To improve our understanding of the wood composite hot-pressing process, viscoelastic consolidation of wood flake mats was investigated in terms of constituent flake properties and mat formation. A fundamental model of mat stress relaxation was developed based on the compressive stress relaxation of wood flakes and Poisson distribution of flake overlaps formed in the mat. Both stress relaxation and creep of wood flakes and flake mats at ambient condition were experimentally tested and analyzed. The results showed that the stress relaxation of wood flakes at different levels of compression follows linear double logarithmic relationships with varying slopes or rates of stress relaxation. The mat stress relaxation model was validated by comparing the model predictions with the experimental data. Like stress relaxation, creep of flakes also varies with the level of compression. Due to porosity difference, creep of flake mats is not quantitatively comparable to creep of flakes in terms of relative creep strain. Instead, relative creep compaction ratio of mats is comparable to that of wood flakes.

Keywords: Wood composites, modeling, mat consolidation, viscoelasticity, pressing.

INTRODUCTION

Hot-pressing is a key operation in wood-based composite manufacture. During such an operation, mats of resinated wood fibers, particles, or flakes are consolidated under heat and pressure to create close contact and form bonds between the wood constituents. Due to limited amount of resin usage, effective bonds rely on a high degree of mat densification. Increasing mat density, on the other hand, causes negative effects such as heavier products, more wood consumption, and more importantly excessive thickness swell in service when the product is subjected to high humidity conditions (Kelly 1977). The necessity and detrimental effects of mat densification suggest the importance of process optimization, which requires a solid understanding of the mechanism of mat consolidation.

The pressing of a wood composite mat involves physical, mechanical, and chemical interactions. Once the press closes, moisture and heat transfer takes place between the hot platens and the mat. During the course of pressing, temperature and moisture content inside the mat are both spatially and temporally dependent (Humphrey and Bolton 1989). At the same time, the platens exert compressive forces onto the mat, causing reduction of voids and compression deformation in wood constituents (Dai and Steiner 1993). The mat deformation is usually not uniform across the mat thickness due to the variations of heat and moisture content from the surface to the core layers. Elevated temperature accelerates resin polymerization, which combines with mat deformation to form permanent bonds between wood constituents. With little springback, the glue bonds also freeze the overall and layered mat deformation upon press opening. This leads to formation of the well-known vertical density profile in pressed wood composite panels, which in turn has a significant effect on the physical and mechanical properties of the final products (Suchsland 1959; Kelly 1977; Harless et al. 1987; Wolcott et al. 1990; Winstorfor et al. 1994).

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If mat consolidation is defined as the compression deformation of randomly arranged wood constituents, the overall mat stress-strain relationship is governed by the initial mat structure and mechanical properties of wood constituents (Dai and Steiner 1993; Lang and Wolcott 1996). Due to viscoelasticity of wood, a mat of wood elements exhibits the time-dependent behavior of deformation (creep) and stress relaxation. The compression viscoelasticity of wood and wood composite mats has received limited attention and therefore forms the main subject of this paper.

BACKGROUND

Compressive viscoelasticity of wood and other cellular materials

Viscoelasticity of wood influences the long-term performance of wooden structures in service. Viscoelasticity also influences wood densification during wood products processing such as in press-drying where wood is under a static pressure and subjected to changes in temperature and moisture content. In these situations, wood can be adequately treated as a linear viscoelastic material, because the applied load is under certain limits within the linear range. The linear viscoelasticity thus became a subject of many studies, which were cited in several review papers (Schniewind 1968; Pentoney and Davidson 1962; Bodig and Jayne 1982; Holzer et al. 1989).

During the manufacture of wood composites, however, high pressure is required in order to consolidate mats of wood constituents into integrated panels. The high pressure, coupled with the random mat structure, results in a highly nonlinear and nonuniform mechanical response of the wood constituents (Dai and Steiner 1993). Youngs (1957) and Kunesh (1961) are two of the earlier researchers who investigated the nonlinear viscoelastic behavior of wood under perpendicular-to-grain compression. Fundamental viscoelastic phenomena such as the time-dependent stress-strain relationship, instantaneous and delayed strain recovery, permanent deformation, and temperature- and moisture-dependent stress relaxation were observed. The global behavior was attributed to the destruction of cellular structure of wood. Bolton and Breese (1987) attempted to interpret viscoelastic behavior wood loaded at right angles to the grain by relating strain development to microstructure change in cell-wall material. They concluded that the majority of strain development involved bond breakage and reformation in regions containing less ordered cellulose, hemicellulose, and lignin.

