RHEOLOGICAL BEHAVIOR OF DOUGLAS-FIR PERPENDICULAR TO THE GRAIN AT ELEVATED TEMPERATURES[1]

Qinglin Wu[2]

Research Associate
Department of Forestry
Michigan State University
East Lansing, MI 48824

and

Michael R. Milota

Assistant Professor
Department of Forest Products
Oregon State University
Corvallis, OR 97331

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ABSTRACT

The rheological properties of Douglas-fir lumber under tangential tension and compression were investigated with a small testing machine in a pressure vessel. The strain fields for matched test samples were monitored remotely with a high-resolution video camera. The required steady- and unsteady-state equilibrium moisture contents (EMCs) were achieved by controlling the total pressure in the absence of air. The moisture content (MC) was monitored with a quartz spring sorption balance. Creep at a constant MC of 10% and mechano-sorptive (MS) effect during drying were measured for temperatures up to 82 C.

The results indicated that the MS strain is the dominant component of the stress-induced strain in drying of small wood samples under load. At 65.6 C, the MS strain in compression along the tangential direction was about three times larger than that in tension under the same stress level and MC change. An increase in temperature from 32.2 C to 82 C led to an increase in MS strain under compression. Constitutive equations quantifying the combined effect of mechanical loading and moisture change were developed and fit to experimental data, and material parameters for various strain components were evaluated.

Keywords: Creep, drying, Douglas-fir, mechano-sorptive effect, shrinkage, tension, compression.

INTRODUCTION

The rheological properties of wood perpendicular to the grain are of fundamental importance to understanding the mechanical behavior of wood in drying and to controlling drying-related defects. However, useful mathematical models to describe the behavior as a function of stress, temperature, moisture content (MC), and MC change have not been developed. This is due mainly to a lack of systematic experimental data on various components of the total deformation. Recent models of drying stress (e.g., Salin 1992) have shown that drying stress could be predicted more realistically if material parameters describing such components were known.

We investigated the rheological properties of Douglas-fir under tangential tension and compression. Our objective was to experimentally characterize the constitutive relations describing wood deformation under different combinations of mechanical loading and moisture change at elevated temperatures.

[1] This is paper 3005 of the Forest Research Laboratory, Oregon State University, Corvallis, OR.

[2] At the time this work was done, the author was a Research Associate, Oregon State University, Corvallis, OR.

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BACKGROUND

The large inelastic strain in drying wood is the sum of four components: instantaneous strain, creep strain, shrinkage strain, and mechano-sorptive (MS) strain (Leicester 1971; Ranta-Maunus 1975; Rice and Youngs 1990). Mathematical modeling of internal stress development in wood during drying requires detailed knowledge about each strain component.

Constitutive equations to quantify strain under combinations of mechanical loading and moisture change have been formulated by Leicester (1971) and Ranta-Maunus (1975). These models all represent the four strain components as separately measurable and linearly additive, so the total strain rate is given by

$$\dot{\epsilon}_T(t) = \dot{\epsilon}_I(t) + \dot{\epsilon}_C(t) + \dot{\epsilon}_S(t) + \dot{\epsilon}_M(t) \qquad (1)$$

where

$\dot{\epsilon}_T$ = total strain,
$\dot{\epsilon}_I$ = instantaneous strain,
$\dot{\epsilon}_C$ = creep strain,
$\dot{\epsilon}_S$ = shrinkage strain,
$\dot{\epsilon}_M$ = mechano-sorptive strain,
t = time (min),

and the overdot represents the time derivative; all components are expressed as mm/mm.

Instantaneous strain is produced immediately after the application of a load. Its magnitude depends on temperature and MC of the wood and the magnitude and direction of the stress. Under a general stress history, instantaneous strain rate is related to stress rate by

$$\dot{\epsilon}_I(t) = D_I\, \dot{\sigma}(t) \qquad (2)$$

where D_I = instantaneous compliance (MPa^{-1}), and σ = stress (MPa). D_I varies with MC, temperature, and stress. In the linear range, D_I is independent of stress and is the reciprocal of the modulus of elasticity. Early studies on mechanical properties perpendicular to the grain concentrated on instantaneous behavior (e.g., Youngs 1957), but this information by itself is insufficient for modeling drying stresses (Salin 1992).

Creep strain is the time-dependent portion of the total deformation resulting from imposed stress. The effects of constant temperature, stress, and MC on creep properties of wood have been widely studied (Schniewind 1968; Grossman et al. 1969). Increases in temperature, stress, and MC increase creep strain radially and tangentially (Youngs 1957; Schniewind 1966). Under certain stress and strain conditions, creep behavior can be represented by linear viscoelastic theory (Schniewind and Barrett 1972). The creep strain of wood under constant stress and MC has been most commonly fitted (Youngs 1957; Schniewind 1968) with the power law equation,

$$\epsilon_C(t) = k_C \sigma t^{nc} \qquad (3)$$

in which the material constants, k_C (MPa^{-1}) and n_C, vary with temperature, MC, and stress.

