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## FUNDAMENTALS OF FLAKEBOARD MANUFACTURE: VISCOELASTIC BEHAVIOR OF THE WOOD COMPONENT

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### ABSTRACT

Theories of the viscoelastic behavior of amorphous polymers are reviewed and are used to describe the density gradient formation in flakeboard. This technique utilizes measured temperature and gas pressure at discrete locations inside a flake mat during hot pressing to predict the glass transition temperature of wood as a function of press time. The difference between the flake temperature and the predicted glass transition temperature is a relative indicator of the amount of flake deformation and stress relaxation at a location in the mat. A knowledge of the stress history imposed in the mat is then used to relate flake deformation and stress relaxation to the formation of a density gradient. This analysis allows for a significant portion of the density gradient to develop after the hot press has closed. Experimental data for various density gradients support the theories presented here.

**Keywords:** Viscoelasticity, wood polymers, pressing, wood composites, flakeboard, density gradient, environmental conditions.

### INTRODUCTION

With the large number and diversity of materials available today, the ability of the manufacturer to control properties is critical for success of the product in

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the marketplace. Although we have little or no control over the engineering properties of solid wood, the potential for the design of material properties in wood composites is great. Large strides are presently being made in the design of non-veneer structural panels by using materials engineering and science principles (Hunt and Suddarth 1974; Laufenburg 1983, 1984; Back 1987). However, a large gap in our fundamental knowledge of wood composite systems is in the understanding of how raw material properties and processing variables interact to influence the internal geometry and material properties of the components *in situ*.

The ability to use production variables to control material properties of wood composites is a valuable tool that has been studied on an empirical basis (Geimer 1980; Kelley 1977). For nonveneer wood composites, the focal point of the production process is the hot press. During the hot pressing cycle, heat is conducted into the mat from platens that attain temperatures in the range of 150 C to 225 C. Both conductive and convective heat transfer occurs inside the mat. Initially, moisture in the wood near the heated platens vaporizes, total gas pressure increases in the outer portion of the mat, and the heat-laden vapor is driven vertically to the center and horizontally to the edges of the mat. This simultaneous heat and mass transfer results in transient temperature, gas pressure, and moisture content gradients in the panel during pressing (Maku et al. 1959; Suchsland 1962; Humphrey 1979; Kamke and Casey 1988a, b).

During the press closing time, a maximum compaction pressure of 4 to 8 MPa is imposed on the panel. After the targeted mat thickness is achieved, the compaction pressure required to hold position declines as a result of stress relaxation. Presumably, higher localized pressures result from the heterogeneity of the mat. The stresses in the mat result in permanent deformation of the wood component because the average product density is usually greater than that of the original wood component.

The transient temperature and moisture gradients inside the mat result in non-uniform and changing compression properties of the wood component. When the compaction pressure applied to the mat is coupled with the changing compression properties, a density gradient develops. After the thermosetting adhesive has sufficiently cured, the venting process begins. The compaction pressure is slowly relieved, allowing the internal gas pressure to dissipate before opening the press.

When the mechanical pressure applied to the mat is coupled with the interior transient temperature and moisture conditions, density gradients form in the processed panel. Density gradients are important to pressed wood composites because they influence material properties of the composite in the following ways:

1. Density is strongly correlated to the strength and engineering properties of the individual wood components (Price 1976; Geimer et al. 1985; Casey 1987).
2. The stress under which the wood is compressed affects the strength and engineering properties of the wood component *in situ* through fractures in the cell walls (Geimer et al. 1985).
3. The bond strength is related to the plasticization of the wood component (Back 1987). Forming an intimate wood-adhesive-wood contact surface is necessary to increase the bonding area.
4. Density gradients determine the geometry of the final internal structure of

the composite (i.e., higher densities correspond with more wood elements per unit volume).

### *Objectives*

While developing a fundamental understanding of how stress, time, heat, and moisture interact during the pressing of wood-based composites, the specific objectives of this work are:

1. To provide a substantive literature review regarding the viscoelastic behavior of the amorphous polymers in wood.
2. To develop a methodology to determine the relation of internal environmental conditions in a pressed panel to the glass transition temperature of the amorphous polymers in wood.
3. To relate the variation in glass transition temperature of lignin during the pressing cycle to the formation of the density gradient.

### LITERATURE REVIEW

Because of the extreme physical conditions described above, the pressing cycle will have a profound influence on the *in situ* material properties and internal geometry of the wood components. Understanding how the environmental factors influence the mechanical behavior of the wood component will provide insight into the effects of pressing conditions on the performance of the composite product. For polymeric materials such as wood, the dependence of mechanical properties on time, temperature, and diluent concentration (i.e., moisture content) is unified through the viscoelastic properties. From our present knowledge of the morphology and structure of the individual polymers in wood, certain information on their viscoelastic response can be inferred using polymer and composite theory. For the moisture contents usually encountered in the processing of wood composites, less than 15%, it is reasonable to assume that the semi-crystalline cellulose is not viscoelastic (Salmen et al. 1985). Therefore, the influence of moisture and temperature is restricted to the amorphous polymers in wood, namely the hemicelluloses and lignin.