The effects of cellular structure on nonlinear viscoelasticity was also observed in other natural and synthetic cellular materials (e.g., Gibson and Ashby 1988; Meinecke and Clark 1973; Rusch 1969). The nonlinearity was attributed to the interaction between linear viscoelastic response of cell-wall polymers and geometric nonlinearities of cellular deformation (Meinecke and Clark 1973; Rusch 1969). This interpretation and the relevant nonlinear viscoelasticity models were adopted by Wolcott (1990) to explain response of wood flakes during the pressing of wood composites.

According to these researchers, the nonlinear stress relaxation modulus E(t) of synthetic cellular polymers and wood could be adequately predicted by multiplying the linear response $E'(t)$ by the nonlinear strain function $\varphi(\epsilon)$, or:

$$E(t) = \varphi(\epsilon)E'(t) = \varphi(\epsilon)Kt^{-\xi} \qquad (1)$$

where the strain function $\varphi(\epsilon)$ depends only on strain ϵ and is independent of time t. The constant K is the relaxed modulus of the material at a certain time (usually 1 s). The constant ξ is the slope in the double logarithmic plot of modulus E(t) versus time elapsed t, which is indicative of the rate of stress relaxation; it depends only on the cell-wall polymer.

The usefulness of Eq. (1) implied a possibility of extending the linear Boltzmann superposition principle to modeling the response of nonlinear cellular material to successive loads, provided that the stress relaxation rate ξ was not too large (Meinecke and Clark 1973). The stress at any time t was then given by:

$$\sigma(t) = \epsilon_0 E_0 + \varphi(\epsilon) \int_0^t E(t - t') \frac{d\epsilon(t')}{dt'} dt' \quad (2)$$

where ϵ_0 and $\epsilon(t)$ are the initial strain and the strain at time t, respectively.

Compared with stress relaxation, nonlinear creep response of cellular materials seems much more complicated. According to the available literature, there has been very limited success in developing a compression creep model for wood and other cellular materials (Meinecke and Clark 1973; Gibson and Ashby 1988; Wolcott 1990). As such, the focus of model development in this study was on stress relaxation, whereas the creep response of wood flakes and mats was experimentally measured and compared.

Rheological behavior of wood composite mats

Despite its critical importance, the rheological behavior of wood-furnish mats in compression has been investigated only to a limited extent. Wolcott (1990) used theories of the viscoelastic behavior of amorphous polymers (Ferry 1980) to explain the formation of vertical density profile in flakeboard. The glass transition temperature of the lignin component in wood was estimated from experimentally measured temperature and vapor gas pressure at different locations inside the flake mat during hot-pressing. Mat strain development was related to the external pressure profile through the difference between the actual flake temperature and the calculated glass transition temperature. The information provided from this analysis contributes to general understanding of density gradient formation. A quantitative prediction certainly requires a more comprehensive treatment of wood viscoelasticity.

The thermo-hydro rheological behavior of randomly formed wood fiber mats was experimentally investigated by Ren (1991). Samples were measured under a wide range of temperature and moisture content conditions encountered in a typical wood composite hot-pressing process. The data were then fitted to a five-element "spring and dashpot" model. The model parameters were determined as functions of the temperature, moisture content conditions inside the mat, and the mat density. Such a model has an immediate application to predicting compression strain development in fiber mats of structure and constituents similar to the tested samples. In order to predict mats of other wood furnish such as wood strands, the model needs to incorporate effects of such factors as wood element geometry, orientation, and species. Like other materials, the global viscoelastic properties of a wood composite mat should be determined by viscoelasticity of its constituent elements and the element organization in the mat.

OBJECTIVES

The overall objective of this study was to improve our fundamental understanding of the mat consolidation process; specific objectives were:

1). To develop a model for prediction of mat stress relaxation based on the compressive viscoelastic properties of wood and the random mat structure;
2). To experimentally study stress relaxation and creep response of wood flakes and flake mats; and
3). To validate the stress relaxation model by comparing the viscoelastic properties between wood flakes and flake mats.

A MODEL FOR PREDICTING FLAKE-MAT STRESS RELAXATION

Random formation of flake mats

If a mat of flakes is divided into columns of very small area, then the number of flake overlaps in individual columns i varies (Suchsland 1959). While effort is made during mat forming to disperse flakes as uniformly as possible, the actual deposition of individual flakes may well be random. Assuming random flake positioning, the mathematical model for characterizing the flake overlaps in the imaginary columns follows the well-known Poisson distribution (Dai 1994):

$$p(i) = \frac{a_i}{A} = \frac{e^{-n}n^i}{i!} \quad (3)$$

where p(i) = fraction of mat areas that have i flake overlaps, a_i = mat areas in which flake overlap is i, A = total mat areas, and n = average number of flake overlaps.

