EFFECT OF STRESS LEVEL ON BENDING CREEP BEHAVIOR OF WOOD DURING CYCLIC MOISTURE CHANGES

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ABSTRACT

This study investigated the effect of stress level on bending creep behavior of Japanese cedar (*Cryptomerica japonica* D. Don) during cyclic moisture changes. Tests were made at 20°C with four cyclic relative humidity changes between 65% and 95% under four stress levels: 12.6, 18.5, 24.3, and 30.2 MPa, corresponding to 17, 25, 33, and 42% of short-term breaking stress, respectively. The effect of moisture content (MC) change on elastic compliance and mechano-sorptive (MS) compliance was examined. The results indicated that the total compliance revealed different behavior under various stress levels over the history of cyclic moisture changes and appeared to be greater under higher stress. Elastic compliance increased linearly with MC and affected the behavior of total compliance during MC change. As MC change increased, the MS compliance during the first adsorption and all desorption increased linearly, while during subsequent adsorption revealed a decrease in lower stress and an increase in higher stress. At a given stress level, the first adsorption led to greater MS deformation than did desorption and subsequent adsorption. The elastic parameter K_E for MC effect on elastic compliance and the MS parameter K_M for relationship between MS compliance and MC increased as quadratic functions of applied stress. The rate of increase in the parameters accelerated above about 25 to 33% stress level. As a result, when MC is cycled, MS compliance increase occurs at lower stress levels relative to creep at constant MC.

Keywords: Creep, cyclic moisture changes, bending, stress level.

INTRODUCTION

Mechano-sorptive (MS) creep is a deformation due to an interaction between stress and moisture content (MC) change (Armstrong and Kingston 1962; Schniewind 1968). In many situations where wood is used as structural members, the wood undergoes MS deformation resulting from applied stress and MC change. MS creep may result in great deformation or early failure of wood (Hearmon and Paton 1964; Rice and Youngs 1990; Wu and Milota 1995, 1996). This phenomenon is important not only for fundamental study but also for practical applications of wood. Thus, numerous investigations have been done on MS deformation. It appears that quantitative description of MS creep is an essential step in more realistically predicting deformation of loaded wood under moisture change (Hunt 1984).

Rheological equations to quantify the deformation of wood under combinations of mechanical stress and moisture change have been proposed (Leicester 1971; Ranta-Maunus 1975; Wu and Milota 1995, 1996; Nakano 1996a). The total deformation of wood stressed in bending under MC change contains elastic deformation and MS deformation. Total compliance can be expressed as

$$D_T(t) = D_E(t) + D_M(t) \qquad (1)$$

where $D_T(t)$ = total compliance (MPa^{-1}), $D_E(t)$ = elastic compliance (MPa^{-1}), $D_M(t)$ = MS compliance (MPa^{-1}), and t = time (min).

Elastic deformation occurs immediately after the application of a load, and varies with MC, temperature, and stress. In the linear range, elastic compliance is independent of stress and is the reciprocal of the modulus of elasticity (MOE). Gerhards (1982) indicated that MC has effect on the mechanical properties of solid wood. Zhou et al. (1999) investigated MC impact on elastic compliance of six species in bending. They found that elastic compliance increased linearly with MC, varying with species. Hunt and Shelton (1987) demonstrated that elastic compliance in ponderosa pine under bending stress increased linearly with MC. Thus, elastic compliance as a function of MC change can be expressed as

$$D_E(t) = D_{E0} + K_E\, M(t) \qquad (2)$$

where D_{E0} = elastic compliance at some standard MC (MPa^{-1}), K_E = elastic parameter for MC effect on elastic compliance ($MPa^{-1}\%^{-1}$), and $M(t)$ = MC change (%).