#### *Mechanical behavior of amorphous polymers*

Amorphous polymers are termed viscoelastic because they can exhibit a range of properties from viscous fluids to linear elastic solids depending on the temperature, diluent concentration, or time scale of the test (Fig. 1) (Ward 1983). The glassy state of a polymer corresponds with low temperatures, low diluent concentrations, and high frequencies (i.e., short times). It is characterized by a high modulus and brittle fractures at small strains. At high temperatures, high diluent concentrations, and low frequencies (i.e., long times), the polymer is in the rubbery state that is characterized by large strains at failure and a modulus that is approximately three orders of magnitude lower than in the glassy state. At higher temperatures and longer time scales, some polymers (i.e., thermoplastics) will exhibit viscous flow. However, the unmodified polymers in wood probably undergo thermal degradation before they exhibit a true viscous region. This should not be confused with the viscous component of viscoelastic behavior, which does occur in wood. Between conditions associated with the glassy and rubbery regions, a

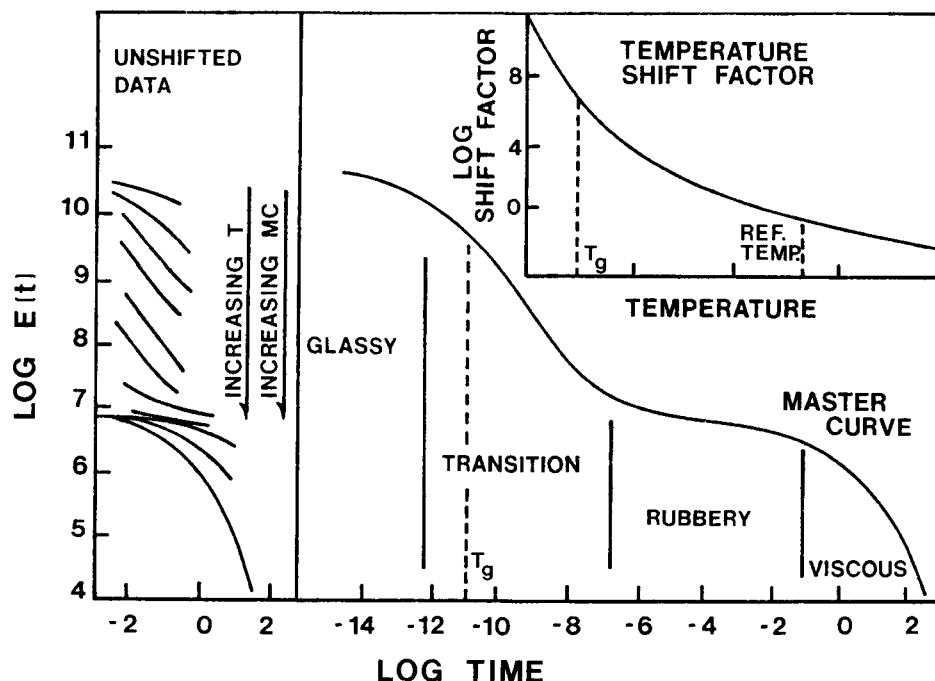


FIG. 1. Typical variation of relaxation modulus  $[E(t)]$  for an amorphous polymer with time, temperature, and diluent concentration. The master curve denotes the specific viscoelastic regions of polymer behavior. (Adapted from Ward 1983.)

polymer is in the transition state. In this region, large changes in polymer properties result from small changes in time, temperature, or diluent concentration.

The analogous behavior of polymers with different time, temperature, and diluent concentrations is exhibited best in thermorheologically simple systems (Christensen 1982). In these polymer systems, the time-dependent mechanical response at different temperatures and diluent concentrations is related by a change in the time scale only. Once the time-dependent response of a polymer is determined over a large range of times (termed a master curve), the effect of a temperature change is equivalent to a horizontal shift of the master curve via a time multiplier (the shift factor) (Fig. 1). A time-temperature equivalence has been verified for wood saturated with water (Salmen 1984) and formamide (Kelley et al. 1987). A time-moisture content equivalence have been verified by Pecht (1985) for paper.

#### *The glass transition temperature*

A material property that results from the relation of temperature to the physical states of a polymer is the glass transition temperature ( $T_g$ ).  $T_g$  is the temperature that corresponds to a change in slope when specific volume is measured against temperature (Ward 1983). In terms of mechanical properties, an abrupt decrease in stiffness is noted at  $T_g$  differentiating the glassy and rubbery regimes of the polymer. The actual  $T_g$  of the polymer is usually denoted as the midpoint of the transition region.

Several researchers have studied the effect of moisture content on the  $T_g$  of extracted hemicelluloses and lignin with varying results (Goring 1971; Back and Salmen 1982; Irvine 1984). Blankenhorn et al. (1973), Kelley et al. (1987), and Irvine (1984) have used dynamic mechanical analysis (DMA) to study this dependence for wood polymers *in situ*. Blankenhorn et al. found thermal transitions in the region of  $-88$  to  $-48$  C and  $237$  C. The low temperature transition was also found by Kelley et al. and is associated with relatively small decreases in modulus. Transitions of this type have been found in many hydrophilic polymers and are thought to be secondary transitions associated with site exchange of moisture (Kapur et al. 1972). Primary glass transitions of the hemicelluloses and lignin were found at higher temperatures by Kelley et al. and Irvine.