Assume a total of N_f flakes with dimensions of λ in length and ω in width. Regardless of flake positions, the average flake overlap always equals the ratio of total flake projection area $\lambda\omega N_f$ to total mat area A, or,

$$n = \frac{\lambda\omega N_f}{A} \quad (4)$$

Relationship between local and global mat stresses

The concept of imaginary columns allows for calculation of overall mat compression stresses based on local flake overlaps. It is assumed that when a load is applied to a mat with thickness T, it is supported by only those columns with flake overlaps i being greater than T/τ (τ: flake thickness). The relationship between the normalized mat stresses at any given time t, $\sigma_n(t)$, and the stresses shared by local flake columns, $\sigma_i(t)$, is:

$$\sigma_n(t) = \sum_{i=T/\tau}^{Nf} \frac{\sigma_i(t)a_i}{A} \quad (5)$$

In the above relationship, the term a_i/A represents the characteristics of random mat formation as described in Eqs. (3) and (4).

Stress relaxation under instantaneous loading

For a standard stress relaxation test in which compression deformation is suddenly applied to a flake mat, the mechanical responses of supporting flake columns take place simultaneously, i.e., the column stress $\sigma_i(t) = 0$, for $t < 0$ and $\sigma_i(t) = \sigma_{i,max}$ for $t > 0$. The stress relaxation in individual flake columns is then given by Eq. (1). Thus the mat stress relaxation can be further defined by substituting a_i/A and $\sigma_i(t)$ in Eq. (5) with Eqs. (3) and (1), respectively, i.e.,

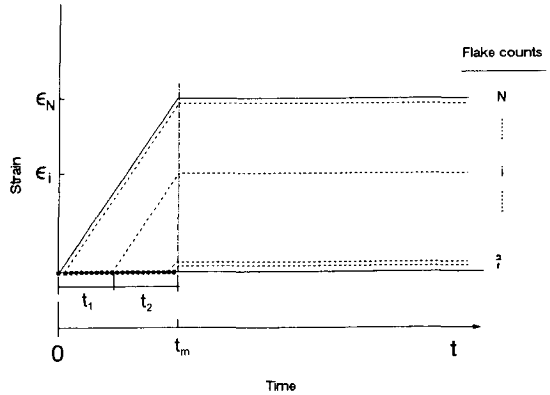


FIG. 1. Linear loading strain histories of flake columns in a mat. t_1 = time elapsed before i-flake columns become under compression; t_2 = time taken for i-flake columns to reach maximum strain ϵ_i.

$$\sigma_n(t) = Ke^{-n} \sum_{i=T/\tau}^{N_f} \frac{\varphi(\epsilon_i)\epsilon_i n^i}{i!} t^{-\xi_i} \quad (6)$$

where ϵ_i = strain in an i-flake overlap columns, given by $(i\tau - T)/i\tau$, and the average flake overlap n is given by Eq. (4).

Stress relaxation under linear press closing

During hot-pressing, platens close at a given rate. Therefore, the overall mat strain is applied in a successive manner. The strain histories of individual flake columns in a mat vary in accordance with their flake overlaps. The more the flake overlaps, the sooner the column areas become compressed. Assume linear loading strain histories (Fig. 1). The compression stresses in flake columns can then be calculated using the extended Boltzmann superposition principle (Eq. 2). But first, the strain and time parameters pertaining to the loading histories need to be determined.

Loading histories.—The maximum strain in the highest flake overlap columns, ϵ_N, is given by:

$$\epsilon_N = \frac{N\tau - T}{N\tau} \quad (7)$$

where N is the maximum number of overlaps contained in flake columns. It can be estimated by designating p(i) = 0.001 in Eq. (3) and solving the equation for i (=N). It should be noted that ϵ_N is 0 when $T > N\tau$.

Likewise, the maximum compression strain in i-flake columns, ϵ_i, is given by:

$$\epsilon_i = \frac{i\tau - T}{i\tau} \tag{8}$$

If a flake mat is compressed with a constant platen speed V during press closing, the time required for all supporting flake columns to reach their maximum strain, t_m, is determined by:

$$t_m = \frac{N\tau - T}{V} \tag{9}$$

The time elapsed from the moment of the external load being applied onto the mat to the moment of i-flake columns start compression, t_1, is given by:

$$t_1 = \frac{N\tau - i\tau}{V} \tag{10}$$

The time needed for i-flake columns to reach their maximum strain, t_2, is obtained by:

$$t_2 = \frac{i\tau - T}{V} \tag{11}$$

Thus the strain history in i-flake columns can be described by the following expression:

$$\epsilon_i(t) = \begin{cases} 0 & (t < t_1) \\ \dfrac{t - t_1}{t_2}\epsilon_i & (t_1 \le t < t_m) \\ \epsilon_i & (t \ge t_m) \end{cases} \tag{12}$$

