

# TEMPERATURE AND MOISTURE INFLUENCE ON COMPRESSION-RECOVERY BEHAVIOR OF WOOD

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(Received August 2000)

## ABSTRACT

The primary limitation of non-veneer wood composites for applications in moist environments is dimensional instability. Thickness instabilities from moisture absorption primarily result from damaged cell structures that recover upon absorption of moisture. Previous research has shown that manipulating the pressing parameters involved in the manufacture of non-veneer wood composites (i.e., temperature and moisture) can lead to a more dimensionally stable product. However, the precise phenomena controlling these changes are not fully defined. To understand development of pressing-induced damage, the large strain, compression-recovery behavior of wood and polyurethane (PUR) foam (i.e., as a model system) was studied at a variety of compression temperatures spanning the glassy to rubber transition. The behavior is then related to polymer phase transitions to discern the role of viscoelastic behavior in damage evolution. The elastic modulus ( $E$ ) and yield stress ( $\sigma_y$ ) were used to characterize the elastic region of compression, whereas fractional recovery ( $R$ ) and dissipated energy ( $\Delta E$ ) represented the inelastic component. The PUR foam displayed a distinct glassy plateau region dominated by  $E$ ,  $\sigma_y$ , and  $\Delta E$  as well as low  $R$ . Wood with 22 and 12% MC behaved similarly to the elastomeric PUR foam; however, limits on environmental control prevented testing in the rubbery regime for the 12% MC samples. The  $E$  and  $\sigma_y$  also decreased with increasing compression temperature for oven-dried yellow-poplar. However, in contrast to yellow-poplar with either 12 or 22% MC, an increase in  $\Delta E$  was accompanied by a decrease in  $R$  with increasing compression temperature of the oven-dried yellow-poplar. An apparent change in mechanism occurs when compressing wood at high temperatures without moisture present. This change was attributed to kinetic effects such as thermal degradation or crosslinking reactions.

**Keywords:** Compression, recovery, springback, glass-transition temperature, pressing.

## INTRODUCTION

Non-veneer wood composites are manufactured by forming individual wood elements blended with polymeric resins, into a mat. The mat is subsequently compressed to high strains

with heated platens to form a panel. The large imposed strains cause the cellular structure of the wood constituent to collapse. Upon absorption of moisture, this collapsed cellular structure recovers, thus irreversibly changing the thickness of the panel and degrading its structural integrity. To fully understand dimensional instability, the fundamental phenomena

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of viscoelastic behavior and polymer structure must be defined. Most previous research addressing dimensional instability of non-veneer wood composites has focused on manipulating the parameters involved in the manufacturing process (i.e., temperature, moisture, and adhesive system). Although some of these attempts have been successful at improving panel stability, the vast array of parameters to be tested and the lack of fundamental knowledge have limited the broad applicability of the results.

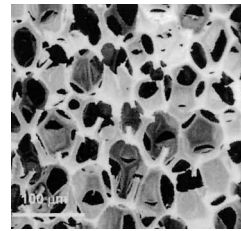
The *in situ* response of wood polymers to temperature and moisture has been defined by others (Kelley et al. 1987; Salmen 1984). The temperature-dependent mechanical behavior of natural and synthetic polymeric cellular materials has also been previously studied (Rosa and Fortes 1988a, b; Meinecke and Clark 1973). By utilizing theories developed to explain the mechanical response of simplified cellular structures under compression and a fundamental understanding of polymer behavior, the response of wood to pressing and subsequent moisture absorption may be more clearly delineated.

In an effort to discern the relationship between cell-wall behavior and of processing-induced damage from composite pressing, this research focuses on the role of moisture and temperature in compression-recovery behavior of yellow-poplar. Synthetic polyurethane foam is used as a model system for qualitative comparisons. The specific objectives are:

1. Corroborate glass transition temperatures with published values,
2. Quantify the elastic and inelastic compression-recovery behavior of yellow-poplar at various temperatures and moisture contents,
3. Qualitatively compare the behavior of wood to that of polyurethane foam for use as a model system, and
4. Relate compression-recovery properties to phase states of the cell-wall polymers.

TABLE 1. *Physical and cellular properties of the flexible polyurethane foam.*

Material	Flexible PUR
Density (g/cm <sup>3</sup> )	0.32
Cell structure	Open
Cell wall thickness (μm)	9.18
Largest cell length, L <sub>1</sub> (mm)	0.5
Intermediate cell length, L <sub>2</sub> (mm)	0.5
Smallest cell length, L <sub>3</sub> (mm)	0.375
Anisotropy ratios	
R <sub>12</sub> = L <sub>1</sub> /L <sub>2</sub>	1.0
R <sub>13</sub> = L <sub>1</sub> /L <sub>3</sub>	1.33
Material fraction in cell edges	1.0
Micrograph	



## MATERIALS AND METHODS

### *Test specimens*

The materials used for this study included a flexible polyurethane (PUR) foam and yellow-poplar (*Liriodendron tulipifera*) sapwood samples. The PUR foam was an open cell foam obtained commercially (Union Carbide, Charleston, WV). A detailed description of the foam and cell properties is presented in Table 1. The yellow-poplar wood samples were obtained from green logs cut into 0.61-m lengths. Boards were then split from the sapwood to optimize ring orientation. The green boards were equilibrated to 0, 12, or 22% nominal moisture content (MC) at standard conditions. The 0% MC samples were dried at 105°C for a period of 48 h and then stored over desiccant until testing. All sample materials were cut into nominal 20-mm cubes with a circular saw. Actual dimensions were measured to the nearest 0.01-mm with a digital micrometer.