Creep is greater at higher MC; however, no well-accepted methods are available to predict creep as a function of MC as MC changes. Attempts to use time-MC superposition, a procedure analogous to time-temperature superposition, have been questioned (Schniewind 1968) because the assumption that no significant structural changes occur may be violated when moisture enters or leaves the cell wall. Grossman et al. (1969) showed that relative creep, the ratio of creep strain, ϵ_C, to initial instantaneous strain, ϵ_I, did not vary strongly with MC if MC did not change with time. They suggested expressing the creep function as a product of the relative creep (ϵ_C/ϵ_I), which is obtained at a reference MC (M_O) and is moisture independent, and the instantaneous deformation, ϵ_I, which is moisture dependent, so that

$$\epsilon_C(t, M) \approx \left[\frac{\epsilon_C(t, M_0)}{\epsilon_I(M_0)}\right]\epsilon_I(M) = \frac{D_I(M)}{D_I(M_0)}\epsilon_C(t, M_0) \qquad (4)$$

where M and M_0 (%) are the current and reference MC, respectively, and the instantaneous strain is expressed as the product of the stress and the instantaneous compliance. When the MC changes from M_1 to M_2, creep can be approximated as

$$\epsilon_C(t, M_1 \rightarrow M_2) = \int_{t_1}^{t_2} \frac{\partial[\epsilon_C(t, M)]}{\partial t} dt \quad (5)$$

where M_1 and M_2 are the MCs at time t_1 and t_2, respectively, and $\epsilon_C(t,M)$ corresponds to various constant MCs defined by Eq. (4).

The free shrinkage strain is the dimensional change resulting from moisture loss in absence of restraint. The rate of shrinkage strain, $\dot{\epsilon}_S$, is proportional to the rate of moisture change, $\dot{M}(t)$, so that

$$\dot{\epsilon}_S(t) = k_S \dot{M}(t) \quad (6)$$

where the shrinkage coefficient, k_S (% MC^{-1}) may vary with the moisture content, but is independent of stress.

Mechano-sorptive strain is due to an interaction between stress and MC change (Armstrong and Kingston 1962; Schniewind 1968). It is independent of time and does not occur during steady-state moisture movement (Armstrong 1972). In tension and compression, the effect is seen as a decrease or increase in the amount of shrinkage. Using Japanese hinoki wood under tangential and radial tension at 80 C, Takahashi and Yamada (1966) showed that the reduced shrinkage, mostly MS strain, increased with an increase in the applied load. Hisada (1979, 1980) showed the MS strain in makanba (*Betula maximowicziana* Reg.) and hinoki (*Chamaecyparis obtusa* Endl.) woods in tension and compression at 20 C to be proportional to stress. Above the proportional limit, MS strain was greater in compression than in tension. Rice and Youngs (1990) found a large MS strain in drying red oak under tension at 43.3 C. Schniewind (1966) demonstrated that the MS strain in beech wood in tangential tension at 20 C varied linearly with MC, that is, for a given change in MC the change in strain was independent of the MC within the hygroscopic range.

Test data for the effect of temperature on MS deformation are more conflicting. Hearmon and Paton (1964) and Schniewind (1966) showed that the temperature at which MC changed had no substantial effect on the deformation. Hisada (1981) and Erickson (1989), however, found that MS strain under a constant stress increased with temperature.

Measurement of MS deformation requires careful control of MC change. In larger specimens, however, moisture gradients occur, and only a mean MC is known. Christensen (1962) demonstrated that moisture gradients can be minimized by testing small specimens in the absence of air, where moisture content is controlled by the temperature and the water vapor pressure.

The rate of MS strain as a function of stress and MC change was expressed by Leicester (1971) as

$$\dot{\epsilon}_M(t) = k_M \, \sigma \, |\dot{M}(t)| \quad (7)$$

where the constant for MS strain, k_M (MPa^{-1} % MC^{-1}) may vary with moisture content, temperature, and stress.

Equations (1) to (7) can be combined to form a general model to predict the perpendicular-to-grain rheological behavior of wood under load during moisture content change if sufficient data for the material constants are available.

EXPERIMENTAL PROCEDURE

Test specimens

A piece of green, flatsawn Douglas-fir (*Pseudotsuga menziesii*) lumber (50.8 mm by 203.2 mm by 4.8 m) was obtained from a local mill. The wood was cut into four 1.2-m-long pieces, which were wrapped in plastic and frozen to preserve their freshness until needed. Two of the 1.2-m-long boards were dried to 12% MC using a mild kiln schedule. The other two were used green. Before samples were cut, approximately 12.7 mm of wood was planed off each 203.2-mm face to remove any surface checks or, in the case of the green half-boards, surface dryness that may have occurred unintentionally.

Three end-matched samples were prepared for each test. The sample for loading (Fig. 1) was cut with the growth rings parallel to the long axis of the sample and the end grain exposed on the wide face. This was done to facilitate rapid moisture equilibrium and to minimize internal moisture gradients. Shrinkage and MC samples were cut with the same thickness as the sample for loading so MC would change at the same rate. Circular reference dots (0.5 mm in diameter) for strain measurement were placed on the samples for loading and for shrinkage with transfer letters. All samples were weighed before and after testing and after oven-drying; MC was determined gravimetrically.

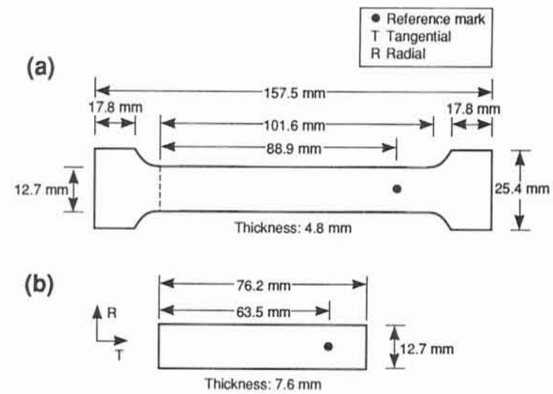

FIG. 1. Test specimens under (a) tension and (b) compression.

