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Bending creep behavior of wood under cyclic moisture changes*

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Abstract This study examined the bending creep behavior in the longitudinal direction of six species under cyclic moisture content (MC) changes. For each species, tests were made at 20°C with five cyclic relative humidity changes between 65% and 95%, beginning from moisture adsorption. A load corresponding to 25% of short-term breaking load of the species was applied to the radial section of each specimen with four-point bending. The effect of MC change on instantaneous compliance was also investigated under the same condition. The quantitative relation between mechano-sorptive (MS) compliance and MC change was examined, and the material parameter K_M for the relation in specific sorption was determined. Results indicated that the total compliance in the six species with different behavior increases with sorption time. As an integral part of total compliance, instantaneous compliance changes linearly with MC and influences to a greater or lesser extent the total compliance behavior. In general, with increasing MC change, the MS compliance linearly increases during the first adsorption and all desorption and decreases slightly during subsequent adsorption. The material parameter K_M varies markedly not only with species but also with specific sorption. The first adsorption causes the largest deformation, followed by desorption.

Key words Creep · Cyclic moisture sorption · Bending stress · Species

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Introduction

Mechano-sorptive (MS) creep is a deformation due to an interaction between stress and moisture content (MC) change.[1,2] It is independent of time and does not occur during steady-state moisture movement.[3,4] In many situations where wood is used as a structural member, the wood undergoes MS creep resulting from the application of a load and MC change. MS creep may result in great deformation or early failure of wood.[5–8] On the other hand, it can have positive consequences in the manufacture of composites and wood forming.[9,10] Thus, MS creep is important not only for a fundamental study but also for the practical application of wood.[11] Quantitative description for MS creep is an essential step in realistically predicting the deformation of loaded wood with MC changes and exploring mechanism of MS creep. So far, however, the quantitative description is still incomplete. [12]

Rheological equations to quantify the deformation of wood under combinations of mechanical stress and moisture change have been proposed.[7,8,13,14] The total deformation in MC change contains instantaneous deformation and MS deformation. Total compliance can be expressed as:

$$D_T(t) = D_I(t) + D_M(t) \tag{1}$$

where $D_T(t)$ is total compliance (GPa^{-1}); $D_I(t)$ is instantaneous compliance (GPa^{-1}); and $D_M(t)$ is MS compliance (GPa^{-1}).

Instantaneous deformation is produced immediately after the application of a load and varies with MC, temperature, and stress. In the linear range, instantaneous compliance is independent of stress and is the reciprocal of the modulus of elasticity (MOE). Gerhards[15] indicated that MC has a marked effect on MOE. Thus, instantaneous compliance may be influenced by MC change over the history of moisture sorption. Much research has been done on creep of stressed wood under MC change,[16] but no study has explored how MC change influences instantaneous compliance, an integral part of total compliance.

MS compliance as a function of MC change can be expressed as

$$D_M(t) = K_M|M(t)| \tag{2}$$

where K_M is the material parameter for MS compliance ($GPa^{-1}\% \ u^{-1}$); $M(t)$ is the MC change (%); and t is time (min). Ranta-Maunus[14] used three material parameters to describe the phenomena: K_M^{++} for the first moisture adsorption, K_M^{+} for any subsequent adsorption, and K_M^{-} for desorption, indicating that those parameters vary with wood species and loading direction. Limited studies have investigated those parameters and covered only one or two species.[7,8,14,17] Few studies have compared different species or groups in terms of their MS deformations in cyclic moisture changes.[17] As a result, general and quantitative knowledge on those parameters in individual species is still ambiguous. It is imperative to fully understand the MS deformation and quantitative relationship of stressed wood under cyclic moisture change for better processing and utilization of the wood.

An attempt was therefore made in this study to (1) determine the behavior of total compliance in different species during cyclic moisture changes, (2) explore how MC change affects the instantaneous compliance of loaded wood and thus quantify the effect of MC change on MS compliance, and (3) evaluate the material parameters (K_M) for specified sorption so we can quantitatively compare the MS deformation of the distinct species in terms of their material parameters in moisture change.