### *Thermal analysis*

Both mechanical and calorimetric methods were used to characterize the thermal response

of both wood and PUR materials. The glass transition temperature ( $T_g$ ) for the materials was determined using a differential scanning calorimetry (DSC, Mettler TA300). Large-volume (120- $\mu$ l), medium-pressure (2 MPa), o-ring sealed crucibles were used to minimize moisture loss. The polyurethane foam samples were manually reduced into fine particles with a razor blade. Yellow-poplar samples were ground, screened (passing 80, retained 100 mesh), and environmentally conditioned prior to testing. Materials were initially quenched to either  $-70$  or  $-30^\circ\text{C}$ , conditioned for 10 min, and subsequently heated to  $200^\circ\text{C}$  using a rate of  $10^\circ\text{C min}^{-1}$ .

### *Mechanical testing*

All mechanical testing was conducted using a universal servo-hydraulic testing machine equipped with an environmental chamber capable of controlling both humidity and temperature. Aluminum platens and water-cooled stainless steel extension rods were firmly attached to the load cell and hydraulic ram. The aluminum platens contacting the specimens were machined flat and parallel to 0.25 mm. Specimen displacement was measured with a linear variable differential transformer (LVDT) connected to the platens. To eliminate the error introduced by the deflection in the testing apparatus, a compression test was conducted on the aluminum platens with no specimen present. The load-deflection relationship of the testing apparatus was found to be linear, and the rigid body deflection was subtracted from the overall deflection. All tests were conducted in displacement control with both load and displacement acquired by computer in real time.

The samples were compressed to a target strain of either 0.25 or 0.45 at a constant strain rate of  $0.06\text{-min}^{-1}$  (Easterling et al. 1982; Kasal 1989). To collect hysteretic behavior, the return strain rate was set at  $0.03\text{-min}^{-1}$ . The target strain levels of 0.25 and 0.45 were chosen to represent the mean and extreme strain that

individual flakes undergo during pressing of oriented strandboard (OSB) (Casey 1987).

The yellow-poplar specimens were compressed in the tangential direction. To characterize the potential anisotropic behavior of the foam, compression tests, well below the proportional limit, were conducted in all three principal material directions. From the resulting modulus data, the three principal material directions were noted as 1, 2, and 3. The 1 and 2 directions had very similar modulus values, and the directions were arbitrarily noted on the larger section of foam before cutting the test samples. The 3-direction corresponded to axis of cell elongation, which resulted in an increased modulus value for the PUR foam. All subsequent foam tests were conducted in the 1-direction to remain consistent with the transverse compression of the yellow-poplar.

Environmental conditions around the specimens were regulated during mechanical testing using a microprocessor controlled, temperature-humidity test chamber. Sub-ambient temperatures were achieved by cooling the air flowing into the test chamber with liquid nitrogen. Humidity conditions were regulated in the chamber by direct injection of water vapor in response to humidity determined by a thin-film capacitance sensor.

The specific testing temperatures for each material type are given in Table 2. In all cases, the specific temperatures chosen for mechanical evaluation were selected to encompass different polymer regimes within each material. Samples were allowed sufficient time to reach temperature equilibrium in the test chamber. The environmental chamber was maintained at a minimum relative humidity (ca. 3–5%) when testing the nominal 0% MC yellow-poplar samples. To assist in maintaining moisture in the 22% MC samples during testing, the sample was encased in aluminum foil envelopes with small pieces of water-saturated foam. This produced a saturated environment and maintained the high moisture content of the samples during testing. The weight of the samples was measured immediately prior to and after the tests to ensure

TABLE 2. Temperature conditions used for compression and recovery tests. The glass transition temperature, as measured by calorimetry, is provided as a reference.

Sample material	Compression temperatures (°C)						T <sub>g</sub> (°C)
Flexible PUR	-100	-70	-60	-50	-30	25	-48
Yellow-Poplar							
0% MC	30	60	100	150	220		—
12% MC	35	60	85				63
22% MC	5	35	60	85	99		57

that the desired moisture content was maintained during the test. Samples changing weight during the test were eliminated from the database.