Taking derivative of $\epsilon_i(t)$ with respect to t in Eq. (12) and substituting ϵ_i and t_2 with Eqs. (8) and (11) yields:

$$\frac{d\epsilon_i(t)}{dt} = \begin{cases} \dfrac{V}{i\tau} & (t_1 \le t < t_m) \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

Modified Boltzmann integral.—The above equation (13) enables the use of the extended Boltzmann superposition integral to calculate stress relaxation in flake columns under successive loading. For $t < t_m$, the integral (Eq. 2) can be rewritten as follows:

$$\sigma_i(t) = 0 + \varphi(\epsilon_i)\int_{t_1}^{t} K(t - t')^{-\xi_i}\frac{V}{i\tau}\,dt' = \frac{KV\varphi(\epsilon_i)}{i\tau(1 - \xi_i)}(t - t_1)^{1-\xi_i} \tag{14}$$

For $t \ge t_m$, the integral becomes:

$$\sigma_i(t) = 0 + \varphi(\epsilon_i)\int_{t_1}^{t_m} K(t - t')^{-\xi_i}\frac{V}{i\tau}\,dt' = \frac{KV\varphi(\epsilon_i)}{i\tau(1 - \xi_i)}[(t - t_1)^{1-\xi_i} - (t - t_m)^{1-\xi_i}] \tag{15}$$

Mat stress relaxation model.—Finally, the mat stress relaxation can be calculated by substituting $\sigma_i(t)$ in Eq. (5) with Eqs. (14) and (15), and a_i/A with Eq. (3), i.e.,

$$\sigma_n(t) = \frac{KVe^{-n}}{\tau}\sum_{i=T/\tau}^{N_f}\frac{\varphi(\epsilon_i)n^i}{i(1 - \xi_i)i!}(t - t_1)^{1-\xi_i} \quad (t < t_m)$$

$$\sigma_n(t) = \frac{KVe^{-n}}{\tau}\sum_{i=T/\tau}^{N_f}\frac{\varphi(\epsilon_i)n^i}{i(1 - \xi_i)i!} \times [(t - t_1)^{1-\xi_i} - (t - t_m)^{1-\xi_i}] \quad (t \ge t_m) \tag{16}$$

The significance of the above equation (16) is that it allows the global mat stress relaxation to be calculated based on viscoelastic properties of local strand columns, which can be determined by testing a stack of flakes or single flakes. Also it has established a quantitative relationship between the mat stress relaxation and such fundamental parameters as press closing rate V, flake relaxation modulus K, flake relaxation rate ξ_i, flake thickness τ and average flake overlaps n.

MATERIALS AND EXPERIMENTAL PROCEDURE

The objectives of this experiment were: 1) to test the viscoelasticity of wood flakes under transverse compression to develop a database needed for predicting mat stress relaxation; 2) to measure the stress relaxation of flake mats and compare with model prediction; and 3) to correlate the creep of flake mats to that of wood flakes.

All mat samples were hand-formed and made of aspen (*Populus tremuloides*) flakes with average length 37.51 mm, width 6.09 mm, and thickness 0.79 mm. Each sample weighed 72 g and was 152-mm by 152-mm square. For testing the viscoelastic properties of wood, 25-mm by 25-mm square flakes with thickness 0.79 mm were hand-cut. To reduce the effect of wood variation, the samples were prepared by randomly selecting six flakes and stacking them together. A more detailed description of sample preparation procedures was presented elsewhere (Dai and Steiner 1993).

All samples were conditioned to 9.1% moisture content at 20°C before being tested on an MTS testing system at room temperature and humidity conditions. Stress and strain were measured and acquired in real time through a computer data acquisition system.

The stress relaxation tests on wood flakes were conducted by suddenly imposing strain on a 6-flake stack and then maintaining this strain for 10 min. Several strain levels were chosen to represent different stress-strain characteristics. During the mat stress relaxation tests, a loading speed of 5 mm/s was used.

To test the creep response of wood flakes, different loading levels representative of the full range of a stress-strain curve were applied in an instantaneous fashion to stacks of 6 flakes and maintained for 10 min. The flake mat creep tests were carried out by first imposing predefined stresses at a constant rate of 5 MPa/s and then maintaining the stress levels for 10 min.