Experimental setup

The testing apparatus (Fig. 2) was constructed to apply a load and measure strain in one sample, measure the strain in an unrestrained sample, and monitor the moisture content of a third sample simultaneously while controlling temperature and relative humidity.

A constant load was applied to the test specimen with steel weights. In tension, two miniature grips transferred tensile force to the specimen. The top grip was fixed to the supporting frame, while the bottom grip was free to move. In compression, a small pressing frame allowed the top grip to move as the load was applied, while the bottom grip was stationary. The weights were lowered or raised by a double-acting pneumatic piston-cylinder unit.

The specimen for monitoring wood MC was suspended from a quartz spring within a tubular safety sight glass. The sensitivity of the spring was 10 mm/g; the change in position of a reference pointer on the spring was read with a cathetometer with an accuracy of ± 0.01 mm.

The strain of the loaded and shrinkage specimens was remotely monitored with a charge-coupled device (CCD) camera (resolution 768 by 494 pixels), image capture board [AT&T Truevision® Advanced Raster Graphics Adapter (TARGA) 16], a personal computer, and in-house scanning software (Irving 1989). The strain measurement was based on the movements of the reference dots on the test samples relative to two stationary points preset on a separate steel specimen at specified distances from the top grip line. Comparison of the positions of the reference dots before and after load application resolved the strain caused by load, MC or both to an accuracy of $\pm 5 \times 10^{-5}$ mm/mm. The details of the algorithm are in Wu (1993).

After the specimens had been mounted in the loading frame, a stainless-steel cylinder was lowered over them. Temperature was measured with thermocouples. The energy supplied to three band heaters and one disc heater was controlled by a proportional-integral-differential (PID) temperature controller and a solid-state relay. The relative humidity was controlled by admitting steam to the vessel through a pneumatic valve and removing air and water vapor with a vacuum pump. A second PID pressure controller operated the valve in response to a signal from a pressure transducer. Commercial PC-based process control software (Control EG 1989) was used to ramp and maintain the temperature and pressure.

Test conditions

Creep was tested at a constant 10% MC at 32.2, 48.9, 65.6, and 82.2 C. The stress level was 0.827 MPa in tension and 0.552 MPa in compression. The applied stress as a percentage of the estimated tangential strength of Douglas-fir (USDA Forest Service 1987; Palka 1973) varied from 40% to 60% and 26% to 40% in tension and compression, respectively,

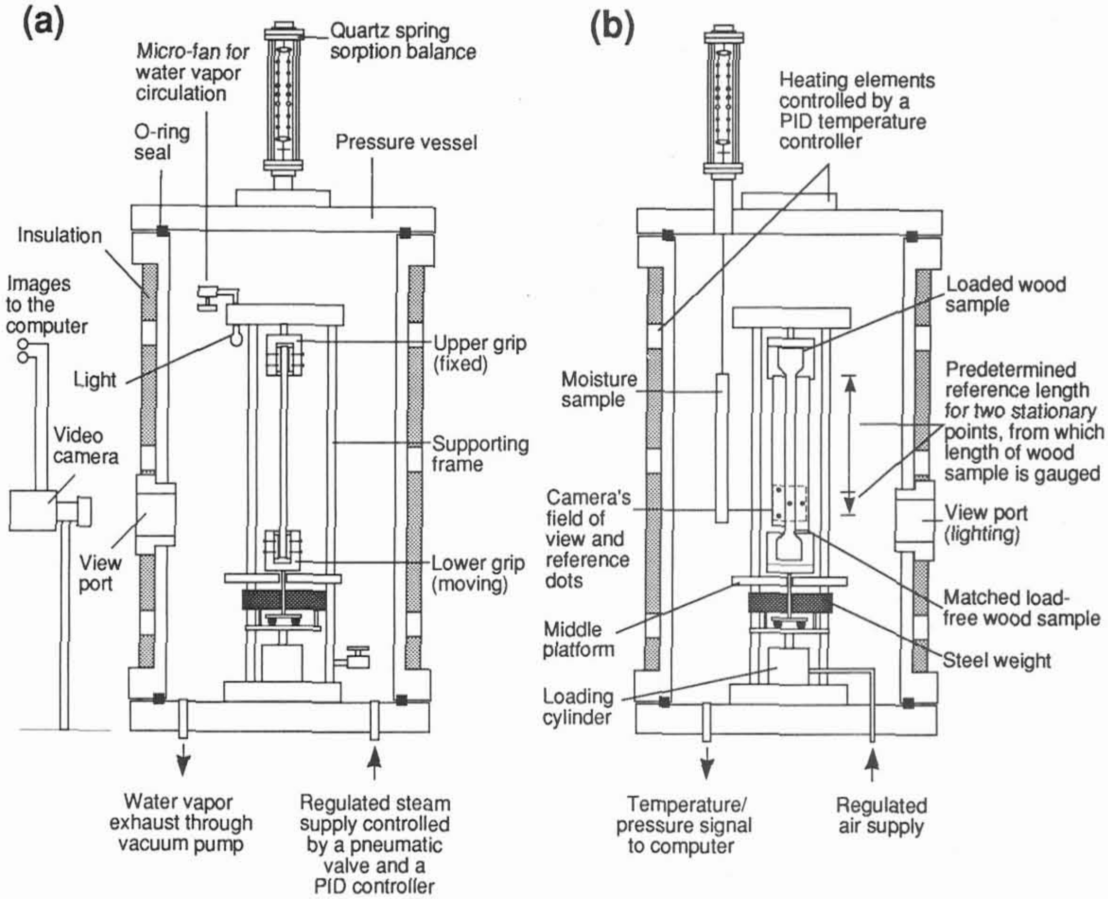

FIG. 2. Testing apparatus configured for tension, shown in (a) side view and (b) front view.

over the range of temperature. Each temperature and stress combination was replicated, for a total of 16 tests.