Materials and methods

Specimen preparation

Six species with distinct physico-mechanical properties were selected for this study. They included three softwoods – sugi (*Cryptomerica japonica* D. Don), hinoki (*Chamaecyparis obtusa* Endl.), and karamatsu (*Larix Leptolepis* Gordon.) – and three hardwoods – kiri (*Paulownia tomentosa* Steud), buna (*Fagus crenata* Blume), and kunugi (*Quercus acutissima* Carruth.). To facilitate rapid moisture equilibrium and minimize internal moisture gradients, small specimens, each 320 (L) × 10 (T) × 10 (R) mm, were cut from the lumber. The specimens then were stored in an air-conditioned room at 20°C and 65% relative humidity (RH) for more than 2 weeks prior to use.

Wood density, dimensions, and bending MOE of all specimens were then measured (Table 1). For each species, five specimens were selected to measure short-term breaking load in four-point bending at 20°C and 65% RH. Five specimens with similar density, dimension, and MOE were selected, and their end faces were then sealed with vapor-proof neoprene paint. Three of them were prepared for measuring swelling or shrinkage, MC, and creep; the other two were prepared for examining the effect of MC change on instantaneous compliance.

Table 1. Physico-mechanical properties and applied stress of loaded specimens in six species at 20°C and 65% relative humidity

Species	Wood density (kg/m³)	MOE (GPa)	Applied stress (MPa)
Sugi	377	11.3	18.45
	390	11.4	18.45
Hinoki	434	14.1	21.39
	443	14.8	21.39
Karamatsu	557	15.9	27.27
	545	15.4	27.27
Kiri	245	7.4	10.22
	243	7.2	10.22
Buna	536	10.8	19.92
	541	10.9	19.92
Kunugi	927	18.8	33.74
	930	19.8	33.74

Experimental setup and conditions

For each species the creep test was performed in a specific, airtight chamber, in which air was circulated by a microelectric fan, and RH was conditioned with supersaturated salt solutions, sodium nitrite ($NaNO_2$), and potassium sulfate (K_2SO_4), corresponding to 65% and 95% RH, respectively. The whole test assembly was placed in an air-conditioned room at 20°C and 65% RH.

The specimen for measuring bending creep in a longitudinal direction was placed on a frame with the span 300 mm inside the chamber; then a load, corresponding to 25% of short-term breaking load in this species, was applied on the radial section of specimen with four-point bending (Table 1). The initial deflection was measured 12 s after load application and was considered to be instantaneous deflection. The deflection development was measured by a dial gauge with an accuracy of 0.01 mm. The specimen for swelling or shrinkage measurement 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, respectively, and recorded with a video recorder connected to the cameras. The measurements were then based on the video recording.

One hour after load application, the RH inside chamber was changed from 65% to 95% using supersaturated potassium sulfate solution, and 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 sodium nitrite solution was put into the chamber to maintain the RH at 65%. A desorption process was therefore conducted subsequently, which also lasted 24 h. The above moisture change cycle (adsorption–desorption) was then repeated four times. Totally, five moisture change cycles were performed in one creep test. The test was replicated once for each species.

The mass and dimension of the two specimens for examining the effect of MC change on instantaneous compliance were determined at 20°C and 65% RH, and their instantaneous deflection under the same load as that in the creep test was then determined. The specimens were transferred to a conditioning chamber maintained at 20°C and 95% RH. At measured time intervals, the specimens were removed from the conditioning chamber. Their mass, dimension, and instantaneous deflection were measured immediately, and the specimens were placed back in the conditioning chamber. The process was repeated until adsorption time reached 24 h as one sorption time in creep test. After adsorption the two specimens were oven-dried, and their oven-dry mass and dimension were then measured. The MCs of the two specimens during the test were determined. The mean radial swelling coefficient, (i.e., the slope of the swelling versus MC curve) of the two specimens was used to calculate the radial dimension change of the specimen for creep measurement in this species.

Calculation and data analysis

The compliance of specimens under bending stress can be expressed as

$$D(t) = 4 \times 10^{-9} bh^3 y(t)\left[Pa\left(3l^2 - 4a^2\right)\right]^{-1} \tag{3}$$

where $D(t)$ is the compliance (GPa^{-1}); $y(t)$ is the deflection of the specimen under bending stress (m); P is the applied load (N); b is the width of specimen (m); h is the depth of the specimen (m); l is the span (m) (0.3 m in this study); and a is the load span (m) (0.1 m in this study).