### Analytical techniques

Various attributes of the compression-recovery data were computed to characterize the behavior. Dissipated strain energy was used as a metric of damage and calculated as the hysteresis in the load-recovery stress-strain curve (Shen et al. 2001; Meinecke and Clark 1973). The reality is that dissipated energy includes both a permanent and time-recoverable component. Therefore, the permanent damage constituted by cell-wall fracture and yielding cannot be identified from this research. Dissipated strain energy ( $\Delta E$ ) was calculated by numerically integrating the compression ( $E_c$ ) and recovery ( $E_r$ ) stress-strain curves, using the trapezoidal method and is expressed as a fraction of the compression strain energy:

$$\Delta E = \frac{E_c - E_r}{E_c} = \frac{\int_0^{\varepsilon_{\max}} (\sigma_c - \sigma_r) d\varepsilon}{\int_0^{\varepsilon_{\max}} \sigma_c d\varepsilon} \quad (1)$$

In addition, recovery ( $R$ ) was measured as the total recovered strain ( $\varepsilon_r$ ) following a single compression-recovery cycle and was expressed as a fraction of the total imposed compression strain ( $\varepsilon_{\max}$ ) (i.e.,  $R = \varepsilon_r / \varepsilon_{\max}$ ).

Both  $R$  and  $\Delta E$  are highly dependent on temperature. To relate the temperature-dependency of each parameter to the thermal anal-

ysis, an exponential growth curve was fit to each data set:

$$\chi = \chi_1 + \frac{\chi_2 - \chi_1}{1 + Ce^{kT}} \quad (2)$$

where:

$\chi$  = dependent variable of interest ( $R$  or  $\Delta E$ )

$T$  = temperature (°C)

$C$  and  $k$  are empirical position constants

Subscripts 1 and 2 denote low and high temperature plateau values for the variable

A characteristic temperature ( $T_c$ ) for each property was taken as the inflection point or point of maximum slope in the curve. This can be calculated by setting the second temperature derivative of Eq. (2) to zero and solving for  $T$  or:

$$T_c = \frac{\ln(1/C)}{k} \quad (3)$$

where:  $T_c$  = characteristic temperature for the process

Although not identical to glass transition temperature ( $T_g$ ),  $T_c$  should be similar if the process controlling the temperature-dependency for that variable is similar to that of the phase change.

### RESULTS AND DISCUSSION

During composite manufacture, wood particles are compressed in the transverse direction to large strains. This compression produces yielding in the material as the cell walls

TABLE 3. Characteristic ( $T_c$ ) and glass transition ( $T_g$ ) temperatures (degrees C) for yellow-poplar at various moisture contents and flexible polyurethane foam. Dual values reported by Kelley et al. (1987) were assigned to transitions for hemicelluloses and lignin, respectively.

Material	MC (%)	DSC ( $T_g$ )	DMA ( $T_g$ ) (Kelley et al. 1987)	$\Delta E$ ( $T_c$ )		R ( $T_c$ )	
				$\epsilon_{\max} = 0.25$	$\epsilon_{\max} = 0.45$	$\epsilon_{\max} = 0.25$	$\epsilon_{\max} = 0.45$
Yellow-Poplar	22	57	-3/52	70	65	56	56
	12	63	22/67	111	118	92	103
	0	—	>200	8	255	78	12
Polyurethane	—	-48	—	-50	-47	-60	-56

buckle from either elastic or plastic instabilities. Likewise, a nonlinear recovery curve is produced upon release of the compression load. The exact forms of the compression and recovery curves are dependent on many factors including temperature and moisture content. For amorphous polymeric materials, a significant change in the mechanical behavior should occur for temperatures above and below the  $T_g$  (Billmeyer 1971). For these conditions, the polymer is in the glassy and rubbery phase, respectively. The glassy phase is characterized by high modulus and brittle failure, whereas polymers in the rubbery phase exhibit low modulus and elastic behavior to large strains. For polymeric foams undergoing large strain compression, cell-wall fracture and yielding will dominate the glassy phase and elastic cell-wall buckling will occur when in the rubbery phase. The phase of the polymer and resulting microscopic failure modes will therefore influence the compression-recovery behavior of the material.

#### Polymer phase transitions

Experimental values for  $T_g$  were determined by DSC in this study and are presented in Table 3. In addition,  $T_g$  values for both hemicellulose and lignin as determined with DMA by Kelly et al. (1987) are estimated with the Kwei equation for comparison:

$$T_g = \frac{W_1 T_{g1} + k W_2 T_{g2}}{W_1 + k W_2} + q W_1 W_2 \quad (4)$$

where:  $W$  = weight fraction  
 $k, q$  = adjustable parameters

The  $T_g$  determined for the PUR foam is  $-48^\circ\text{C}$ , which is reasonable for this elastomeric polymer. Since the  $T_g$  of network polymers like polyurethanes are sensitive to cross-link density (Billmeyer 1971), no reported  $T_g$  would be accurate for this material.