MS compliance as a function of MC change was expressed by Leicester (1971) as

$$D_M(t) = K_M\, |M(t)| \qquad (3)$$

where K_M = MS parameter for the effect of MC change on MS compliance ($MPa^{-1}\%^{-1}$). Ranta-Maunus (1975) proposed using three material parameters to describe the phenomena: K_M^{++} for the first adsorption, K_M^{+} for subsequent adsorption, and K_M^{-} for desorption, indicating that those parameters vary with wood species and loading direction. Hearmon and Paton (1964) suggested that MS deflection of beech in bending under cyclic moisture changes increased with applied stress. Szabo and Ifju (1970) investigated creep of small yellow poplar beams under two different constant load levels in conditions of moisture adsorption and desorption. The results indicated that MS strain showed a direct relationship to average MC of the beams and increased with increase in duration of load application and magnitude of load during moisture adsorption and desorption. Ozawa et al. (1995) studied creep of cedar beams under five stress levels ranging from 20 to 75% of short-term breaking stress during moisture adsorption and desorption. The results showed that MS strain of the beams increased with applied stress, and adsorption led to greater MS strain than did desorption at a given stress. However, a quantitative knowledge on how stress affects the MS parameters (K_M) of wood in bending during cyclic moisture changes is still very ambiguous.

An attempt was therefore made in this study (1) to investigate the behaviors of total compliance of Japanese cedar wood at different stress levels during cyclic moisture changes, (2) to explore how MC change affects elastic compliance and MS compliance, and (3) to evaluate elastic parameter (K_E) and MS parameter (K_M) for specified sorption.

MATERIALS AND METHODS

Specimen preparation

A piece of green, flat-sawn Japanese cedar (*Cryptomerica japonica* D. Don) lumber was air-dried to 14% MC in an experimental room. The sapwood with an average specific gravity of 0.32 (at 14% MC) was selected for this study. To facilitate rapid moisture equilibrium and to minimize internal moisture gradients, small specimens, each 320 (L) × 10 (T) × 10 (R) mm, were cut from the wood. The specimens were stored in an air-conditioned room at 20°C and 65% relative humidity (RH) for more than two weeks prior to use.

Five specimens were used to test short-term breaking load in four-point bending at 20°C and 65% RH. Four groups of specimens were selected for elastic compliance and creep tests with nine specimens in each group, and their end faces were sealed with vapor-proof neoprene paint. For each group, three specimens were used for examining the effect of MC on elastic compliance, and others for creep tests.

Experimental setup and conditions

The creep test was performed in an air-tight chamber, in which air was circulated by a small fan, and 95% RH for moisture adsorption was conditioned with a supersaturated potassium sulfate solution. The whole test assembly was placed in the air-conditioned room at 20°C and 65% RH.

The specimens for creep measurement were placed on a frame with the span 300 mm inside the chamber, and then a load was applied on the R-L face to create four-point bending. The stress of the specimens was chosen to give the values 12.6, 18.5, 24.3, and 30.2 MPa, as 17, 25, 33, and 42% of short-term breaking stress, respectively. One group of specimens was prepared for each stress level. In this study deflection at 12 s after load application was defined as the initial elastic deflection under a given stress. The deflection was measured by a dial gauge with an accuracy of 0.01 mm. A load-free specimen for measuring swelling or shrinkage due to moisture change was also placed on the frame, and the tangential swelling or shrinkage was continuously measured by another similar dial gauge. The mass change of the MC specimen was constantly monitored by a digital balance (accuracy up to 0.001 g), placed outside the conditioning chamber with an attached specimen hanger passing into the chamber. The changes of shrinkage or swelling, MC, and creep were continuously monitored with three high-resolution cameras outside the chamber, and recorded with a videotape machine connected with the cameras. The measurements of shrinkage or swelling, MC, and creep were made by reading the dial gages and the digital balance in the videotape recording.