As Eq. (3), instantaneous compliance $D_I(t)$ of the specimen under MC change was computed. For examining the effect of MC on instantaneous compliance, regression analysis on the instantaneous compliance and MC data yielded an equation of $D_I(t)$ as a function of MC. The change of $D_I(t)$ during sorption history was therefore calculated by subtracting $D_I(60)$ from $D_I(t)$ (where $t > 60$ min) as the yielded equation.

For the creep test, the deflection of the loaded specimen under MC change contained a tangential dimension change of the specimen due to swelling or shrinkage, which was measured directly from the load-free specimen with the dial gauge. To calculate the total deflection of the loaded specimen, the dimensional change was added to the measured deflection. The dimensional change of the loaded specimen was then determined in terms of the tangential swelling or shrinkage of load-free specimen and radial swelling coefficient. As Eq. (3), the total compliance $D_T(t)$ under MC change was therefore computed. During sorption, the total compliance $D_T(t)$ change included instantaneous compliance $D_I(t)$ change, and MS compliance $D_M(t)$, where $t >$ 60 min. Thus, $D_M(t)$ was obtained by subtracting $D_I(t)$ change and $D_T(60)$ from $D_T(t)$. To obtain material parameter K_M for each moisture sorption condition, least-squares regression was used to fit Eq. (2), with MC as the independent variable and MS compliance $D_M(t)$ as the variable.

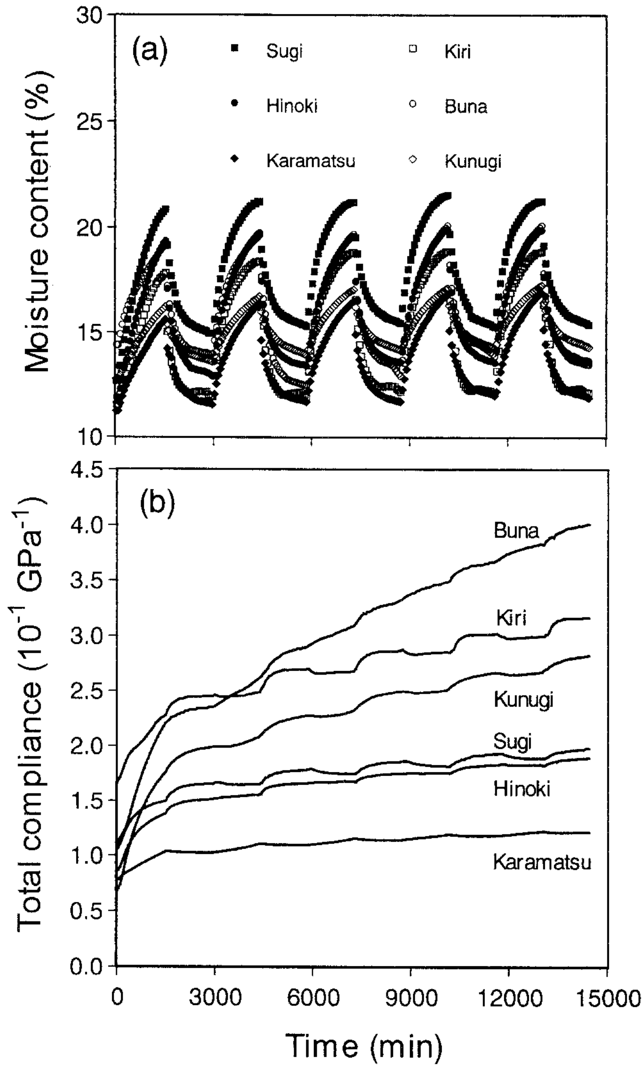

Fig. 1. Moisture content (**a**) and total compliance (**b**), respectively, as a function of sorption time in the six species

Results and discussion

Moisture content and total compliance

Figure 1a summarizes the MC variations in specimens of the six species under cyclic RH change between 65% and 95%. During moisture sorption, some specimens did not reach the tabulated equilibrium MC (EMC) corresponding to the surrounding RH, and the magnitude of MC change varies with species. That is probably due to insufficient sorption time or lower EMC during adsorption and higher EMC during desorption as hysteresis.