Mechano-sorptive strain was measured while the MC changed from 25% to 5%. At 65.6 C, three levels of constant stress (0.413, 0.621, and 0.827 MPa) were used in tension and three levels (0.276, 0.413, and 0.552 MPa) in compression. Tests were also conducted at a stress level of 0.552 MPa in compression and temperatures of 32.2, 48.9, 65.6, and 82.2 C. Two or three replications were done at each condition.

Test procedure

After the test specimens had been prepared and mounted, the vessel was sealed and heated to the desired temperature. Simultaneously, air was evacuated and the pressure of the water vapor in the vessel was brought to the initial EMC (10% for creep tests, 25% for MS tests). This condition was maintained long enough to allow the entire system to reach a steady state before the load was applied.

The initial deformation was measured 0.2 min after load application. In creep tests, the initial load and vessel pressure were maintained for 10 h. In MS tests, the vessel pressure was linearly decreased over 6 to 7 h to obtain a 5% EMC. Deformation of matched specimens and the weight of the MC sample were monitored continuously.

Material properties

Instantaneous compliance.—The instantaneous compliance, D_I, was calculated from the stress-strain data collected in both the creep and the MS tests. The strain, ϵ (mm/mm), at 0.2 min after load application was used, so that

$$D_I = \frac{\epsilon(0.2)}{\sigma} \tag{8}$$

where the stress, σ (MPa), is based on the initial dimensions of the specimen.

Creep strain.—The coefficients for creep strain were determined by fitting the mean strain-time curve with least-squares regression using

$$\frac{\epsilon(t)}{\sigma} = D_I + k_C t^{n_C} \tag{9}$$

where D_I is the observed instantaneous compliance, k_C (MPa^{-1}) and n_C are the constants for creep strain, and t is time (min).

Shrinkage strain.—The shrinkage coefficient, k_S (% MC^{-1}), was determined from the unrestrained specimen during the MS tests. Two values for k_S in Eq. (6) were obtained by linear regression, one for use above and one for use below 20% MC.

MS strain.—The MS strain was calculated by subtracting the other three strain components from the total strain of the loaded specimen. The stress-induced strain was obtained first by subtracting the shrinkage strain (Eq. 6) from the total strain. The instantaneous strain measured during tests and the calculated creep strain were then subtracted from the stress-induced strain to obtain the MS strain at each time during the test. The creep strain as a function of time at different moisture contents was obtained from Eq. (3) and Eq. (4) with the fitted creep parameters at the reference moisture content (10%) and measured instantaneous compliances. The obtained creep functions were then used in Eq. (5) to calculate the creep strain as a function of MC. Integration was done by summing the creep increments obtained from the creep functions corresponding to different MCs among different time steps. The coefficient k_M (MPa^{-1} % MC^{-1}) for each test condition was obtained by fitting Eq. (7) to the obtained MS strain and MC data by least-squares regression.

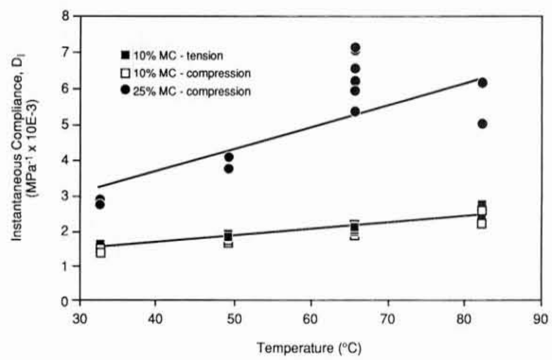

FIG. 3. Instantaneous compliance as a function of temperature, showing results of a linear fit.

Finally, regression analysis was used to express the obtained material properties as a function of temperature, stress, or both at a given MC.

RESULTS AND DISCUSSION

Instantaneous compliance

The values of D_I in tension and compression at 10% MC were similar and increased with temperature (Fig. 3). Regression analysis on the compliance data at 10% (Fig. 3) yielded

$$D_I(T, 10\%) = D_I(32.2, 10\%) \cdot [1 + 0.01259(T - 32.2)] \quad R^2 = 0.77 \tag{10}$$

where $D_I(32.2, 10\%) = 1.54 \times 10^{-3}\ MPa^{-1}$ represents the compliance data at 32.2 C and 10% MC, and T is temperature in C. A similar regression on the data taken at 25% MC (Fig. 3) yielded

$$D_I(T, 25\%) = D_I(32.2, 25\%) \cdot [1 + 0.01859(T - 32.2)] \quad R^2 = 0.61 \tag{11}$$

where $D_I(32.2, 25\%) = 3.26 \times 10^{-3}\ MPa^{-1}$. The coefficient for the effect of temperature at 25% MC (0.01859 C^{-1} in Eq. 11) is about 45% higher than that at 10% MC (0.01259 C^{-1} in Eq. 10). Thus, the influence of temperature on instantaneous compliance is greater at higher MC.