After load application, the supersaturated potassium sulfate solution was placed into the chamber, and therefore the RH inside the chamber was changed from 65% to 95%. A moisture adsorption was then performed until adsorption time reached 24 h. After the adsorption, the potassium sulfate solution was removed from the chamber and the chamber was kept open to maintain the RH at 65%. A moisture desorption was therefore conducted subsequently and also lasted 24 h. The above moisture change cycle (adsorption-desorption) was then repeated three times. In all, four moisture change cycles were performed in one creep test. The test was replicated once for each stress level.

At a given stress studied, the mass and dimension of the three specimens for examining the MC effect on elastic compliance were determined at 20°C and 65% RH, and then their elastic deflection under the same load as that in the creep test was measured. Subsequently, the specimens were transferred to a conditioning chamber maintained at 20°C and 95% RH using supersaturated potassium sulfate solution. The air inside the chamber was circulated by a small fan. At measured time intervals, the specimens were removed from the conditioning chamber. Their mass, dimension, and elastic deflection were measured immediately, and then the specimens were placed back into the conditioning chamber. The process was repeated until adsorption time reached 24 h. After adsorption, the three specimens were oven-dried and their oven-dry mass and dimensions were measured.

Calculation and data analysis

For examining the effect of MC on elastic compliance, a regression analysis on the elastic compliance and MC data was used to fit Eq. (2), and therefore the elastic parameter K_E was determined. In creep tests, the deflection of the loaded specimen contained a tangential swelling or shrinkage of the specimen due to MC change, which was determined based on the measurement of the load-free specimen. In calculation for total compliance, the total de-

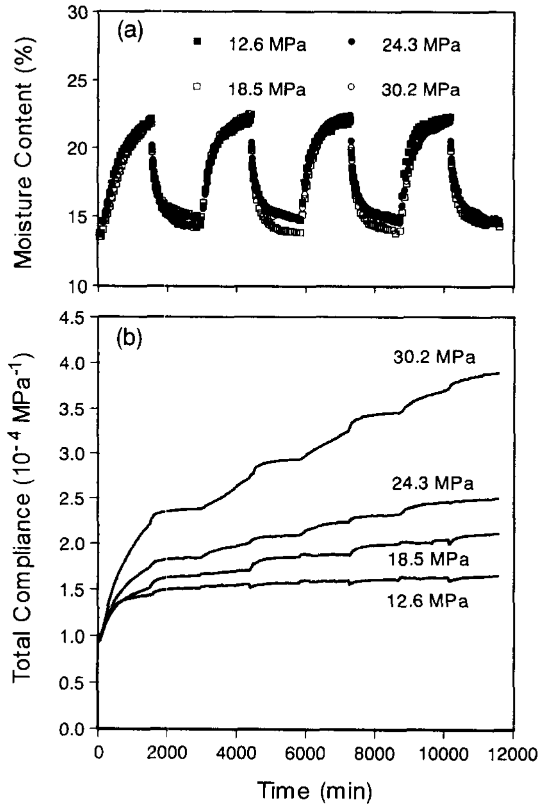

FIG. 1. Moisture content change (a) and total compliance (b) as a function of sorption time at four stress levels.

flection of the loaded specimens was calculated by adding the tangential swelling of the specimens to the measured deflection in adsorption and subtracting the tangential shrinkage of the specimens from the measured deflection in desorption. As in Eq. (1), MS compliance $D_M(t)$ was obtained by subtracting elastic compliance $D_E(t)$ from total compliance $D_T(t)$. To obtain MS parameter K_M for each moisture sorption condition, least-squares regression was used to fit Eq. (3), with MC change as the independent variable and $D_M(t)$ as the dependent variable.

RESULTS AND DISCUSSION

MC and total compliance

Figure 1 summarizes the variations of MC and total compliance of specimens over the history of cyclic RH change between 65% and 95%. During moisture sorption, specimens did not reach the tabulated equilibrium MC (EMC) corresponding to the surrounding RH. That is probably due to insufficient sorption time, or lower EMC during adsorption and higher EMC during desorption as hysteresis.