As shown in Fig. 1b, an initial instantaneous compliance appeared immediately after the load was applied at 65% RH, varying with species. During cyclic moisture sorption, the behavior of total compliance is closely related to MC change, suggesting the significant effect of MC change. For each species, the total compliance increases markedly with time during the first adsorption. The total compliance in

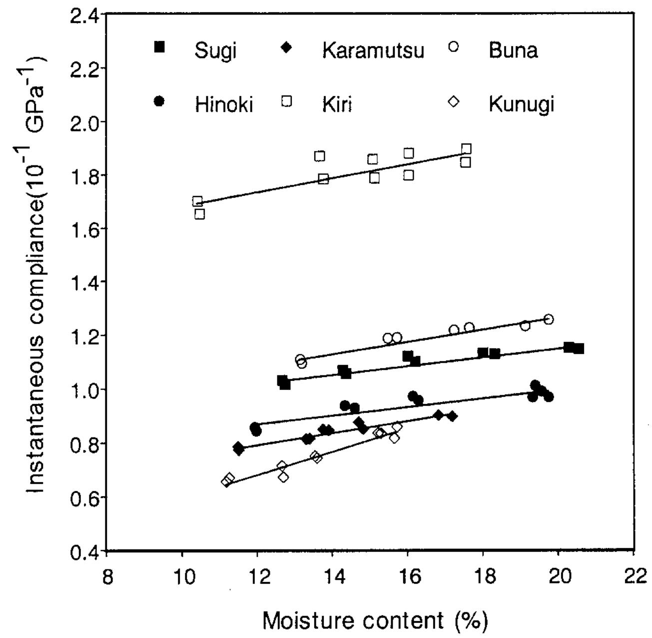

Fig. 2. Instantaneous compliance as a function of moisture content in the six species, showing results of a linear fit

sugi, hinoki, kiri, and kunugi gradually increases with time during desorption and slightly decreases during subsequent adsorption. A similar result was found in other species.[1,5,18–20] In contrast, karamatsu revealed an opposite phenomenon, the reason for which is discussed below. The total compliance in buna increases in both adsorption and desorption. By the end of cyclic moisture sorption, the total compliance is apparently greater in hardwoods than in softwoods. The variation of total compliance among the six species comes from various effects of MC change on instantaneous compliance and MS compliance, and a different amount of MC change.

Instantaneous compliance

Figure 2 reveals instantaneous compliance as a function of MC in the six species, showing a linear fit. Regression analyses on the instantaneous compliance at 20°C yielded:

$$\text{Sugi:} \quad D_I(u) = 0.0161\,u + 0.8237 \quad R^2 = 0.91 \tag{4}$$

$$\text{Hinoki:} \quad D_I(u) = 0.0158\,u + 0.6780 \quad R^2 = 0.81 \tag{5}$$

$$\text{Karamatsu:} \quad D_I(u) = 0.0222\,u + 0.5235 \quad R^2 = 0.92 \tag{6}$$

$$\text{Kiri:} \quad D_I(u) = 0.0261\,u + 1.4198 \quad R^2 = 0.70 \tag{7}$$

$$\text{Buna:} \quad D_I(u) = 0.0226\,u + 0.8095 \quad R^2 = 0.93 \tag{8}$$

$$\text{Kunugi:} \quad D_I(u) = 0.0428\,u + 0.1653 \quad R^2 = 0.94 \tag{9}$$

where $D_I(u)$ represents the instantaneous compliance (10^{-1} GPa^{-1}) at a given MC in the range tested. For species studied, to estimate D_I at u, Eqs. (4) to (9) can be used to determine D_I at the desired u, respectively. It can be clearly found that the coefficients (10^{-1}% u^{-1}GPa^{-1}) for the effect of MC vary with species at 20°C.