To estimate D_I at MCs and temperatures between those tested, Eqs. (10) and (11) are

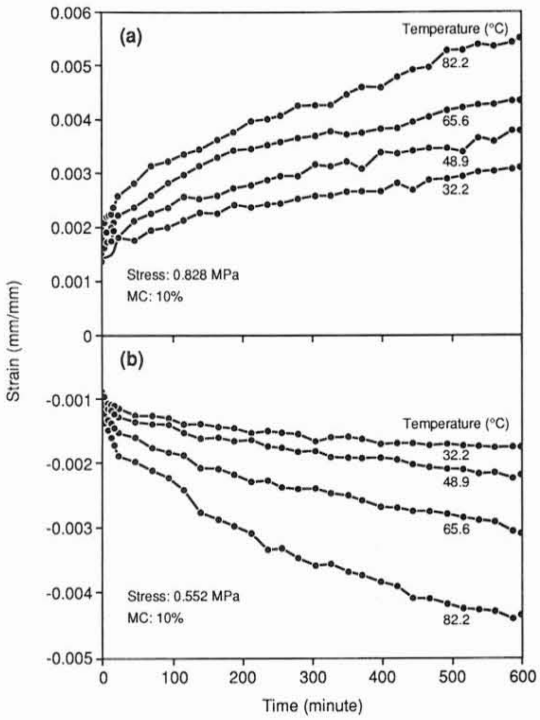

FIG. 4. Creep strain as a function of temperature under (a) tension and (b) compression.

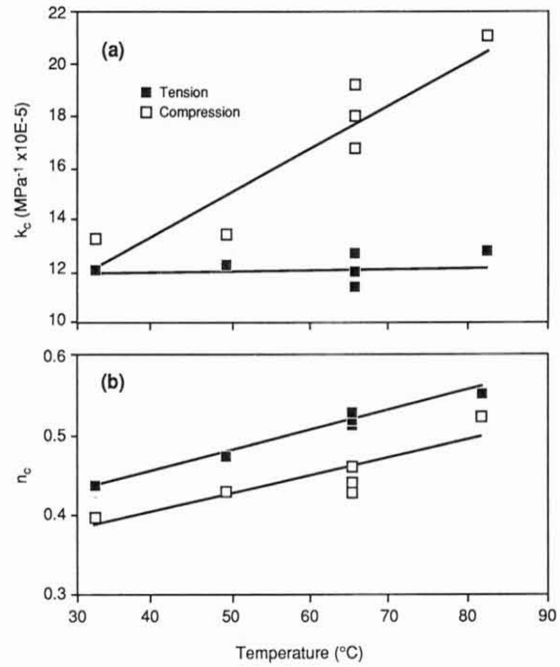

FIG. 5. Creep parameters as a function of temperature, showing result of a linear fit of (a) k_C and (b) n_C.

used to determine D_I at the desired temperature and 10% and 25% MC, respectively. Then D_I at the desired MC is obtained by linear interpolation, with the assumption that D_I is linear with MC (Palka 1973).

Creep strain

Under constant stress, creep strain was greater at higher temperatures (Fig. 4), indicating a strong dependence on temperature. The increase was greatest between 65.6 C and 82.2 C, especially under compression loading (Fig. 4b), which suggests a behavior transition within the temperature step.

Wood as a polymer presents a glass transition in its rheological behavior over a certain temperature range. Salmén (1975) and Kelly et al. (1987) found the glass transition temperature for both lignin and hemicellulose to be 200 C at 0% MC. The temperature for lignin decreases with increasing MC, but starts to plateau at 71.1 C near 10 to 15% MC. The transition temperature for hemicellulose, however, continues to decrease with increasing MC, reaching −20 C near 30% MC. Thus, the observed increase in the creep strain between 65.6 C and 82.2 C may be due to the glass transition that occurs in wood.

The creep data followed the power law relationship with time (Eq. 9). Regression analysis for the material constants, k_C and n_C, in tension (Fig. 5) yields

$$k_C(T) = 11.8 \times 10^{-5} + 4.05 \times 10^{-8}T$$

$$R^2 = 0.01 \tag{12}$$

$$n_C(T) = 0.363 + 0.00237\ T$$

$$R^2 = 0.94 \tag{13}$$

where temperature, T, is from 32.2 to 82.2 C.

In compression (Fig. 5) these relations become

$$k_C(T) = 7.05 \times 10^{-5} + 1.62 \times 10^{-6}T$$

$$R^2 = 0.83 \tag{14}$$

$$n_C(T) = 0.323 + 0.00207T$$
$$R^2 = 0.76 \qquad (15)$$

In tension, k_C did not vary with temperature, whereas in compression it increased linearly with temperature (Fig. 5a). Values of k_C at 32.2 C were similar in tension and compression, diverging at higher temperatures. An increase in temperature led to an increase of n_C for both loading modes (Fig. 5b), and n_C was higher in tension than compression. Apparently, k_C in tension is independent of temperature, which is not easily explained. The material constants have no basis in physical reality. However, their correlations with temperature are valuable for prediction purposes. To estimate creep strain at a desired temperature and MC within the experimental range, k_C and n_C are calculated from Eqs. (12) and (13) or (14) and (15). These are used in Eq. (3) to obtain ϵ_C for 10% MC and the desired temperature. Equation (4) is then used to adjust ϵ_C to the desired MC, using the ratio of D_I at the desired MC to that at 10% MC.