It can be found in Fig. 1b that initial elastic compliance occurred immediately with almost identical value after the load was applied at 65% RH. The total compliance at 12.6, 18.5, 24.3, and 30.2 MPa increased 68, 121, 167, and 304%, respectively, over the history of cyclic moisture changes. The total compliance was apparently greater at higher stress levels, suggesting a strong dependence on stress. The increase was greatest between 24.3 and 30.2 MPa. The total compliance increased 137% within the stress step, compared to 53 and 46% within the other stress steps. The variation of total compliance, with different behavior at the four stress levels, was closely related to cyclic MC change, suggesting the significant impact of MC change on creep. At a given stress level, the total compliance increased progressively with time during the first adsorption and all desorption, and the increase became more remarkable at higher stress levels. During subsequent adsorption, with increasing time, the total compliance kept an almost constant value at 12.6 and 18.5 MPa, while it increased remarkably at 24.3, and 30.2 MPa.

Effect of MC on elastic compliance and MS compliance

Figure 2 reveals elastic compliance as a function of MC at four stress levels, showing results of a linear fit. Elastic compliance at 65% RH showed almost identical values at the four stress levels and increased linearly with MC. For an MC change from 13.5 to 22.5%, elastic compliance under 30.2 MPa increased 28%, compared to an average increase of 14% under the other stresses. A regression analysis on the elastic compliance and MC data was

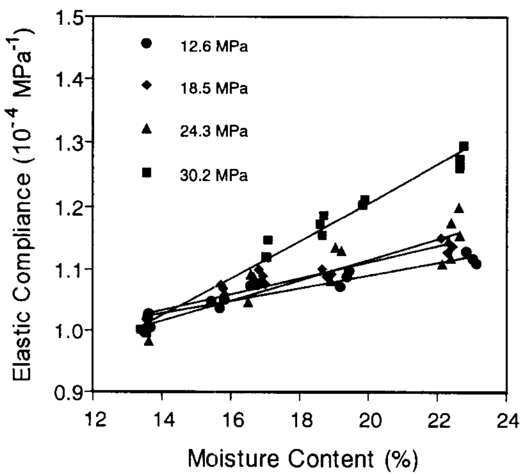

FIG. 2. Elastic compliance as a function of moisture content at four stress levels, showing results of a linear fit.

used to fit Eq. (2), and therefore elastic parameter K_E was obtained (Table 1).

Figure 3 shows MS compliance as a function of MC change. At a given stress, the MS compliance during the first adsorption and all desorption increased linearly with increasing MC change, except at 30.2 MPa. But the MS compliance in the first adsorption more remarkably increased than in desorption. A similar behavior has been found in tangential tension of Douglas-fir (Wu and Milota 1995, 1996). Much of the MS creep is due to molecular mobility in the amorphous region, as explained by Nakano (1996b). When the MC in a loaded specimen changes due to moisture sorption, the hydrogen bonds between hydroxyl groups of adjacent cellulose chains and water molecules in the wood are broken. Thus, molecules or flowing segments in wood substances have mobility, and then under external stress, relative displacement between segments may arise, which therefore results in an appreciable deformation in wood.

As shown in Fig. 3, during subsequent adsorption, with increasing MC the MS compliance revealed a decrease at 12.6 and 18.5 MPa but an increase at 24.3 and 30.2 MPa. The decrease in MS compliance is regarded as a recovery of MS deformation. For the MS creep, the recovery during subsequent adsorption should be related to the previous desorption and is due to relaxation of stress built up in wood during the previous desorption (Armstrong 1972; Nakano 1996b). Norimoto and Gril (1989) suggested that the recovery takes place at the molecular level, but in combination with the ultrastructural (or macromolecular) level, as the microfibrillar framework keeps the memory of the initial shape of cell wall and takes advantage of matrix softening to recover its initial shape. Meanwhile, with increasing mobility of molecules or flowing segments in wood substances during the subsequent adsorption, relative displacement between segments increases under applied stress. In other words, the relative displacement for increasing deformation and the recovery to initial shape exist simultaneously during the subsequent adsorption. In this study, the MS compliance in subsequent adsorption did not recover completely under lower stress, and even slightly increased under higher stress at the end of adsorption (Fig. 3). Thus, the magnitude of applied stress influenced the recovery behavior of MS compliance; that is, the recovery appeared to decrease with increasing applied stress. A similar