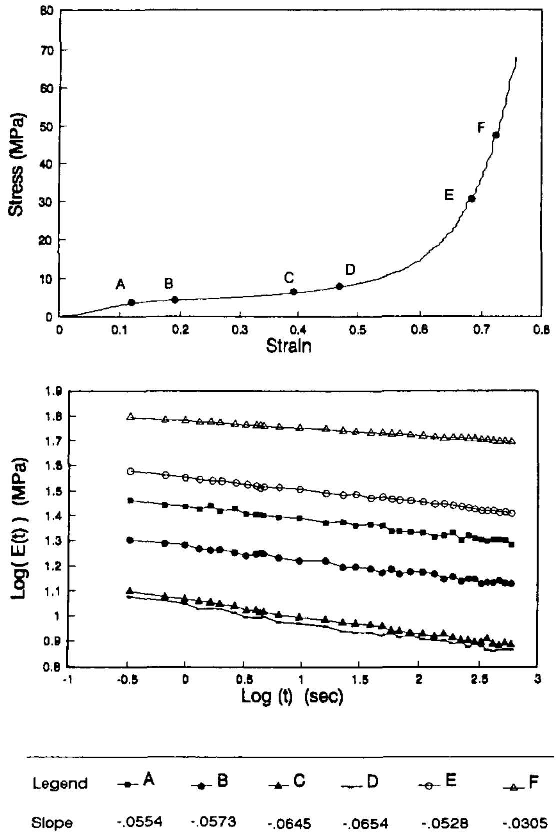


FIG. 2. (a) The strain levels imposed during flake stress relaxation tests, as indicated in a typical stress-strain curve. (b) Double logarithm plots of stress relaxation in 6-layer flake columns in compression.

RESULTS AND DISCUSSION

Flake stress relaxation

A full stress-strain curve of wood in perpendicular-to-grain compression is highly nonlinear. Thus the stress relaxation modulus E(t) is not only time-dependent but also strain-dependent. Such nonlinear stress relaxation behavior was evaluated by testing the relaxed modulus E(t) at different strain levels, as shown in Fig. 2a. The double logarithmic plots of modulus E(t) versus time are straight lines with varying slopes (Fig. 2b). Therefore, the modulus E(t) model as given by Eq. (1) is validated, and the stress relaxation rates as indicated by the slopes of the lines in Fig. 2 vary with the strain levels. The finding on double logarithmic linearity agrees with what was reported by many other researchers (Youngs 1957; Kunesh 1961; Rosa and Fortes 1988; Wolcott 1990). However, the variable slopes or stress relaxation rates, although implied by Youngs (1957) and Kunesh (1961), appear to be not consistent with the results cited by Rosa and Fortes (1988) and Wolcott (1990), where the slopes or relaxation rates were reported to be independent of strain levels.

The fact that stress relaxation rate varies with the strain level may be related to changes in both free volume (Knauss and Emri 1981; Ferry 1980) and chemical bonds in wood cell polymers (Kwei 1984; Kelley et al. 1987). The free volume theory states that the viscoelasticity of a polymer is ultimately attributed to the presence of free volume, which may be present as holes of the order of molecular dimensions or smaller voids associated with packing irregularities. In the case of wood, such free volume exists in the amorphous sites in the cell walls. The amount of free volume and chemical bonds in wood cell wall is affected by bond breakage caused by imposed stresses (Kauman 1966; Bolton and Breese 1987). The way stresses influence the formation of free volume and chemical bonds depends on both the stress mode and magnitude. Generally speaking, tensile, shear, bending, and buckling stresses can cause failure in chemical bonds and promote formation of free volume, whereas compression stresses hinder the development of free volume (Ferry 1980). According to Gibson and Ashby (1988), wood cell wall (polymer), when subjected to transverse compression stresses, can subsequently experience three different stress modes: bending, buckling, and compression, which respectively correspond to the three distinct stress-strain relationships (Fig. 2a). Therefore, free volume and bond failure in the cell-wall polymer increase during the first two phases when the cell wall encounters bending and buckling stresses, and decrease during the last phase when the cell wall is under compression. As a result, the compression stress relaxation rate increases with strain during the first two phases and decreases during the last phase (Fig. 2).