Kelley et al. (1987) described the variation in  $T_g$  of hemicelluloses and lignin *in situ* with solid wood moisture content using the Kwei model. Good agreement was found with the results presented by Irvine (1984). However, Salmen (1984) observed a  $T_g$  of approximately  $100$  C for *in situ* lignin under water-saturated conditions using dynamic mechanical analysis at the same frequency used by Kelley et al. The results of Salmen were consistent with those presented by other authors but differed from the  $65$  C determined by both Kelley et al. and Irvine. The difference between these results could stem from the nonequilibrium moisture conditions. Salmen maintained strict moisture control during the temperature changes. Kelley et al. and Irvine conditioned the samples to an initial moisture content and then provided no explicit control for moisture content during the tests. The results of Kelley et al. are used in the analysis presented here because the nonequilibrium moisture states of the pressing operation are similar to the transient moisture states of their  $T_g$  scans.

The variation of  $T_g$  with moisture content calculated with the Kwei equation is presented in Fig. 2. At  $0\%$  moisture content, the  $T_g$  of both hemicelluloses and lignin was assumed to be approximately  $200$  C as given by Salmen (1984). This value is difficult to validate because both polymers rapidly degrade near this temperature (Schaffer 1973; Back and Salmen 1982). The  $T_g$  of lignin decreases with increasing moisture content and begins to plateau at  $70$  C with a moisture content of  $10$  to  $15\%$ . However, the  $T_g$  of hemicelluloses continues to decrease with increasing moisture content until it reaches a value of approximately  $-20$  C near  $30\%$  moisture content. The  $T_g$  of hemicelluloses is  $30$  C at approximately  $10\%$  moisture content. Therefore, at higher moisture contents, phase changes in hemicelluloses are only important at subambient temperatures. Likewise, it can be inferred that for moisture contents between  $10$  and  $15\%$ , the moisture dependence of solid wood modulus at ambient temperatures is primarily a function of phase changes in the hemicelluloses.

#### *Mechanical response of wood undergoing phase changes*

The magnitude of the drop in mechanical properties associated with the phase change will be different for hemicelluloses and lignin. This cannot be measured directly *in situ*. However, approximate figures can be determined through knowledge of the polymer morphology and studies of extracted polymers. Hemicelluloses are linear polymers and should show a change in modulus of approximately three orders of magnitude. Lignin is a moderately branched, three-dimensional polymer. Such a system usually exhibits a decrease in log modulus on the order

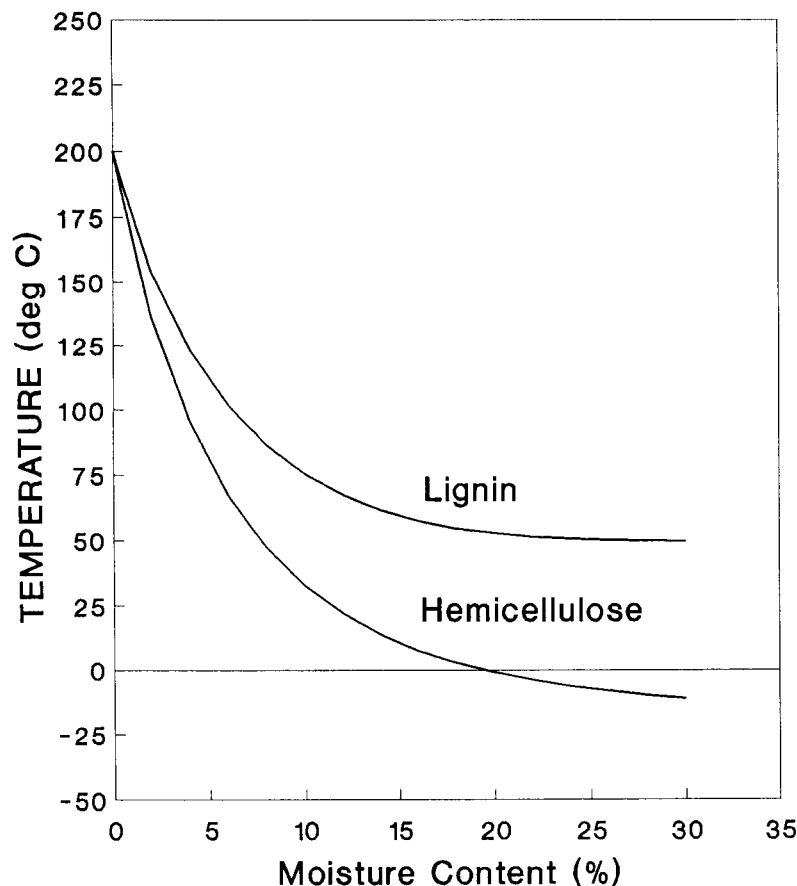


FIG. 2. The moisture dependence of  $T_g$  for *in situ* lignin and hemicellulose as predicted by the Kwei model (Kelley et al. 1987).

of 1.5. Data from Cousins (1978) show a drop in log modulus of 2.6 for extracted hemicelluloses. Salmen (1982), in modelling the temperature and moisture dependence of wood fibers, estimated a drop in log modulus of 1.8 for lignin. Similar decreases in modulus are noted for crosslinked lignin co-polymers (Rials and Glasser 1986).