Shrinkage strain

Tangential shrinkage of Douglas-fir started at 25% moisture content (Fig. 6). From 25% to 20% MC, the shrinkage per unit change in MC increased, then became constant. Thus, the shrinkage-MC curve was divided into two parts: one above and one below 20% moisture content. A linear regression on each part gave a shrinkage coefficient, k_S, of 0.00175 % MC^{-1} above 20% MC and 0.00295 % MC^{-1} below. These are similar to an overall shrinkage coefficient of 0.0027 % MC^{-1}, the published value for Douglas-fir wood (USDA Forest Service 1987). Lower shrinkage was observed at higher temperature, which may be caused by internal stress resulting from moisture gradients during drying.

MS strain

The MS strain cannot be measured directly, but must be calculated by subtracting the instantaneous and creep strains from the stress-induced strain. The instantaneous strain was

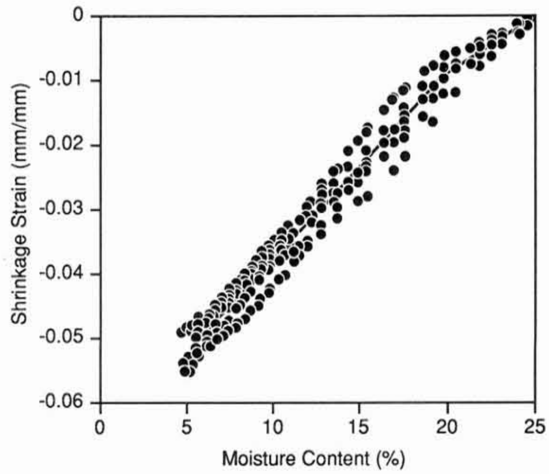

FIG. 6. Shrinkage-moisture content relation, showing a bilinear fit.

obtained directly from the tests. The total stress-induced strain at 65.6 C is plotted against MC in Figs. 7a and 7b for tension and compression, respectively. Typical sample-to-sample variation in stress-induced strain was ±6%. Compared to data taken at a constant MC and the same temperature and stress level (Fig. 4), the strain was significantly larger because of the MC change and the MS effect. The strain under compression (Fig. 7b) was greater than that under tension (Fig. 7a) at 65.6 C.

The creep portion of the stress-induced strain was calculated for the stress, MC, and temperature conditions matching those in the MS tests. The resulting values (Figs. 7c and 7d) were subtracted from the stress-induced strain to obtain the MS strain (Figs. 7e and 7f). The creep strain rate (slope in Figs. 7c and 7d) was large at high MCs, decreasing as the samples dried. The calculated creep strain accounted for 14% of the stress-induced strain in tension and 4.5% in compression because the stress-induced strain is greater in compression. Thus, the time-dependent creep strain would be relatively small in rapid drying of small wood samples, especially under compression. However, with a slower change in MC, as in drying of large boards, the contribution of time-dependent creep strain would be expected to increase.