TABLE 1. *Summary of parameters (K_E and K_M) (10^{-6} MPa^{-1} $\%^{-1}$) at four stress levels.*

Stress (MPa)	K_E	K_M Adsorption 1	Adsorption 2	Adsorption 3	Adsorption 4	Desorption 1	Desorption 2	Desorption 3	Desorption 4
12.6	1.04	4.88	−0.78	−0.30	−0.14	2.00	1.68	1.42	0.96
18.5	1.30	5.27	−0.22	−0.21	−0.65	2.69	2.16	1.93	1.87
24.3	1.66	10.18	1.13	1.52	1.54	2.40	1.74	3.01	2.65
30.2	3.02	16.18	2.11	2.22	1.58	5.08	5.10	5.24	5.22

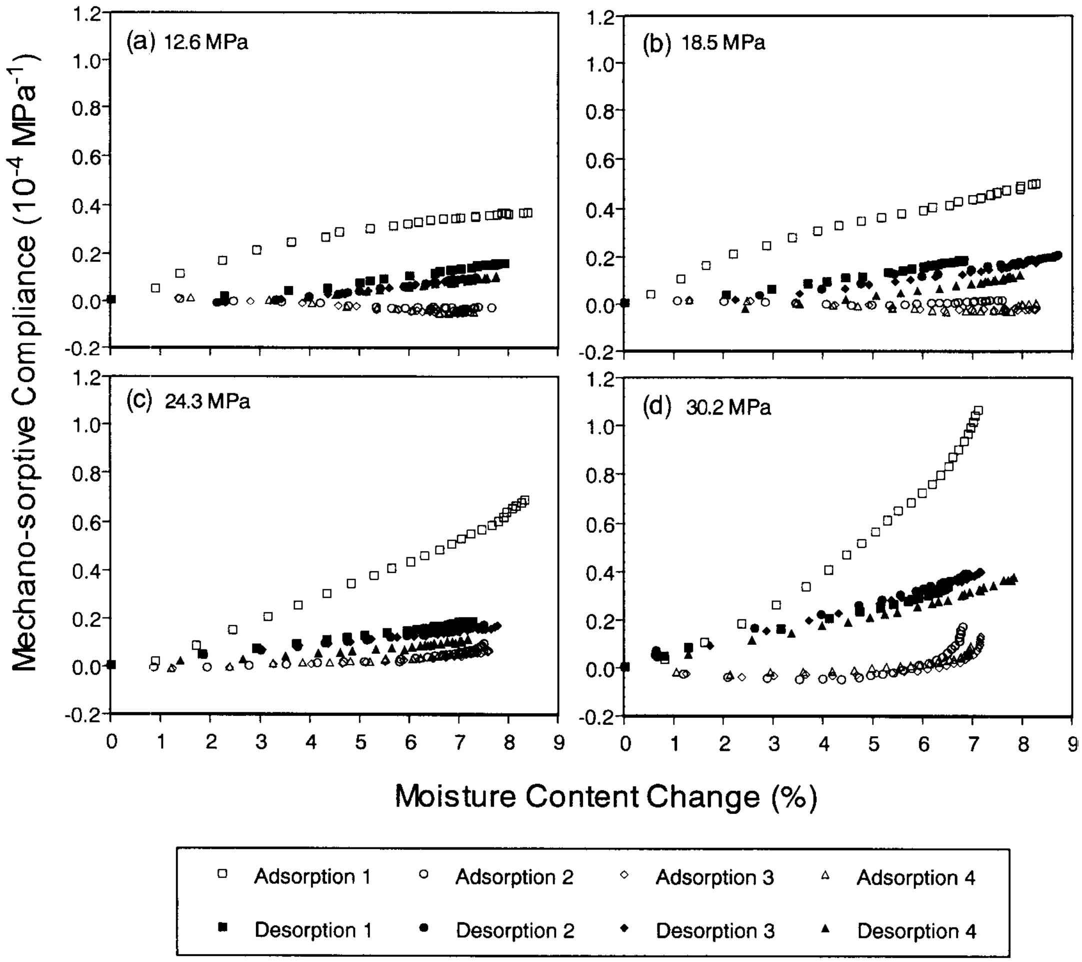

FIG. 3. The relationship between mechano-sorptive compliance and moisture content change at four stress levels.

result has been found in red pine stressed in compression perpendicular to the grain (Lu and Erickson 1996).

The MS parameter K_M, i.e., the slope of the MS compliance versus MC change curve, is also shown in Table 1. At a given stress level, K_M in the first adsorption was more than two times as great as the mean value for K_M in desorption. The parameter K_M in desorption appeared to be greater than the absolute value in subsequent adsorption. This implies that at a given stress, with the same amount of MC change, the first adsorption led to greater MS deformation than did desorption and subsequent adsorption during cyclic moisture changes. Similar behavior has been found in longitudinal bending of