Because of the spiral winding and reinforcing nature of the cellulose microfibrils, the decrease in modulus of solid wood will be less than that in the individual polymer undergoing the phase change. Differences are seen parallel and perpendicular to the fiber direction resulting from the preferential orientation of the microfibrils. Greater drops will occur in modulus perpendicular to the grain than parallel to the grain (Salmen 1982). Because of the complexity of this subject, a more complete treatment of this subject is beyond the scope of this paper.

#### *Consequences of viscoelasticity on the pressing cycle*

We propose that the concepts of polymer viscoelasticity can be used to optimize many facets of the pressing cycle. The primary application deals with understand-

ing and predicting how the vertical density gradient is formed in nonveneer composite panels. However, as a consequence of the viscoelastic response resulting in the density gradient, many other panel properties and production parameters are affected. These properties include but are not limited to adhesive bond quality, springback, and dimensional stability. The following discussion will concentrate on how the density gradient is formed using some experimental data and theoretical calculations.

Wood is a heterogeneous material that is composed of anisotropic cells. When flakes, veneers, or other particles are cut from solid wood, the irregularity inherent to the resulting surface will yield little contact area between adjacent wood elements. To produce a good adhesive bond, the wood must deform sufficiently to produce an intimate wood-adhesive-wood contact (Back 1987). The largest contact area will result when the polymers of the wood are in a physical state to allow maximum deformation under minimum pressure; i.e., the rubbery state. It is also imperative that the resin flow and form a continuous layer rather than individual droplets (Wilson and Krahmer 1976; Brady 1987). Because viscosity of a resin increases while curing, the temperature in the mat must be carefully controlled to allow maximum wood deformation prior to initiating the curing process. Moisture interacts with the wood polymer to affect  $T_g$  and consequently affect the deformation. However, to control this process successfully, an understanding of resin curing under different moisture regimes is necessary (Chow and Mukai 1972).

The out-of-plane tension strength of nonveneer composite panels is frequently used in industry as a measure of the internal bond strength. Low internal bond strengths are usually attributed to poor adhesive performance; however, the wood may also fail prematurely. Smith (1982) and Strickler (1959) studied the effect of production parameters on the mechanical properties of flakeboard. Both researchers concluded that the direct relationship between local density and internal bond strength did not hold for all pressing schedules. The cell walls of wood buckle when it is densified in compression perpendicular to the grain (Easterling *et al.* 1982). Fractures and plastic hinges have been noted in the buckled cell walls of some flakes, whereas pure elastic buckling seems to occur in others (Fig. 3) (Geimer *et al.* 1985). The conditions are most favorable for fractures to occur when the hemicelluloses and lignin are in the glassy state and the polymers are brittle. However, when the temperature of the wood is above the  $T_g$  of both amorphous polymers, then large strains can occur without fractures. Micro-fractures in wood can be detrimental to strength by providing places for larger fractures to originate. Annealing at high temperature could possibly minimize the strength loss by blunting the crack tip, thereby, increasing the strain energy needed to propagate the fracture.

Springback may also be related to how the cell walls buckle. If the cell walls do not fracture when they buckle, they will exert a certain restoring force when the amorphous polymers are in the rubbery state. This restoring force will result in a pressure needed to keep the press closed after initial relaxation has occurred. When the press is opened, the cell walls will rebound and the springback results. The amount of springback in the panel will be dependent on how the cell walls collapse and the amount of stress relaxation that occurs during the pressing cycle.

The dimensional stability of the end product is merely an extension of the viscoelastic response resulting in springback. A force is exerted on the panel that



FIG. 3. Cross-sectional views of Douglas-fir flakes recovered from a pressed panel showing (A) elastic collapse and (B) fractures in the cell walls (Geimer et al. 1985).



is equal to the swelling pressure of adsorbed water. Like springback, the manner in which the cell walls collapse will strongly influence how they will respond to stresses. The stress relaxation that occurs in the press will also affect dimensional stability because the viscoelastic response of a material is a function of the entire stress history.

## METHODS

### *Panel manufacture*

Three replications of yellow poplar (*Liriodendron tulipifera*) flakeboard panels were produced with a 1-minute press closing time at two levels of initial mat moisture content (4% and 15%) and platen temperature (154 C and 190 C). Gas pressure and temperature were monitored at a face and core location within each panel during the pressing cycle (Kamke and Casey 1988a, b). Six samples from each of the 12 panels were used to determine an average density profile through the thickness of the panel (Brady 1987) using a gamma radiation method (Lauenburg 1986).