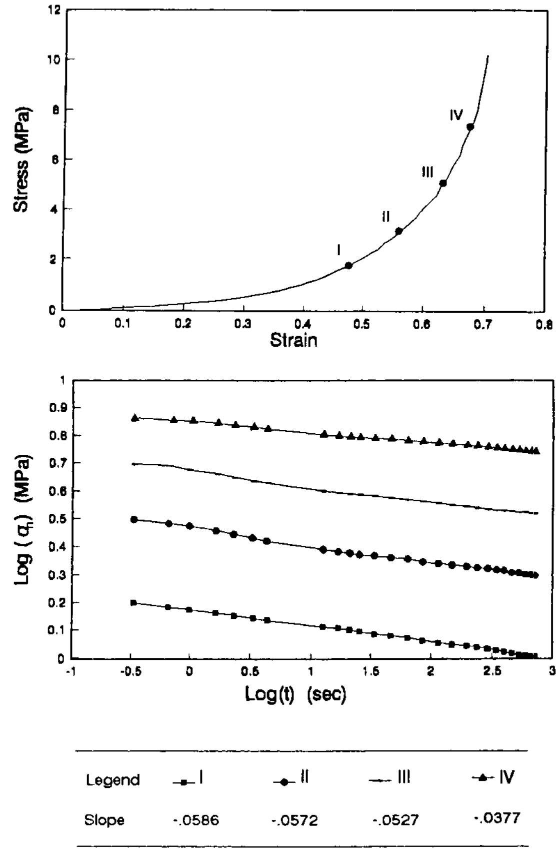
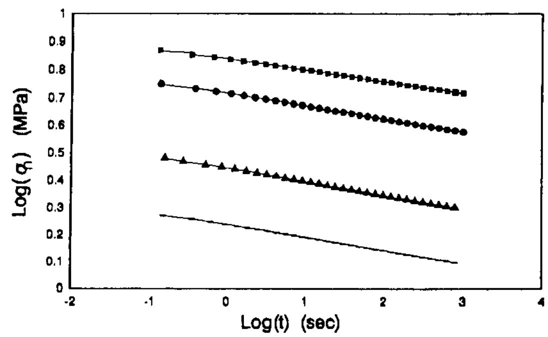


FIG. 3. (a) The strain levels imposed during mat stress relaxation tests, as indicated in a typical stress-strain curve. (b) Double logarithm plots of experimentally measured stress relaxation in flake mats in compression.

Validation of the mat stress relaxation model

We reported in a previous study (Dai and Steiner 1993) that the stress-deformation relationship of a randomly formed flake mat in compression is nonlinear. The nonlinear stress relaxation of mats was tested by compressing the mat samples under sustained deformation at different loading levels, as indicated in Fig. 3a. The double logarithmic plots of the stress relaxation versus time appear to be straight lines (Fig. 3b), and the line slopes indicating the stress-relaxation rates decrease with the loading levels. The global mechanical response of mats seems to be directly related to the stress relaxation behavior of its constituents—wood flakes.

The stress relaxation relationship between a mat and flakes was examined by predicting the



Legend	—	-▲-	-●-	-■-
Strain level	0.49	0.56	0.67	0.7
Slope	-.0483	-.0482	-.0456	-.0397

FIG. 4. Double logarithm plots of predicted stress relaxation in flake mats in compression.

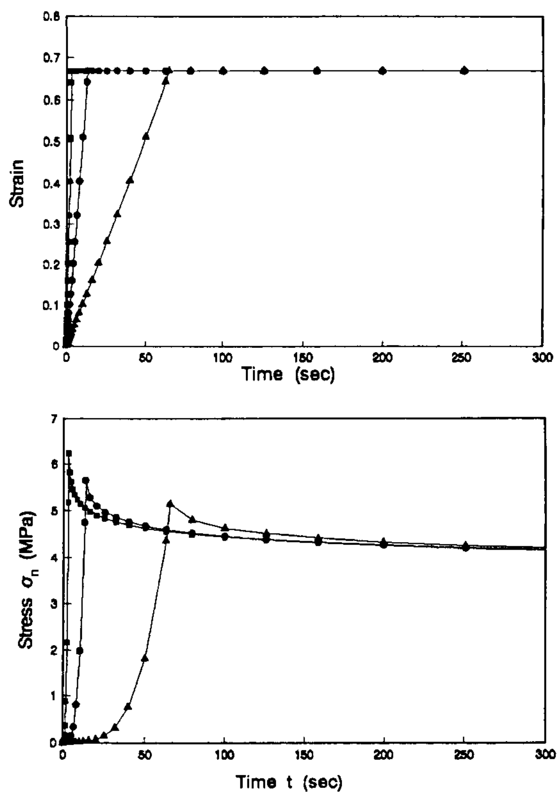


FIG. 5. (a) Three strain histories in mat stress relaxation tests. (b) Typical predicted time-dependent compression stresses in flake mats as affected by loading rate.

time-dependent stresses of the mat from those of flakes. The double log plots of the predicted mat stress relaxation versus time (Eq. 16) are shown in Fig. 4. The model predictions in trend follow the experimental observations (compare Fig. 3 with Fig. 4). It should be noted that the flake stress relaxation rate ξ_i, an important input parameter to the model, was estimated from the limited experimental database obtained in this work. The heterogeneity of wood flakes and especially the variation of climatic conditions under which the tests were conducted, suggest that more controlled tests are needed in order to more accurately determine the flake viscoelastic properties. The lack of such controlled tests is believed to largely contribute to the discrepancies in stress-relaxation rate between the model predictions (Fig. 4) and the experimental observations (Fig. 3).