pine (Armstrong and Christensen 1961) and birch (Ranta-Maunus 1975), longitudinal tension of pine (Armstrong and Kingston 1962), and tangential tension of Douglas-fir (Wu and Milota 1995). The parameters in desorption and subsequent adsorption varied with moisture cycle number, and there was no general trend of the variation for the four stress levels.

As shown in Table 1, at a given stress, the MS parameter K_M for the first adsorption was more than four times as great as the elastic parameter K_E. And the mean value for K_M in desorption was about one and half times as

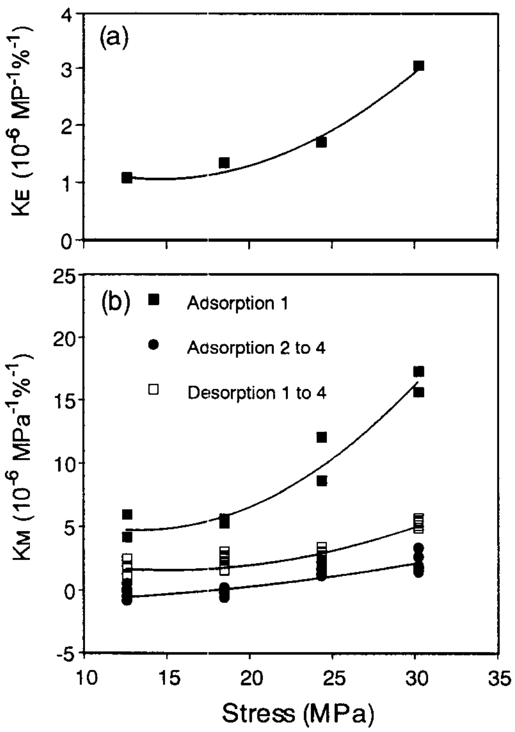

FIG. 4. Elastic parameter K_E (a) and MS parameter K_M (b) as a function of applied stress.

great as K_E. This indicates that MS creep was the major deformation during the first adsorption and all desorption, and thus the change in total compliance was mainly due to changes in MS compliance. However, the mean absolute value for K_M in subsequent adsorption was apparently smaller than the elastic parameter K_E. This suggests that during subsequent adsorption, total compliance behavior was mainly dependent on elastic compliance. As a result, elastic compliance influences the behavior of total compliance under MC change and therefore cannot be ignored in a creep study.