### *Determining flake temperature and moisture content*

As discussed earlier,  $T_g$  of the wood polymers varies throughout the pressing cycle as a function of moisture content. Therefore, the moisture content variations in the wood component of the mat must be determined. To date, moisture content has not been continuously measured during processing of a composite panel. Maku et al. (1959) intermittently measured moisture content at different depths in the mat by stopping the press and weighing the wood particles. However, resin was excluded from the panels and the measurements were not continuous. Mathematical models have been developed that predict mat temperature and moisture content during the press cycle (Humphrey 1979; Wagner et al. 1987). However, the mat is treated as a continuum and local thermodynamic equilibrium is assumed. This is equivalent to allowing the wood particles to instantaneously equilibrate with the surrounding environment. The actual change of the particle moisture content is not known.

Without experimental data available on moisture content variations during the press cycle, measurements of temperature and gas pressure were used in conjunction with a one-dimensional heat and mass transfer computer program developed by Schajer (1984) to predict moisture content in the mat. The computer program is based on fundamental transport theory and consists of a system of coupled partial-differential material and energy balance equations (Stanish et al. 1985). Assuming any increase in total gas pressure in the mat during pressing is entirely attributed to increases in water vapor content, relative humidity changes in the mat can be calculated (Kamke and Wolcott 1990). The measured temperature and predicted relative humidity profiles are then used as boundary conditions for a flake at a given location in the mat. The heat and mass transfer model is then solved to yield a predicted average flake moisture content and temperature. This procedure is described in detail elsewhere (Kamke and Wolcott 1990).

### *Calculating variations in $T_g$ during the pressing cycle*

Knowing the moisture content variations through the press cycle, the  $T_g$  of hemicelluloses and lignin in wood can be tracked through the press cycle and

compared with the wood temperature at any given time. The variation of  $T_g$  for hemicelluloses and lignin with solid wood moisture content were described using the Kwei equation as described by Kelley et al. (1987). The form of the Kwei equation reported by Kelley et al. is:

$$T_g = \frac{W_1 T_{g1} + kW_2 T_{g2}}{W_1 + kW_2} + qW_1 W_2 \quad [1]$$

where:

- $W$  = weight fraction (1, 2 denote wood and water respectively)
- $k$  = adjustable parameter (10 for lignin, 13 for hemicellulose)
- $q$  = adjustable parameter (585 for lignin, 355 for hemicellulose)
- $T_g$  = glass transition temperature (200 C for wood polymers, -137 C for water)

Although Kelley's results are not entirely consistent with that of Salmen (1982, 1984), the conditions of drying under which the experiments were conducted by Kelley et al. are more like the hot pressing process than are the equilibrium moisture conditions used by Salmen.

## RESULTS AND DISCUSSION

### *Mechanical pressure and formation of the density gradient*

The formation of the density gradient is a complex phenomenon that involves the simultaneous processes of momentum, heat, and mass transfer. The momentum transfer is initiated by the mechanical pressure exerted by the press. These processes are interrelated through the sorption characteristics and the viscoelastic behavior of the mat. In particular, the viscoelastic theories of amorphous polymers can account for the influence of temperature and moisture content on mat deformation by using a single variable,  $T_g$ . Because the most significant effect of temperature on the modulus of amorphous polymer occurs around  $T_g$  and the moisture influence is primarily in altering  $T_g$ , then comparing wood temperature during the pressing cycle to the  $T_g$  of lignin and hemicelluloses can provide valuable insight into how density gradients form.

Because densification will only occur from a mechanical force being applied, the compaction pressure applied to the mat during the pressing cycle must be examined. A typical compaction pressure curve is presented in Fig. 4. The curve can be divided into several distinct regions: (A) press closure; (B) transient relaxation; (C) asymptotic relaxation; (D) venting.

Press closure occurs during a predetermined amount of time known as the press closing time (PCT). During the early portion of the PCT, the pressure is low while the flakes consolidate to eliminate large voids. As the mat densifies, the pressure increases rapidly in the latter portion of PCT. If the mat densifies in an elastic manner, the density gradient will form entirely during this portion of the press cycle. However, if the material properties of the wood elements are a function of time, temperature, and moisture content, then the density gradient must continue to develop during other portions of the press cycle.

The transient relaxation region begins when the stress on the mat decreases rapidly with time. Mechanically the mat is undergoing stress relaxation at a con-