The measured  $T_g$  values for the yellow-poplar were  $57^\circ$  and  $63^\circ\text{C}$  for 12% and 22% MC, respectively (Table 3). These temperatures are similar to the values of  $52^\circ$  and  $67^\circ$  reported by Kelley et al. (1987) and  $60^\circ\text{C}$  reported for saturated wood by Salmen (1984). Both researchers assigned these transitions to the  $T_g$  of native lignin. The  $T_g$  for hemicellulose at 22% MC is at cryogenic temperatures and  $22^\circ\text{C}$  for wood at 12% MC (Kelley et al. 1987).

In contrast to the samples at elevated moisture contents, the 0% MC samples exhibit no apparent  $T_g$  in the DSC analysis. Kelley et al. (1987) reported that the  $T_g$  of hemicellulose and lignin for oven-dried samples was well above  $200^\circ\text{C}$ , possibly higher than the thermal degradation temperature of the polymers. Ostberg et al. (1990) conducted DSC scans on moist and oven-dry wood and concluded that due to the low endotherm exhibited by wood, it was not possible to determine a  $T_g$  for oven-dry wood by this method. The same problem was encountered with the DSC scan for oven-dry wood in this study.

#### Linear compression behavior

Both the compression modulus ( $E$ ) and yield stress ( $\sigma_y$ ) of all materials decrease with increasing temperature (Figs. 1 and 2). Like-

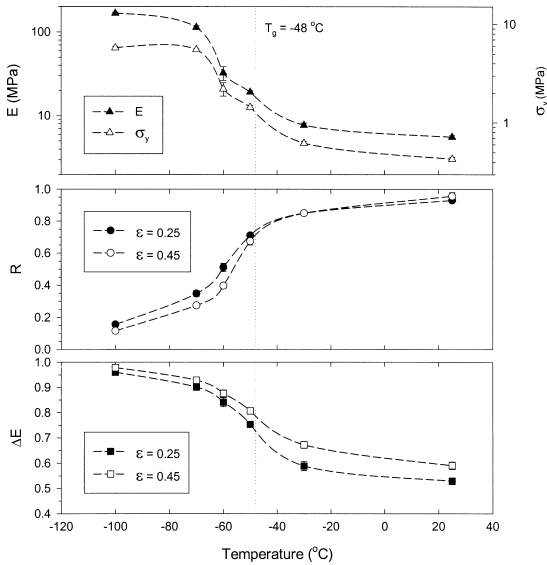


FIG. 1. Elastic and inelastic compression properties of flexible polyurethane foam evaluated at various temperatures.

wise, for yellow-poplar, these parameters decrease with increasing moisture content. The temperature-dependence of  $E$  and  $\sigma_y$  for the PUR foam specimens follow the classical sigmoid shape found in the dynamic modulus data (Fig. 1). Note the dramatic drop in modulus between  $-70$  and  $-30^\circ\text{C}$ , corresponding to the glass transition. The mid-point of the  $E$  and  $\sigma_y$  drop corresponds roughly with the measured  $T_g$  value of  $-48^\circ\text{C}$  (Table 3). Glassy and rubbery plateaus are evident at  $-100$  to  $-70^\circ\text{C}$  and  $-30$  to  $25^\circ\text{C}$ , respectively.

The  $E$  and  $\sigma_y$  curves for the yellow-poplar samples exhibit broader temperature-dependence when compared to the PUR foam (Fig. 2). An upper glassy plateau is evident at  $E$  of the 22% and 0% MC specimens. However, the limited temperature range attainable for the 12% MC specimens encompasses only a portion of the transition regime. Despite this limitation, a significant modulus decrease is noted for the temperatures studied. Like the PUR foam, the measured  $T_g$  values of  $57^\circ$  and  $63^\circ\text{C}$  for 12% and 22% MC, respectively (Table 3), correspond roughly with the center region of the decrease in compression properties. How-

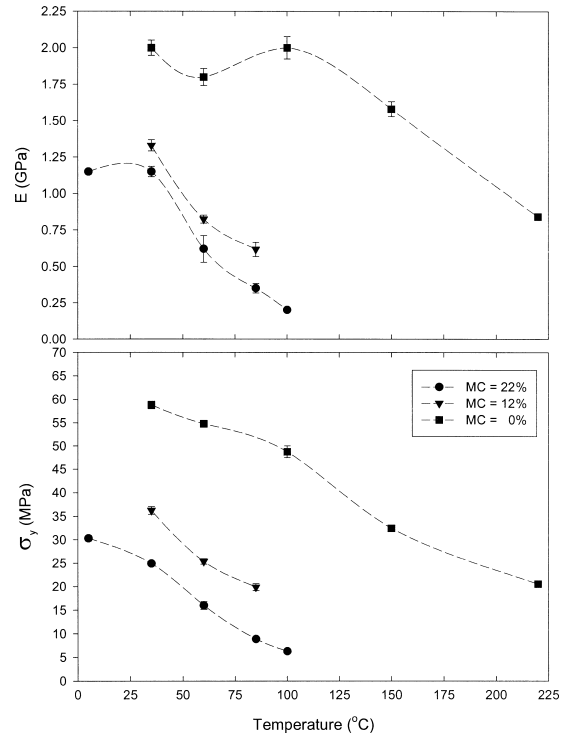


FIG. 2. Elastic compression properties of yellow-poplar evaluated at various temperatures and moisture contents.

ever, no lower rubbery plateau was evident in any of the wood materials tested.