One of the prediction capabilities of the proposed model is that it can calculate the effect of the loading rate (or press closing rate) on the time-dependent stresses in a mat (or mat pressure). Figure 5 shows that a faster loading rate results in higher maximum stress in the mat at a given mat compression strain and consequently more stress relaxation. Despite the differences in the loading and relaxation history, the asymptotic stresses appear to approach a common level, which is influenced only by the mat strain level, but independent of the loading rate. Under the hot-pressing condition, the effect of loading rating (or press closing rate) on stress relaxation should be more pronounced. The fact that mats exhibits more stress relaxation in hot-pressing could be due to several interactive effects. First, the elevated temperature makes mats more viscoelastic or higher flake stress relaxation rate ξ_i. Secondly, the transient heat and mass flow soften the mat or reduce modulus K of constituent mat layers. Finally, mechano-sorptive effects can occur when both loading and environmental conditions in mats are changing. Further investigations are underway to model the hot pressing behavior of composite flake mats.

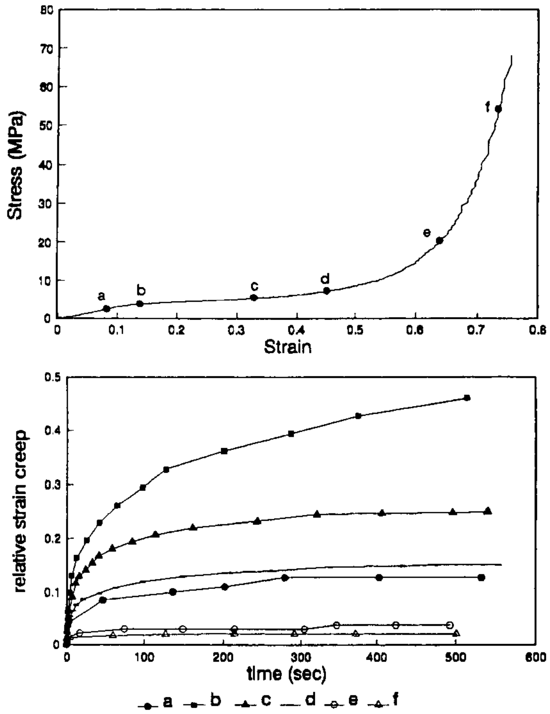


FIG. 6. (a) The stress levels imposed during flake strain creep tests, as indicated in a stress-strain curve. (b) Experimental results of relative creep strain $((\epsilon(t) - \epsilon(0))/\epsilon(0))$ in 6-layer flake columns.

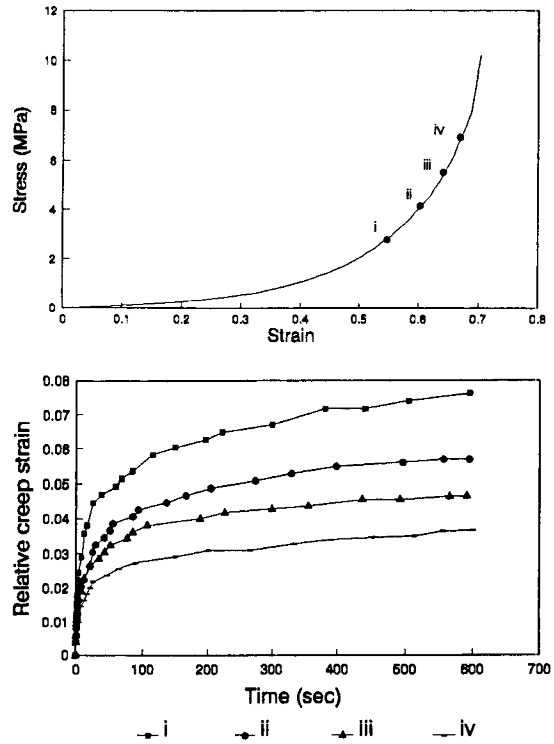


FIG. 7. (a) The stress levels imposed during mat creep tests, as indicated in a stress-strain curve. (b) Experimental results of relative creep strain $((\epsilon(t) - \epsilon(0))/\epsilon(0))$ in flake mats.

Creep of flakes and mats

The nonlinear creep behavior of flakes was tested by suddenly applying and maintaining different levels of stresses onto 6-flake stack samples. The stress loading levels represent different characteristics of the compression stress-strain relationship as shown in Fig. 6. The highest creep strain is found to be associated with the cell-wall yield point (Rosa and Fortes 1988; Wolcott 1990), where wood starts buckling. The extent to which flakes deform under sustained stresses, however, decreases as the stress level increases. The creep in both the linear range and the highly densified range is considerably lower than that in the cell-wall buckling range.