Mechano-sorptive compliance

As shown in Fig. 3, for each species the MS compliance during the first adsorption and all desorption linearly increases with increasing MC change despite some curvature in the specified MC range. MS compliance increases more remarkably during the first adsorption than during desorption. A similar behavior has been found in tangential tension of Douglas fir.[7,8]

Table 2 clearly shows the material parameter K_M (i.e., the slope of MS compliance versus MC change) in the six species. The parameter varies not only with species but with specific sorption. The parameters (K_M^{++}) for the first adsorption in kunugi and buna are markedly greater than those of other species. Also, hardwoods have a larger K_M^{++} than softwoods.

It can be found in Table 2 that the parameter K_M^- for all desorption presents positive values in the six species. Compared with softwoods, hardwoods have a greater K_M^-, with the largest value in kunugi and the lowest value in karamatsu. In addition, K_M^- varies slightly with specific desorption in each species.

Basically, K_M^{++} and K_M^- are considered to be inversely proportional to the density of the species, but in this study they are greater in kunugi and buna with higher density than in other species. This fact suggests that not only density but also other structural factors cause marked variation in the material parameters among the six species. In a study on the creep of ponderosa pine and Scots pine in bending under moisture changes, Hunt indicated that the parameter K_M increases with increasing the mean microfibril angle of the S_2 layer.[17] Erins et al. suggested that lignin, a three-dimensional network polymer, forms covalent bonds with the polysaccharide molecules and increases the ability of the wood to conform to applied stress.[21] In this study, the parameter (K_M) is relatively smaller in softwoods probably because lignin content in softwoods is generally larger than in hardwoods. Analysis of the slope of creep strain versus MC curve in spruce shows a considerable scatter between 0.25 and 3.10, with a mean value of 1.85,[22] implying that there is a marked variation of creep even in the same species.

Much of the MS creep is due to molecular mobility in an amorphous region.[23] When the environment exchanges a steady state of moisture during the sorption process, the hydrogen bonds between hydroxyl groups of water molecule and adjacent cellulose chains are broken. Thus, molecules or flowing segments in wood substances have mobility, and under external stress relative displacement between segments may arise, resulting in appreciable deformation of the wood.

During subsequent adsorption, with increasing MC the MS compliance in the species studied (except buna) gradually decreases (Fig. 3). As shown in Table 2, only in buna does the K_M^+ show a positive value, whereas the parameter