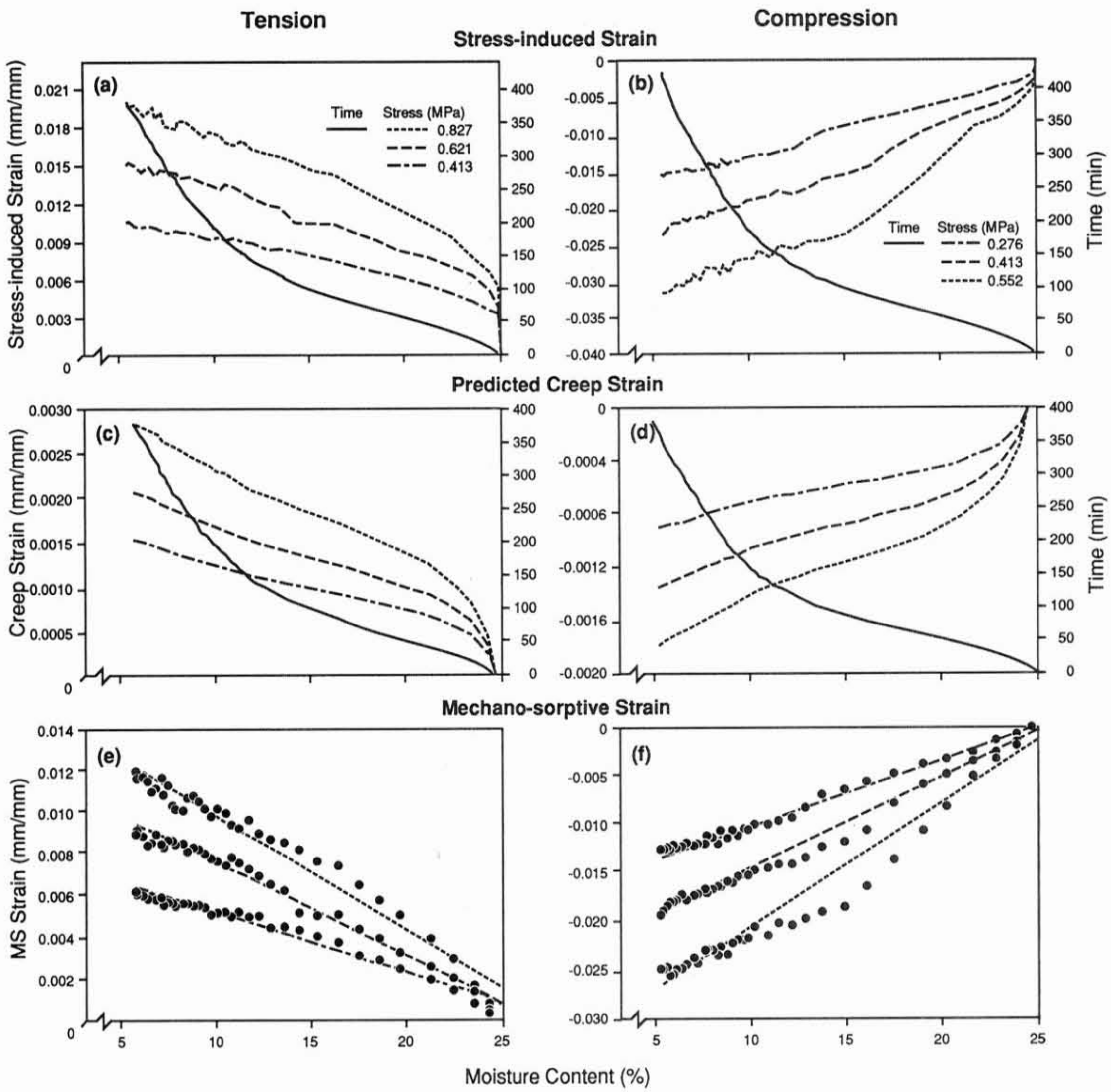

FIG. 7. Components of total strain from drying under tension or compression at 65.6 C. Stress-induced strain, (a) and (b); predicted creep strain, (c) and (d); and mechano-sorptive (MS) strain with fitted lines, (e) and (f).

On the basis of previous work (e.g., Grossman 1976), we elected to fit the MS strain linearly despite some curvature in the data at high MC, especially at higher stress levels. The nonlinearity above 20% MC may be related to that in the shrinkage-moisture content relation. The higher creep predicted at higher MC helped to reduce the nonlinearity, but some uncertainty remains in predicting the exact magnitude of the creep strain at higher moisture content under varying MCs. In both tension and compression, k_M (the ratio of the slope of the MS strain-MC curve to stress) is independent of the stress level, suggesting that MS strain is proportional to stress over a matched sorption history. Similar observations were made by Takahashi and Yamada (1966) and Hisada (1981). However, quantitative fitting of their strain data to moisture content change was not performed.

The mean MS strain at 65.6 C (Figs. 7e and 7f) was three times larger in compression [$k_M = 22.33 \times 10^{-4}$ MPa^{-1} % MC^{-1}] than in tension [$k_M = 7.29 \times 10^{-4}$ MPa^{-1} % MC^{-1}]. This is similar to observations in other wood species and wood-based composite materials (Armstrong 1972; Mårtensson and Thelandersson 1990; Hisada 1980). Mårtensson and Thelandersson (1990) reported a ratio of 2.0 of compression to tension for MS strain in hardboard at room temperature. Hisada (1980) showed that the total strain in drying Japanese makanba wood under tangential tension and compression was greater in compression than in tension at 68 F when the stress levels were above the proportional limit, whereas strains were similar below the limit. The relatively small magnitude of the MS strain in tension may explain why flatsawn Douglas-fir lumber is prone to surface checking during drying, a major drying defect of this species (Espenas 1952).

The fitted parameter k_M from drying under compression increased with temperature (Fig. 8), indicating increased MS deformation with temperature. Regression analysis of the data led to

$$k_M(T) = 9.21 \times 10^{-4} + 1.95 \times 10^{-5}\, T \qquad R^2 = 0.76 \qquad (16)$$

for the relationship between k_M and temperature from 32.2 C to 82.2 C. McMillen (1955, 1968) attributed a considerable increase in board shrinkage with temperature to increased compression set in the interior of the board during drying of 50.8-mm red oak and ponderosa pine. Increased MS strain in compression with increased temperature no doubt was an important influence in his results.

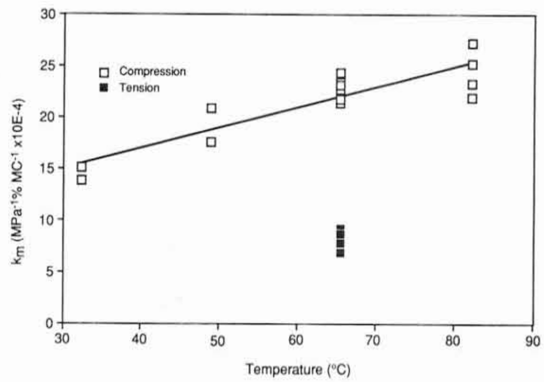

FIG. 8. Mechano-sorptive parameter as a function of temperature with a linear fit. Results were obtained during desorption.

CONCLUSIONS

The experimental technique developed can be used successfully to study creep and MS behavior of wood at elevated temperatures under tension and compression. The observed EMC of small wood samples in the absence of air agrees generally with those in air.

Along the tangential direction, the creep strain of Douglas-fir observed at constant moisture content and stress level follows the power-law relation with time. The magnitude of creep is small compared to the MS strain for the 6- to 7-h drying time used. However, with a slower change in MC, as occurred in drying of large boards, creep may be important in relieving internal stress.