While relative creep strain has been commonly used to describe creep behavior for wood and most other materials, it does not seem to be suitable for the highly porous flake mats in question. The mat creep described by the relative strain as shown in Fig. 7 is almost an order less than that of solid wood flakes of which the mats are made. Such a small mat creep strain results directly from a considerably higher initial deformation, which is, in turn, due to the porous mat structure.

To compare the creep behavior between solid wood flakes and porous flake mats on the same density basis, a new terminology—relative creep compaction ratio—is proposed. Note that compaction ratio, CR, is the ratio of current mat density to original wood density and is indicative of the degree of mat consolidation. The relative creep compaction-ratio, RCR, is defined by:

$$RCR = \frac{CR(t) - CR(0)}{CR(0)} \quad (17)$$

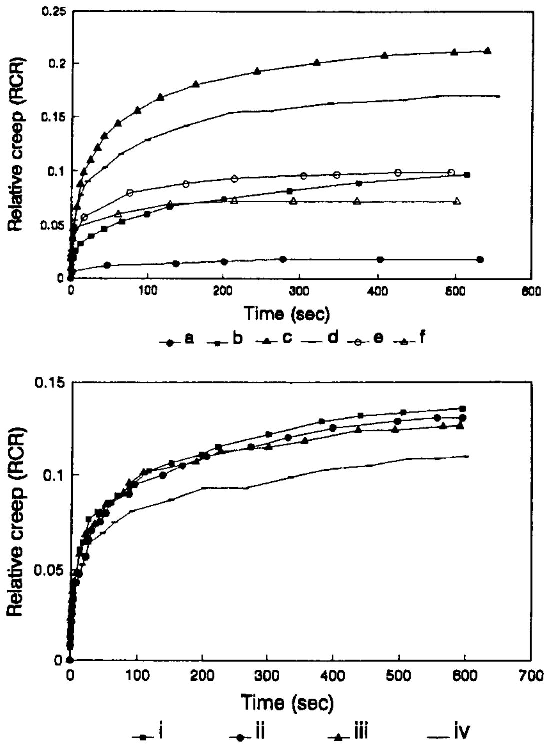


FIG. 8. (a) Experimental results of relative creep compaction ratio ((CR(t) − CR(0))/CR(0)) in 6-layer flake columns, legends as in Fig. 6. (b) Experimental results of relative creep compaction ration ((CR(t) − CR(0))/CR(0)) in flake mats, legends as in Fig. 7.

where CR(t) and CR(0) are, respectively, the compaction ratio at time t and at time 0.

The relative creep compaction ratios of wood flakes and flake mats are compared in Fig. 8, from which some noticeable changes occur as a result of using the RCR evaluation. First, the effect of loading stress levels on flake RCR is different from that using relative creep strain. For example, "line b" representing the highest relative creep strain in Fig. 6b is not the highest relative creep compaction ratio in Fig. 8a. This is because the rate at which wood density changes with compression deformation (neglecting the lateral expansion of compressed wood) is proportional to the initial material density. Higher loading stress levels result in higher mat density; therefore, the rate at which the mat density increases with further deformation becomes faster. Secondly, the creep behavior of flake mats in terms of RCR is quantitatively comparable to that of wood flakes (compare Fig. 8a with Fig. 8b). From this comparison, it appears that the global creep of a mat in compression is an average creep response of its constituents under the similar loading conditions. This finding may allow for deduction of mat consolidation creep behavior based on the transverse compression creep properties of wood flakes or solid wood.

SUMMARY AND CONCLUSIONS

A fundamental model for predicting the stress relaxation of a flake mat during consolidation is developed based on the compressive stress relaxation of wood flakes and Poisson distribution of flake overlaps formed in the mat. The predicted results agree well with the experimental observations despite some quantitative discrepancies in the relaxation rates. The significance of such a model is that it explicitly describes the time-dependent mat stress behavior in terms of press closing rate, flake relaxation modulus, flake relaxation rate, flake thickness, and average flake overlaps in the mat. The model can be used to predict hot-pressing behavior of wood composites by taking into account the heat and mass transfer inside mats during pressing.

The experimental results obtained in this work confirm that the double logarithmic relationship between flake stress and time is linear. The flake stress relaxation rates, however, vary with the loading strain levels. This phenomenon seems to be related to the characteristics of free volume change in cell walls of wood flakes under different compression loading levels.

The creep behavior of wood flakes and flake mats was tested and compared. Due to porosity difference, creep of wood flake mats is not quantitatively comparable to creep of wood flakes in terms of relative creep strain. Instead, mat creep seems related to flake creep on the basis of relative creep compaction ratio—a parameter indicative of material densification. In that regard, the global creep properties of flake mats seem to be affected by the constituent flakes through their average responses.

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