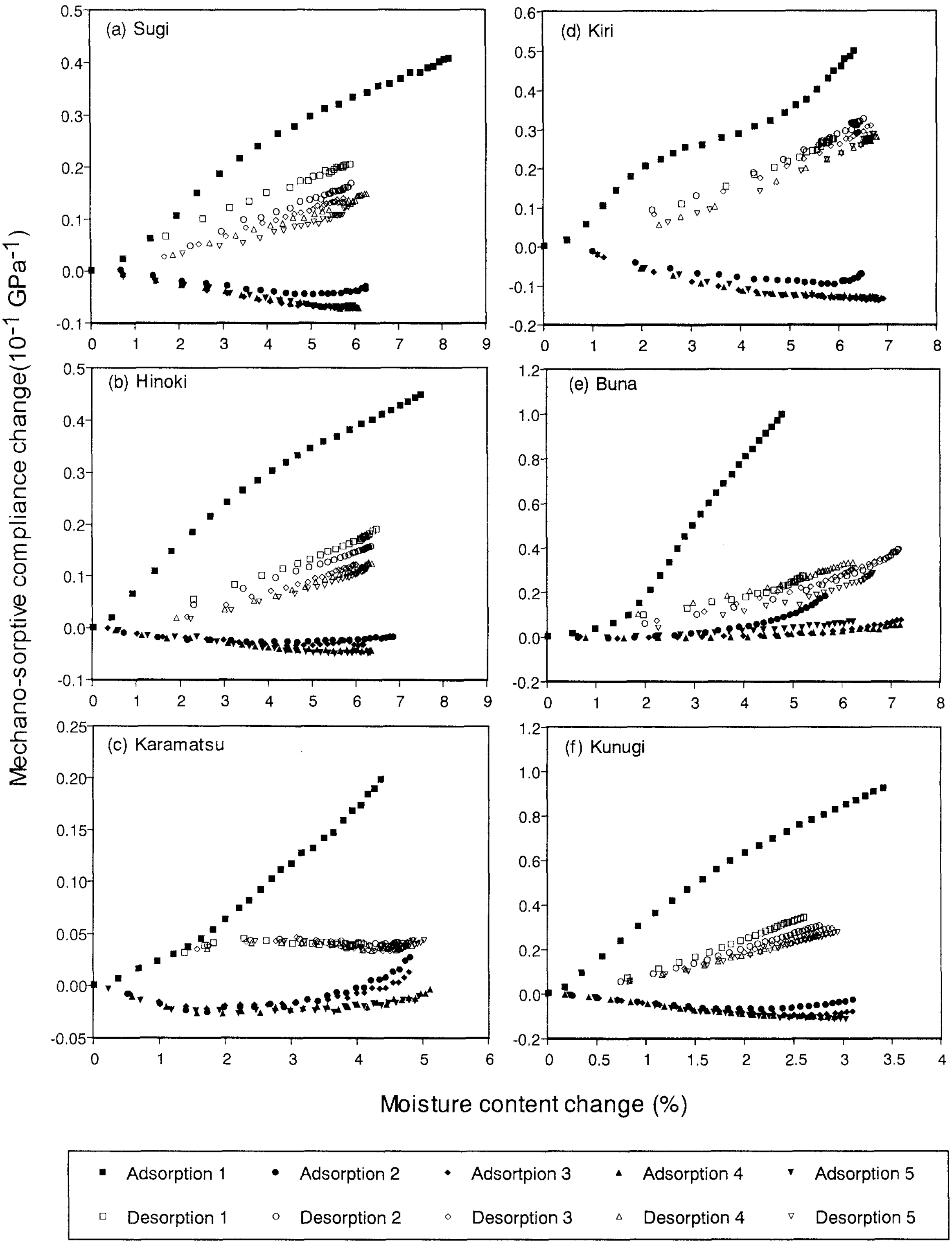

Fig. 3. Relation between mechano-sorptive compliance and moisture content change in the six species

K_M^+ in other species presents negative values. A considerable variation of K_M^+ can be found among the subsequent adsorption in each species, and K_M^+ decreases with increasing adsorption number.

The decrease of MS compliance is considered to be a recovery of MS deformation. For the MS creep, the recovery in the moisture adsorption should be related to the previous desorption process and is due to relaxation of

Table 2. MS parameter between MS compliance and moisture content change in six species under bending stress during cyclic moisture changes at 20°C

Species	MS parameter (K_M) (10^{-3} GPa^{-1}% u^{-1})									
	Adsorption					Desorption				
	1	2	3	4	5	1	2	3	4	5
Sugi	4.57	−0.57	−1.23	−1.32	−1.45	3.15	2.52	2.35	2.29	2.17
	(4.05)	(−1.29)	(−1.89)	(−1.90)	(−1.92)	(3.94)	(3.58)	(3.25)	(3.18)	(2.86)
	(5.09)	(−0.14)	(−0.57)	(−0.73)	(−0.99)	(2.37)	(1.47)	(1.45)	(1.40)	(1.49)
Hinoki	5.16	−0.22	−0.74	−0.71	−0.73	3.14	2.72	2.31	2.32	2.32
	(5.80)	(−0.12)	(−0.45)	(−0.65)	(−0.78)	(2.98)	(2.59)	(2.25)	(2.19)	(2.02)
	(4.53)	(−0.32)	(−1.03)	(−0.77)	(−0.69)	(3.31)	(2.86)	(2.36)	(2.45)	(2.61)
Karamatsu	4.12	−0.04	−0.42	−0.71	−0.87	1.49	1.25	1.23	1.29	1.34
	(4.14)	(−0.05)	(−0.37)	(−0.63)	(−0.77)	(1.24)	(1.22)	(1.15)	(1.20)	(1.27)
	(4.09)	(−0.02)	(−0.48)	(−0.78)	(−0.98)	(1.74)	(1.28)	(1.31)	(1.38)	(1.42)
Kiri	7.02	−0.75	−1.29	−1.28	−1.44	4.42	4.59	4.03	4.04	4.24
	(7.17)	(−1.13)	(−1.77)	(−1.64)	(−1.86)	(4.87)	(5.21)	(4.84)	(4.61)	(4.80)
	(6.86)	(−0.37)	(−0.80)	(−0.92)	(−1.02)	(3.97)	(3.97)	(3.21)	(3.47)	(3.68)
Buna	17.97	2.92	2.52	1.95	2.07	4.32	5.00	4.73	4.48	4.29
	(24.50)	(3.22)	(1.06)	(0.84)	(1.17)	(4.67)	(5.93)	(5.38)	(4.84)	(4.69)
	(11.44)	(2.61)	(3.98)	(3.05)	(2.97)	(3.98)	(4.08)	(4.07)	(4.12)	(3.88)
Kunugi	20.91	−0.05	−1.86	−2.77	−3.00	12.34	9.64	8.75	8.02	7.57
	(27.34)	(−1.10)	(−2.90)	(−3.67)	(−3.90)	(14.37)	(11.93)	(11.24)	(10.35)	(10.05)
	(14.49)	(1.20)	(−0.82)	(−1.87)	(−2.10)	(10.30)	(7.35)	(6.27)	(5.69)	(5.09)