Effect of applied stress on parameters (K_E and K_M)

Figure 4a shows that elastic parameter K_E increased with applied stress. The increase in K_E appeared to be relatively small in lower stresses (below 24.3 MPa) and larger in higher stresses. Figure 4b shows MS parameter K_M as a function of applied stress. With increasing applied stress, K_M for the first adsorption kept an almost constant value in lower stresses (below 18.5 MPa) while it increased considerably in higher stresses. This suggests that MS compliance was independent of stress in lower stresses but dependent on stress in higher stresses. Similarly, the MS parameters for desorption and subsequent adsorption also more or less increased with applied stress. According to Table 1, with increasing applied stress, the mean values of K_M in desorption and subsequent adsorption at each stress level increased (from 1.52 to 5.16 and from −0.41 to 1.97, respectively) and thus the MS compliance at the end of cyclic moisture changes increased. Dinwoodie et al. (1991) investigated the effect of stress level on relative creep (expressed as a fraction of initial elastic deformation) behavior of redwood in bending under steady-state MC. They suggested that the rate of increase in relative creep for redwood accelerated above about 45% stress level, especially with respect to high RH. Ota and Tsubota (1966) found that in both creep and relaxation tests in bending, linear behavior could not be observed if the stress level exceeded the proportional limit as found in static tests. Kingston and Clarke (1961) found that creep in bending was linear up to loads corresponding to 50% of the modulus of rupture. Sawada (1957) reported great increases in creep response above stress levels of 50 to 60%. Sugiyama (1957) observed slight increases in relative creep with stress up to 40 to 50% stress level, but reported sharp increases beyond this level. Fushitani (1968) found that with increasing applied stress, the rate of increase in creep accelerated above a lower stress level more rapidly in the water-saturated condition than in the air-dried condition.

In this study, stresses in beams were well below the elastic limit of wood at 20°C and 65% RH. The fact that the rate of increase in material parameters accelerated above about 25 to 33% stress level, obviously lower than seen at constant MC, may be attributed to the significant effect of moisture change on the

TABLE 2. *Summary of regression results on parameters (K_E and K_M) as a function of stress level.*

Parameter	Condition	A	B	C	R^2
K_E		8.0×10^{-3}	-0.23	2.76	0.98
K_M	Adsorption 1	4.13×10^{-2}	-1.10	12.05	0.90
	Adsorption 2 to 4	3.80×10^{-3}	1.19×10^{-2}	-1.00	0.75
	Desorption 1 to 4	1.51×10^{-2}	4.54×10^{1}	4.98	0.81

mechanical properties of wood and therefore the relationships of stress level to elastic compliance and MS compliance.

A quadratic polynomial was used to fit the relationships of applied stress to parameters (K_E and K_M):

$$K = A\sigma^2 + B\sigma + C \qquad (4)$$

where K is parameter (K_E or K_M) (MPa^{-1}%$^{-1}$), σ represents applied stress (MPa), and A, B, and C are regression constants. The regression results are shown in Table 2. Equation (4) and Table 2 may be used to determine K_E or K_M under desired applied stress and specified sorption. And therefore elastic deformation, MS deformation, and total deformation of beams under MC change can be estimated in terms of Eqs. (1) to (3).

CONCLUSIONS

The total compliance, with different behavior at various stress levels, increased over the history of cyclic moisture sorption and was greater under higher stress. Elastic compliance increased linearly with MC and was dependent on stress level. With increasing MC change, the MS compliance increased linearly during the first adsorption and all desorption, while during subsequent adsorption it revealed a decrease at lower stresses and an increase at higher stresses. The first adsorption led to greater MS deformation than did desorption and subsequent adsorption, with the same amount of MC change at a given stress. As an integral part of total compliance, elastic compliance had some influence on the behavior of total compliance during MC change. The elastic parameter K_E and MS parameter K_M increased as a quadratic function of applied stress. The rate of increase in material parameters accelerated above about 25 to 33% stress level. As a result, when MC is cycled, MS compliance increase occurs at lower stress levels relative to creep at constant MC.

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