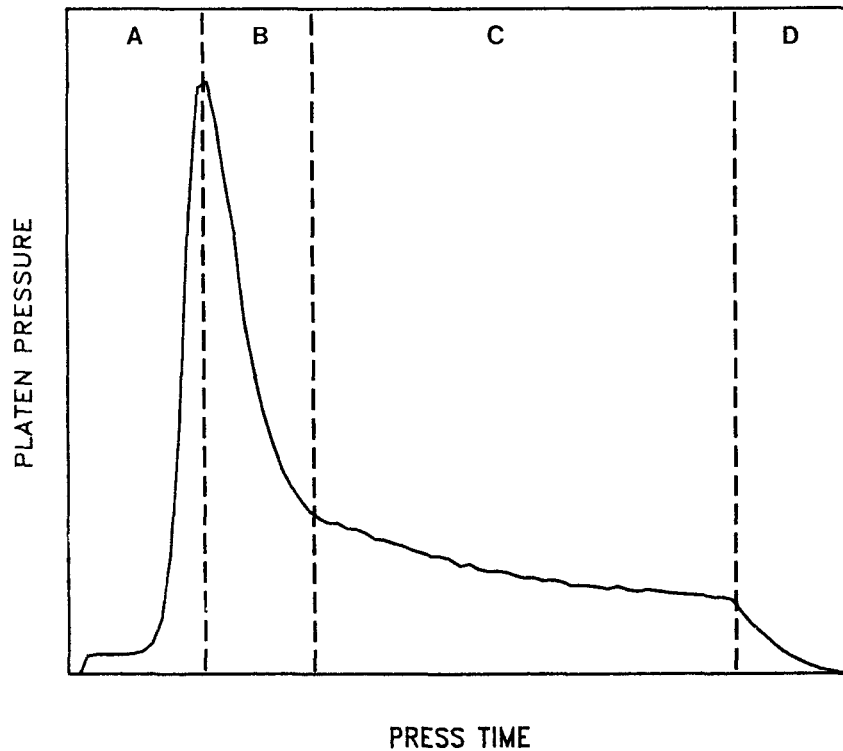


FIG. 4. A typical platen pressure curve denoting specific regions. A: press closing; B: transient relaxation; C: asymptotic relaxation; D: venting.

stant deflection. However, the individual wood elements in some regions of the mat can continue to densify with time while others recover stored elastic deflection. This process is possible because of differential stress relaxation within the mat caused by the transient environmental conditions. The additional densification results in plastic deformation from cell collapse.

The asymptotic relaxation region begins when the change of stress with time decreases to a relatively constant value. The separation between the two relaxation regions is not exact or important. The distinction between these regions is that changes in local mat density and therefore, plastic deformation can continue during the transient relaxation but are unlikely during asymptotic relaxation. This differentiation can be made because the pressure needed to maintain press position changes little with time during asymptotic relaxation. The role that the asymptotic relaxation region is likely to play in density gradient formation is through continued stress relaxation in different regions of the mat thereby affecting the amount of springback that occurs with individual wood elements. For example, suppose the temperature of the wood elements in the face of a panel is above  $T_g$  throughout the asymptotic relaxation region, but that in the core is not. The rate and amount of stress relaxation in the face are much greater than in the core. Upon opening the press, more elastic deflection will be recovered from the core than the face, thereby contributing to the density gradient in the end product.

During venting, the press slowly opens and the pressure applied to the mat is

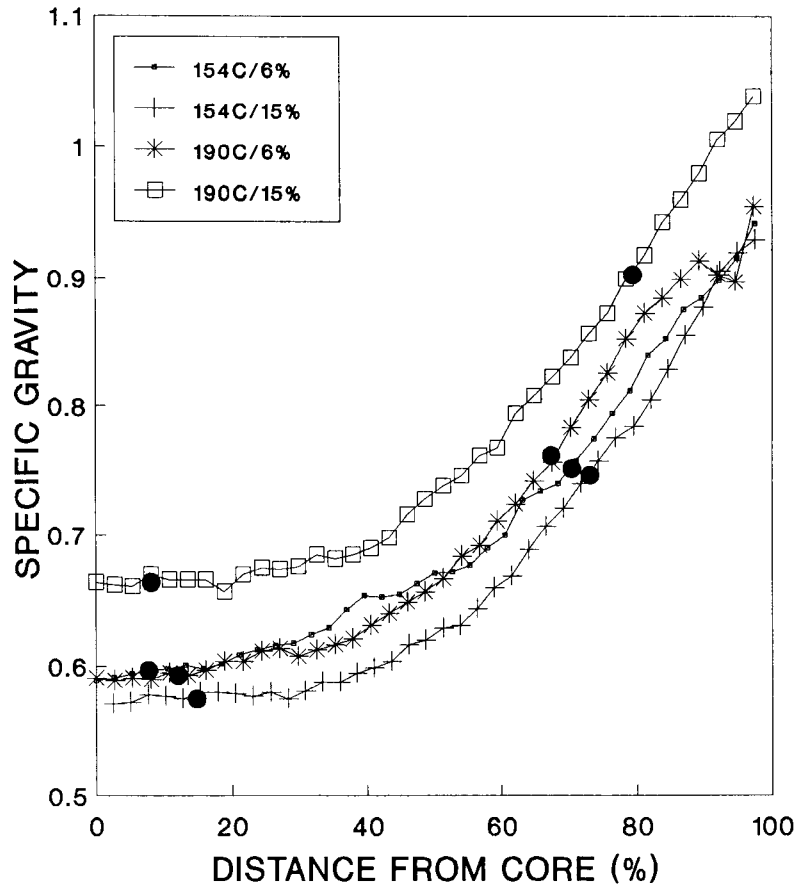


FIG. 5. Average vertical density gradient profiles for panels. The actual probe locations are marked for the core and face.

lowered to relieve the internal gas pressure. Venting usually occurs over a pre-determined period of time depending on the platen temperature and mat moisture content. Elastic recovery (springback) will occur during this portion of the press cycle. Additional viscous recovery will occur after the panel has been removed from the press. Both the elastic and viscous portions of recovery depend on the viscoelastic behavior of the wood polymers during the pressing cycle.