### Inelastic compression-recovery behavior

The fractional recovered strain ( $R$ ) and dissipated strain energy ( $\Delta E$ ) were used to relate the inelastic compression and recovery behavior to the state of the polymers and potential cell-wall damage. A perfectly elastic response would correspond with  $R$  and  $\Delta E$  equal to 1 and 0, respectively. However, the combined effects of viscoelastic behavior of the constituent polymers and cell-wall damage cause deviation from these ideal conditions (Shen et al. 2001). The deviation is particularly noted in  $\Delta E$  even when  $R$  is close to 1.

Exponential growth curves (Eq. 2) were fit to temperature-dependent data for  $R$  and  $\Delta E$  and plotted with the experimental data. The model coefficients (Table 4) were used with



TABLE 4. *Fitted model parameters for the temperature dependence of fractional recovery (R) and dissipated energy ( $\Delta E$ ) of yellow-poplar compressed at different moisture contents and maximum imposed strain ( $\epsilon_{\max}$ ).*

Imposed strain MC	$\epsilon_{\max} = 0.25$			$\epsilon_{\max} = 0.45$		
	22%	12%	0%	22%	12%	0%
$\Delta E$						
$\Delta E_1$	0.4912	0.4200	0.8758	0.5283	0.5191	0.9322
$\Delta E_2$	0.8322	0.9043	0.948	0.8419	0.9294	0.9646
C	0.0023	0.00003	7.38	0.0023	0.00009	27.58
k	0.0870	0.0940	-0.0260	0.0930	0.0790	-0.0310
R						
$R_1$	0.6826	0.3651	0.2081	0.6224	0.2743	0.1288
$R_2$	0.9420	0.9251	0.4588	0.9524	0.9743	0.4291
C	10337	50422	0.1213	9777	53484	0.8443
k	-0.1650	-0.1178	0.0270	-0.1650	-0.1055	0.0138

Eq. (3) to determine characteristic temperatures ( $T_c$ ) for the change in R and  $\Delta E$ , which are presented along with measured and literature  $T_g$  values in Table 3.

**PUR foam behavior.**—Flexible PUR foam, although considered elastic at room temperature, displayed considerable deviations in R and  $\Delta E$  from ideal elastic behavior when compressed at different temperatures (Fig. 1). The R was found to vary from 0.12 to 0.95 for compression temperatures of  $-100$  to  $25^\circ\text{C}$ , respectively. Although the magnitude of change for  $\Delta E$  was less than that of R, the qualitative temperature-dependence was found to be similar but opposite. The  $\Delta E$  was greatest for a compression temperature of  $-100^\circ\text{C}$  ( $\Delta E = 0.96$ ) declining to a value of 0.53 at  $25^\circ\text{C}$ . As with the modulus decrease, the temperature-dependence of both R and  $\Delta E$  is controlled by the phase change in the PUR cell-wall material centered at  $T_g = -48^\circ\text{C}$ . The relative independence of both R and  $\Delta E$  on  $\epsilon_{\max}$  indicates that a single failure mechanism is controlling across the strain levels of 0.25 to 0.45. The cell-wall fracture and yielding, indicative of large strain compression of glassy polymer foams, result in a large amount of dissipated energy and a low degree of recovered strain. In contrast, the elastic behavior of the same polymer in the rubbery state, results in decreased dissipated energy and increased recovery at elevated temperatures.

Scanning electron micrographs (SEM) (Fig.

3) of samples compressed at  $-100^\circ\text{C}$  confirm that cell-wall fracture dominated the cell collapse mechanisms in this glassy state. However, samples compressed at temperatures above  $-70^\circ\text{C}$  showed no plastic hinge or brittle fracture in the cell walls, appearing virtually identical in microstructure to the uncompressed samples. The dominance of elastic collapse even in the low temperature range of the transition region highlights the role of viscoelastic properties for inelastic deformation and recovery.