The stress-induced strain from drying small wood samples under load is largely due to the MS effect and increases with stress and temperature. The magnitude of the MS strain in compression at 65.6 C is three times larger than in tension.

Determination of the material parameters for strain components from drying of small wood samples has permitted derivation of a set of constitutive equations that describe the material behavior of wood under drying conditions. In continuing work, we are using these equations to model the stress and strain that occur in large boards during drying (Wu and Milota 1994).

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REFERENCES

ARMSTRONG, L. D. 1972. Deformation of wood in compression during moisture movement. Wood Sci. 5:81–86.

———, AND R. S. T. KINGSTON. 1962. The effect of moisture content changes on the deformation of wood under stress. Aust. J. Appl. Sci. 13:257–276.

CHRISTENSEN, G. N. 1962. The use of small specimens for studying the effect of moisture content changes on the deformation of wood under load. Aust. J. Appl. Sci. 13:242–256.

CONTROL EG. 1989. Measurement and control software, user's manual. Quinn-Curtis, Newton, MA. 136 pp.

ERICKSON, R. W. 1989. Mechano-sorptive phenomena in drying red oak. Pages 79–91 *in* Proceedings, IUFRO International Conference on Wood Drying, Seattle, WA.

ESPENAS, L. D. 1952. Minutes of annual meeting of western dry kiln clubs. Redding, CA. May.

GROSSMAN, P. U. A. 1976. Requirements for a model that exhibits mechano-sorptive behaviour. Wood Sci. Technol. 10:163–168.

———, L. D. ARMSTRONG, AND R. S. T. KINGSTON. 1969. An assessment of research in wood rheology. Wood Sci. Technol. 3:324–328.

HEARMON, R. F. S., AND J. M. PATON. 1964. Moisture content change and creep of wood. Forest Prod. J. 14(8): 357–359.

HISADA, T. 1979. Creep and set of wood relating to kiln drying. II. Effect of stress level on tensile creep of wood during drying. Mokuzai Gakkaishi 25:697–706.

———. 1980. Creep and set of wood relating to kiln drying. IV. Effect of stress level on compressive creep and set of wood during drying. Mokuzai Gakkaishi 26: 519–526.

———. 1981. Creep and set of wood relating to kiln drying. V. Effect of temperature on creep of wood during drying. Mokuzai Gakkaishi 27:381–389.

IRVING, D. C. 1989. A study of load-induced microdeformation within wood-based structural members using optical scanning techniques. M.S. thesis, Oregon State University, Corvallis, OR. 106 pp.

KELLY, S. S., T. G. RIALS, AND W. G. GLASSER. 1987. Relaxation behaviour of amorphous components of wood. J. Mater. Sci. 22:617–624.

LEICESTER, R. H. 1971. A rheological model for mechano-sorptive creep of beams. Wood Sci. Technol. 5:211–220.

MÅRTENSSON, A., AND S. THELANDERSSON. 1990. Effect of moisture and mechanical loading on wooden materials. Wood Sci. Technol. 24:247–261.

MCMILLEN, J. 1955. Drying stresses in red oak: Effect of temperature. Forest Prod. J. 5(4):230–241.

———. 1968. Transverse strains during drying of 2-in. ponderosa pine. USDA Forest Serv. Res. Pap. FPL 83. Forest Prod. Lab., Madison, WI. 26 pp.

PALKA, L. C. 1973. Predicting of specific gravity, moisture content, temperature, and strain rate on the elastic properties of softwoods. Wood Sci. Technol. 7:127–141.

RANTA-MAUNUS, A. 1975. The viscoelasticity of wood at varying moisture content. Wood Sci. Technol. 9:189–205.

RICE, R. W., AND R. L. YOUNGS. 1990. The mechanism and development of creep during drying of red oak. Holz Roh- Werkst. 48:73–79.

SALIN, J. G. 1992. Numerical prediction of checking during timber drying and a new mechano-sorptive creep model. Holz Roh- Werkst. 50:195–200.

SALMÉN, N. L. 1975. Viscoelastic properties of in situ lignin under water-saturated conditions. J. Mater. Sci. 10:3090–3096.

SCHNIEWIND, A. P. 1966. On the influence of moisture content changes on the creep of beech wood perpendicular to the grain including the effects of temperature and temperature change. Holz Roh- Werkst. 24:87–98.

———. 1968. Recent progress in the study of rheology of wood. Wood Sci. Technol. 2:188–206.

———, AND J. D. BARRETT. 1972. Wood as a linear orthotropic viscoelastic material. Wood Sci. Technol. 6:43–57.

TAKAHASHI, A., AND T. YAMADA. 1966. Studies on the drying set of wood. I. Tensile creep in relation to the non-equilibrium state in the wood-water system, especially the dependence on load. Mokuzai Gakkaishi 12:6–10.

USDA FOREST SERVICE. 1987. Wood handbook: Wood as an engineering material. Agric. Handb. 72. Forest Prod. Lab., Washington DC. 466 pp.

WU, Q. 1993. Rheological behavior of Douglas-fir as related to the process of drying. Ph.D. dissertation, Oregon State University, Corvallis, OR. 228 pp.

———, AND M. R. MILOTA. 1994. Effect of creep and mechano-sorptive effect on stress development during drying. Drying Technol. 12(8):2057–2085.

YOUNGS, R. L. 1957. The perpendicular to grain mechanical properties of red oak as related to temperature, moisture content, and time. USDA Forest Serv. Rep. FPL-2079. Forest Prod. Lab., Madison, WI.