#### *Panel attributes*

The vertical density profiles for each of the four panel types are presented in Fig. 5. Each line represents an average of the 18 density gradient samples. Because the thermocouples and gas pressure probes were placed at approximately the same depth while forming the mat (Kamke and Casey 1988a), the probe location in the final panel differed slightly depending on how the density gradient formed. The actual face and core probe locations are marked on each density profile.

Examples of the predicted change in flake moisture content and temperature during the press cycle are presented in Fig. 6. The measured mat temperatures

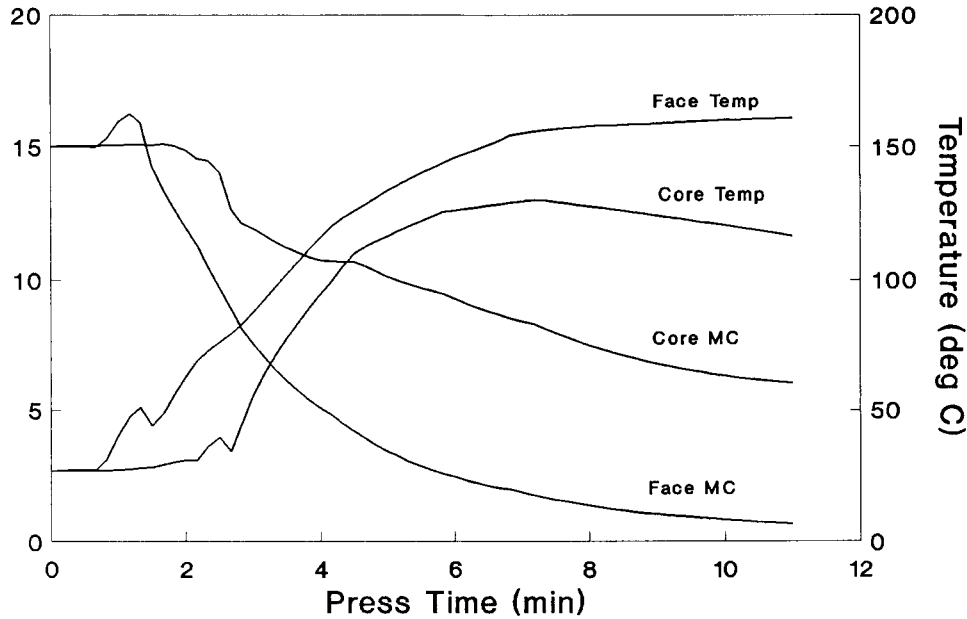


FIG. 6. Average flake temperature and moisture content for the 190 C-15% panel type as predicted using a one-dimensional heat and mass transfer model.

and gas pressures used as boundary conditions to predict the flake conditions are presented elsewhere (Kamke and Casey 1988b). For simplicity, the  $T_g$  for lignin, calculated using Eq. 1, is presented as the difference between  $T_g$  and the predicted flake temperature ( $T$ ) (Fig. 7). Only the data for  $T_g$  of lignin are presented because this transition dominates the behavior of these panel types.  $T_g$  is presented for the first 6 minutes of the press cycle, which corresponds to the end of the asymptotic relaxation period. The end of the transient relaxation period is denoted for each panel type. Horizontal lines drawn at 25 C and -25 C indicate the approximate transition zone for lignin. Values of  $T_g - T$  greater than 25 C indicate that the lignin is in the glassy state, whereas, values of  $T_g - T$  less than -25 C indicate that the lignin is in the rubbery state. Values between 25 C and -25 C will be referred to as the transition zone.

#### *Transient relaxation period*

We postulate that changes in localized density can occur during the transient relaxation period from differential stress relaxation through the thickness of the panel. Results presented here support this hypothesis.

The density at the face and core probe locations is similar for all panel types except for the 190 C and 15% panel (190 C-15%) (Fig. 5). Despite the fact that all the panel types were pressed to the same thickness and target density, the entire density profile of the 190 C-15% panel is shifted upward with respect to the other panel types. The wood at the face location of this panel type was in the transition zone for much of the transient relaxation period and all of the asymptotic relaxation period (Fig. 7). This is not true for any other panel type presented here. Although the face entered the transition zone near the end of press closing, the