An interesting observation emphasized the role of viscoelastic properties in the time-dependent recovery of the PUR foam. Samples compressed at  $-60^\circ$  and  $-50^\circ\text{C}$  experienced significant residual strain following the compression-recovery cycle. However, upon removal from the cryogenic temperatures of the environment chamber, recovery of the original dimensions was immediate. This behavior was not evident with samples dominated by cell-wall fracture and yielding. The observed recovery phenomenon may be similar to the extreme thickness swell experienced by strands in many OSB panels where the moisture change mimics the role of temperature in accelerating the viscoelastic response (Wolcott et al. 1995). It is possible, that the mode of failure may also result in varying properties of the foam after compression, including swelling-induced recovery of the compressed

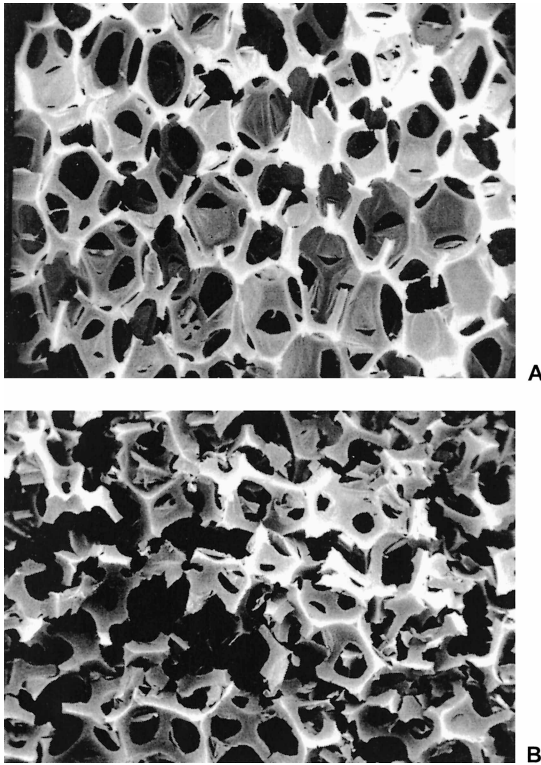


FIG. 3. Scanning electron micrographs of flexible polyurethane foam specimens before (A) and after (B) compression at  $-100^{\circ}\text{C}$ . Cell-wall fracture is noted in the material following compression.

strain, specific strength, creep, and load-duration effects.

**Yellow-poplar behavior.**—The recovery and dissipated energy behavior of yellow-poplar specimens compressed at various temperature and moisture contents are presented in Fig. 4. As with the PUR foam, the  $R$  and  $\Delta E$  of the 12 and 22% MC yellow-poplar samples exhibited qualitatively similar and opposite trends with respect to compression temperature. The 22% MC samples displayed distinct high and low temperature plateaus for  $R$ . A low temperature plateau was also evident in the  $\Delta E$  curves; however, a high temperature counterpart was absent over the range of environmental conditions evaluated. In comparison to the PUR foam, the range of observed  $R$ -values was greatly reduced. This phenomenon could be caused by several factors in-

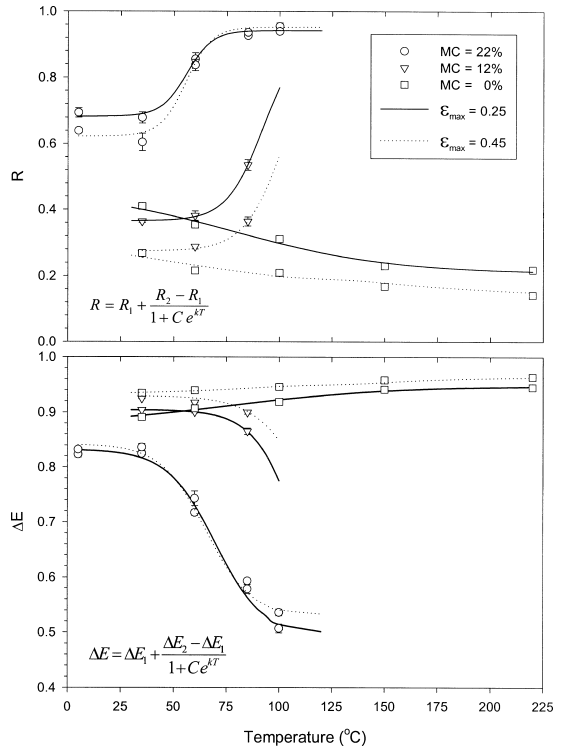


FIG. 4. Inelastic compression properties of yellow-poplar evaluated at various temperatures and moisture contents.

cluding (1) the presence of reinforcing cellulose micro-fibrils not participating in the transition, (2) the plasticization attributed to bound moisture in the wood, or (3) the role of hemicelluloses in the rubbery phase.

The 12% MC samples exhibited similar but less pronounced transitional behavior to that of the 22% MC samples. In general, the decrease in moisture content resulted in lower recovery and greater dissipated energy when compared to the 22% MC samples. The form of the entire curve was shifted up approximately  $30^{\circ}\text{C}$ . Note also the absence of the high temperature plateau in the  $R$  and  $\Delta E$  curves, which might have been realized if equilibrium moisture conditions could have been maintained at elevated temperatures.