The data in parentheses and first row are values from two creep tests and the mean of the two values, respectively.

stress built up in wood during the previous desorption.[3,16,23] Thus, MS creep shows a decrease or an increase during subsequent adsorption.[16] Norimoto and Gril[9] suggested that the recovery involves the molecular level but in combination with the ultrastructural (or macromolecular) level, as the microfibril framework keeps the memory of the initial shape of the 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 recovery to the initial shape exist simultaneously during the subsequent adsorption. In this study the MS deformation during adsorption does not recover completely: It partially recovers or even slightly enhances.

For each species, K_M^- during desorption appears to be larger than the absolute value of the parameter K_M^+ for subsequent adsorption but smaller than K_M^{++} for the first adsorption. This indicates that, compared with subsequent sorption, the first moisture adsorption causes the largest MS deformation under the same bending stress and amount of MC change. Similar behavior has been found in the tangential tension of Douglas fir[8] and longitudinal tension of pine.[1] According to Table 2, K_M^-/K_M^{++} varies considerably with species, ranging from 0.24 in buna to 0.69 in sugi.

It can be found by Eq. (6) and in Table 2 that in karamatsu the coefficient for MC effect on instantaneous compliance (2.22×10^{-3} GPa^{-1}% u^{-1}) is apparently larger than the absolute values of parameters K_M after the first adsorption (ranging from 0.04×10^{-3} to 1.49×10^{-3} GPa^{-1}% u^{-1}). As Eq. (1), total compliance contains instantaneous compliance and MS compliance. Thus, the behavior of total compliance in karamatsu is mainly dependent on instantaneous compliance during subsequent sorption, which is why total compliance decreases during desorption and increases during adsorption in karamatsu (Fig.1b). In the other species studied, instantaneous compliance change also influences the behavior of total compliance in terms of the parameters and the coefficient for MC effect on instantaneous compliance. As a result, instantaneous compliance more or less affects the behavior of total compliance under MC change and thus cannot be ignored in any study of creep.

Conclusions

In the six species studied, the total compliance, with different behavior, increases with sorption time; and its behavior is closely related to MC change. By the end of sorption, hardwoods have more total compliance than softwoods.

Instantaneous compliance increases linearly with increasing MC, varying among the species. In karamatsu, total compliance is mainly dependent on instantaneous compliance after the first adsorption. As a result, instantaneous compliance more or less influences the behavior of total compliance under MC change and thus cannot be ignored in any study of creep.

In general, with increasing MC change, MS compliance during the first adsorption and all desorption linearly increases and gradually decreases during subsequent adsorption. The MS compliance is more sensitive to MC change in hardwoods than in softwoods in terms of the material parameters (K_M), and the first adsorption causes the largest MS deformation, followed by desorption.

This study may provide an experimental basis for exploring the mechanism of MS creep. Among the six species, the effects of MC on instantaneous compliance and MS compliance are greater in hardwoods than in softwoods, likely due to the different anatomical and chemical characteristics between hardwoods and softwoods. Further work therefore should be done to examine anatomical and chemical characteristics of wood in relation to the variation of instantaneous compliance and MS compliance in the species investigated.

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