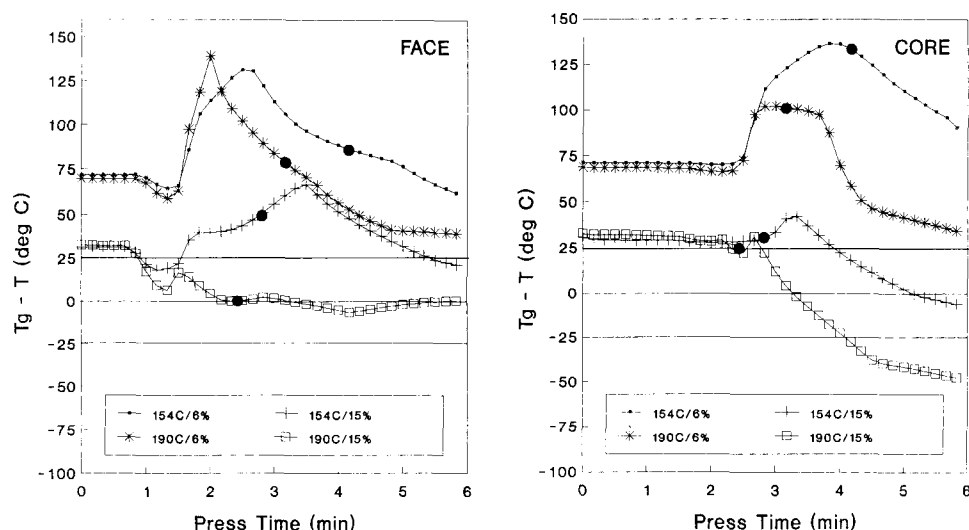


FIG. 7. Predicted difference between  $T_g$  and average flake temperature for *in situ* lignin in the face and core probe locations for panels. The end of the transient relaxation period is marked for each panel type.

time that the core started a transition was well after the press was closed. Therefore, if densification ceased at the end of the press closing, then no further densification should have occurred in the core.

Kamke and Casey (1988b) noted that a small plateau occurred in the gas pressure data for the face layer of the 190 C-15% panel. This plateau coincided with a slope change in the platen pressure curve and the initiation of gas pressure buildup in the core. They suggested that a possible explanation for this occurrence was a change in the void volume of the face location from differential relaxation through the thickness of the mat. The gas pressure plateau occurs at approximately 2 minutes in the press cycle. Note that the core location of the 190 C-15% panel enters the transition zone at approximately this time. This plateau did not exist on any other panel type with a 1-minute press closing time. Likewise, none of the core locations for these panel types were in the transition zone during the transient relaxation period.

Given the theories presented here, a possible scenario for the behavior of the 190 C-15% panel during the transient relaxation period is as follows. When the core of this panel entered the transition region, the relaxation modulus of the wood began to decrease rapidly. These conditions allowed the core to densify while some of the elastic deformation recovered in the face. The increased void volume of the face caused the rate of gas pressure build up to slow, resulting in a plateau in the gas pressure data. The decreased void volume in the core resulted in an increased gas pressure at this location.

#### *Asymptotic relaxation period*

From both an intuitive and experimental standpoint, it seems likely that the density gradient continues to actively form during the transient relaxation period.

However, the role that stress relaxation plays during the asymptotic relaxation period has not yet been addressed. The higher density of the 190 C-15% panel may be attributed to either the transient or asymptotic relaxation periods because this panel was in the transition zone for a longer period of time during both relaxation periods than any other panel type studied here. Comparing the two panel types made with 15% initial mat moisture content may provide insight into the role of the asymptotic relaxation period.

The wood in the face location of the 154 C-15% panel enters the transition zone for only very short periods of time during the transient and asymptotic relaxation periods. However, the core was in the transition zone for over half of the asymptotic period. The fact that the density of the core was not as great as in the 190 C-15% panel indicates that a significant amount of stress relaxation must have occurred during the asymptotic relaxation period to affect the density gradient.

The vertical density profiles of both panel types produced at 6% initial mat moisture content are extremely similar to that of the 154 C-15% panel. The wood in both the face and core probe locations of these panels was in the glassy region throughout the transient relaxation period. However, the core of the 154 C-15% panel was in the transition zone for at least half of the asymptotic relaxation period, whereas, the 6% moisture content panel types were not. From this data, it is also apparent that stress relaxation during the asymptotic relaxation period must be substantial to affect the density gradient. A more thorough understanding of the viscoplastic nature of wood will be necessary to better differentiate between unrecoverable viscous and plastic deformation.

#### CONCLUSIONS

With prior knowledge of internal mat temperature and gas pressure, it is possible to track  $T_g$  of *in situ* lignin and hemicelluloses using a one-dimensional heat and mass transfer model to predict wood temperature and moisture content and the Kwei equation to describe the  $T_g$  dependence on moisture content. Using this method of  $T_g$  tracking, differences in the observed density gradients of panel types were generally consistent with the theories presented here except when the wood temperature did not exceed the  $T_g$  of lignin during periods when gross densification was postulated to occur. This discrepancy results from the lack of difference between  $T_g$ - $T$  of face and core within a panel type when differences clearly exist in the panel density at these locations. Given these results, the values for  $T_g$  of lignin derived under nonequilibrium moisture conditions by Kelley et al. (1987) are adequate for describing  $T_g$  variations with moisture content during the pressing cycle of wood composites. However, further research on nonequilibrium effects is required.

Determining the simultaneous effects of moisture content and temperature on the viscoelastic response of wood during the pressing cycle can be accomplished by studying the difference between wood temperature and  $T_g$  when sufficient differences exist in the environmental conditions to produce different states of the polymers. However,  $T_g$  of lignin is not likely to be a useful variable to study when the environmental conditions are such that lignin is in the glassy state throughout the press closing and transient relaxation periods. Under these conditions, a full viscoelastic treatment of wood is necessary to understand the density

gradient formation and how it may affect macroscopic panel properties. In addition, boundary effects similar to St. Venants principle are likely to play a large role in the mat deformation. The importance of this effect is evident in the compressive deformation of cellular materials (Wolcott et al. 1989).

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