Although the oven-dried yellow-poplar was tested across a wide temperature range, the trends for  $R$  and  $\Delta E$  were the opposite of that



for the moist wood samples and flexible PUR. Interpretation of this behavior suggests that different mechanisms may prevail in the absence of moisture. Previous researchers have also reported a decrease in recovery at elevated temperatures for oven-dried wood samples and attributed the phenomenon to lignin flow (Higgins 1946, 1953; Seborg and Stamm 1941); although this hypothesis has never been tested. Compression-recovery behavior of the 22% MC wood distinctly indicates glassy and rubbery plateaus. These findings are indicative of a structure similar to crosslinked synthetic polymers. The different compression-recovery behavior of the oven-dried yellow-poplar can be attributed to either (1) kinetic effects (e.g., thermal degradation or chemical reactions), or (2) a wood polymer structure that is altered with significant amounts of bound water.

Gardner et al. (1992) presented additional evidence of kinetic polymer phenomenon occurring when wood is pressed at high temperatures and low moisture contents. Using X-ray diffraction, cellulose crystallinity was found to increase slightly for wood strands pressed with either a heat or steam treatment. However, results of solid-state NMR analysis indicated that when wood was heated without water present, cleavage of the alkyl-aryl ether bonds in lignin occurred, resulting in the formation of free phenolic groups in the lignin polymer structure. Plagemann et al. (1984) studied the response of hardwood flakes and flakeboard to high-temperature drying, noting that total acid content of the flakes increased with increasing temperature. This acid production might be consistent with the conditions needed to catalyze hemicellulose degradation (Biermann et al. 1984; Schultz et al. 1983; Lora and Wayman 1978).

Scanning electron micrographs (Fig. 5) illustrate that different mechanisms contribute to the compression-recovery behavior of moist and oven-dried wood samples. Note that the sample compressed at 35°C/12% MC and 30°C/0% MC exhibit cell-wall fracture and yielding. The primary distinction between the two micrographs is that the cell walls of the

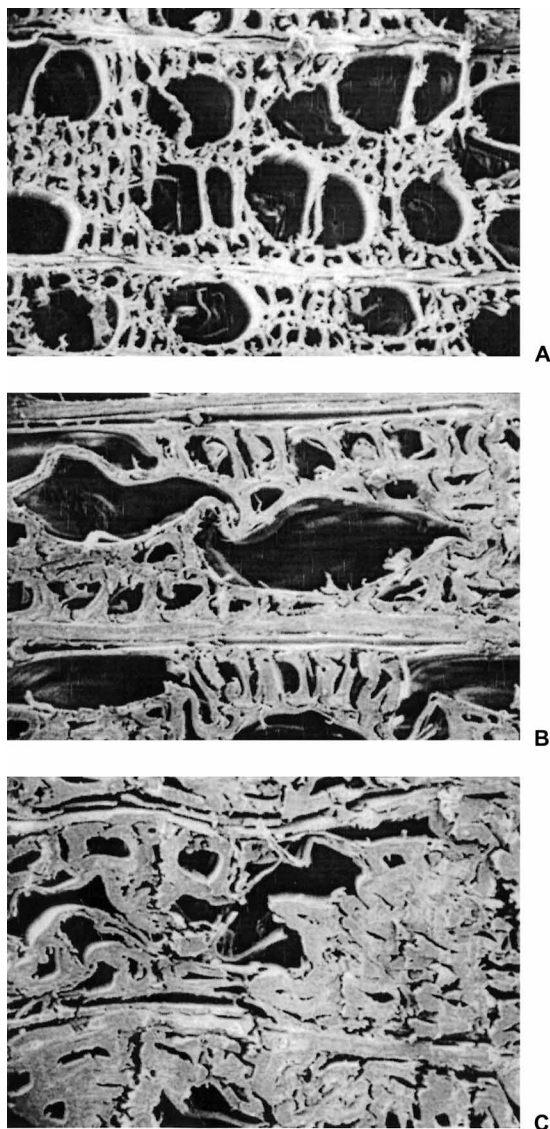


FIG. 5. Scanning electron micrographs of yellow-poplar specimens (12% MC) before compression (A) and following compression at 85°C (B) and 35°C (C). Elastic buckling and fracture of the cell walls is evident in B and C respectively.

oven-dry sample appear to have buckled elastically but did not recover upon removal of the compressive force. In contrast, the samples compressed at 22% MC appear relatively unchanged for the uncompressed wood. Interpretation of these observations suggests that the presence of moisture in wood substantially al-

ters the wood polymer behavior at elevated temperatures resulting in either kinetic effects or altered polymer structures.

#### *Effect of strain level on recovery*

The absolute values for recovery and dissipated energy should increase with the maximum applied strain ( $\epsilon_{\max}$ ); however, for both modeling and material behavior reasons, we are interested in the fractional values of  $R$  and  $\Delta E$ . The simplest case for modeling purposes would be constant values for  $R$  and  $\Delta E$  over the range of  $\epsilon_{\max}$  values typically found in panel consolidation. In fact, both Koch (1964) and Kunesh (1961) found this condition to be approximately true for the range of  $0.05 < \epsilon_{\max} < 0.45$ . Here, this behavior was also noted for the PUR foam compressed to  $\epsilon_{\max}$  levels of 0.25 and 0.45 (Fig. 1). For yellow-poplar, however, this condition was evident only for specimens compressed at 22% MC (Fig. 4).

At all moisture content values studied, the temperature-dependent trends of  $R$  and  $\Delta E$  were found to be similar when the specimens were compressed to  $\epsilon_{\max}$  values of 0.25 and 0.45 (Fig. 4). However, subtle but definite differences existed for certain conditions. Both the  $R$  and  $\Delta E$  values of the 22% MC specimens were extremely close for all temperatures. With specimens compressed at MC values of 12% and 0%, increased compression strain resulted in lower values of  $R$  and higher values of  $\Delta E$ . Interpretation of these results indicates that at conditions conducive to elastic, rubbery behavior, the amount of damage appears to be proportional to the applied strain. These conditions are most prominent in the high moisture content, high temperature samples when the material is definitely above  $T_g$  of both polymers. However, at brittle conditions, the material appears to be more sensitive to the amount of compression strain, possibly producing more or different modes of damage to the wood cells.

From a practical standpoint, both  $R$  and  $\Delta E$  might be modeled assuming strain independence. Ignoring the small dependence of  $R$

and  $\Delta E$  on applied strain level would allow a single temperature-dependent relation to be used when modeling the pressing operation.

#### CONCLUSIONS

The compression-recovery behavior of cellular polymeric materials can be attributed to the combination of the cellular structure and properties of the cell-wall polymers. The influence of temperature and moisture can be attributed primarily to the changes occurring in the viscoelastic nature of the cell-wall polymers since these variables should have little influence on the cell structure. The compression-recovery behavior of PUR foam and yellow-poplar at various moisture contents was examined through the temperature-dependence of elastic parameters such as  $E$  and  $\sigma_y$  and measures of inelastic behavior of fractional recovery ( $R$ ) and dissipated energy ( $\Delta E$ ).

All of the elastic and inelastic properties of PUR foam exhibited a classical sigmoidal function with temperature. Distinct low and high temperature plateaus were noted, corresponding to the glassy and rubbery polymer phases, respectively. An increasing  $R$  and decreasing  $E$ ,  $\sigma_y$ , and  $\Delta E$  with temperature exemplified this behavior. All of these trends are approximately centered on the  $T_g$  as measured by DSC at  $-48^\circ\text{C}$ . Compression in the glassy phase results in a high  $E$ ,  $\sigma_y$ , and  $\Delta E$  with a correspondingly low  $R$ . In contrast, the rubbery phase results in low  $E$ ,  $\sigma_y$ , and  $\Delta E$  with a correspondingly high  $R$ .

Yellow-poplar at 22% MC behaved qualitatively similar to the PUR foam, the only wood MC where distinct glassy and rubbery plateaus were noted. Although the 12% MC yellow-poplar exhibited a distinct glassy plateau, limitations on temperature and humidity control prevented the verification of a rubbery plateau. It is notable that with moisture present, the wood acted similarly to a crosslinked polymer system where increased temperature produced significant increases in elastic behavior.

In contrast, oven-dried yellow-poplar react-

ed differently to temperature than any of the other systems tested. Without moisture present,  $E$  and  $\sigma_y$  decreased with increasing temperature as with other wood materials; however, as temperature increased,  $R$  decreased and  $\Delta E$  increased. The combination of softening, increased energy dissipation, and decreased recovery with compression-recovery at increased temperatures indicates a change in the polymer behavior without moisture present. From purely the mechanical results, the different behavior can be attributed either to an increased thermoplasticity (i.e., lignin flow) or kinetic factors (e.g., thermal degradation or crosslinking) of the wood polymers. Findings by others suggest that kinetic factors are the most likely factors controlling the behavior.

Brittle cell-wall fracture was characteristic of PUR foam and yellow-poplar compressed in the glass region. Elastic cell-wall buckling occurred for PUR foam at ambient temperatures and 22% MC at above 80°C. The elastic behavior resulted in increased  $R$  and decreased  $\Delta E$ , supporting the notion that the cell-wall polymers were in the rubbery phase.

From a practical standpoint, these results might be extrapolated to pressing of wood-based composites undergoing densification (e.g., OSB and particleboard). Damage to the wood component would be minimized by maintaining high moisture conditions through the pressing cycle. These same conditions would facilitate recovery and minimize the potential for swelling of the panel with field exposure to moisture. Compression at high temperatures and low moisture content appears to result in kinetic changes in the cell-wall polymers that may produce a stable compressed structure; however, long-term or moisture stability need further evaluation.

#### ACKNOWLEDGMENTS

The authors gratefully acknowledge the research funding by the USDA National Research Initiative and the USDA/CSREES Wood Utilization Special Grants Program.

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