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ORIGINAL ARTICLE

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Bending creep behavior of hot-pressed wood under cyclic moisture change conditions

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Abstract This study examined the bending creep behavior of hot-pressed wood during cyclic moisture changes. Sugi (*Cryptomerica japonica* D. Don) specimens were pressed in the radial direction under six combinations of nominal compressive strain (33% and 50%) and press temperatures (140°C, 170°C, 200°C). Creep tests were conducted at 20°C with three cyclic relative humidity changes between 65% and 95% under 25% of short-breaking stress. The effect of moisture content (MC) change on elastic compliance and mechanosorptive (MS) compliance was investigated. The relation between MS compliance and thickness swelling was studied. The results indicated that total compliance increased over the history of cyclic moisture changes; and its behavior was closely related to the changes in MC and thickness swelling. The total compliance increased during adsorption and decreased during desorption. Elastic compliance increased linearly with MC and was dependent on press temperature and compression. With increasing MC change, MS compliance increased during adsorption and decreased during desorption. The first adsorption led to greater MS compliance than did the subsequent adsorption with the same amount of MC change. In general, the elastic parameter K_E and the MS parameter K_M increased with compression and decreased as the press temperature increased. The MS parameter K_M was apparently greater than the elastic parameter K_E. The MS parameter K_M increased with swelling coefficient K_{SW} of the hot-pressed specimen during adsorption and decreased with an increasing shrinkage coefficient K_{SH} during desorption.

Key words Hot-pressed wood · Creep · Cyclic moisture sorption · Bending stress · Sugi

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Introduction

With the worldwide move to intensive forest management to meet the demand for wood and to preserve the environment, the quality of wood supply has been undergoing significant changes that present great challenges to the wood industry and governments. Nowadays, the wood industry must utilize their existing resources more efficiently. Sugi (*Cryptomerica japonica* D. Don) accounts for half of the wood resources in Japan and is highlighted as a sustainable wood resource. The density of sugi wood appears to be relatively low, so it becomes imperative to increase its density and strength for better utilization of the wood resource.[1,2]

Radial compression has been found to be an effective way to increase wood density.[3] The compressed wood products may become a substitute for commercial woods with high density and strength.[4] Saito[5] found that heat treatment (200°C for 2h) after pressing markedly reduced the springback of hot-pressed wood. Arima[6] indicated that hot-pressed wood seems to recover linearly with increasing moisture content (MC), and the magnitude of applied compressive load has a significant effect on the rate of recovery. Suematsu et al.[7] demonstrated that thickness swelling of hot-pressed wood after water absorption decreased with increasing press temperature and increased with an increasing amount of compression. Inoue et al.[8] suggested that the recovery of compression set after boiling in water decreased with increases in heating time and temperature, and the moisture in wood played an important role in the fixation of deformation. Norimoto[9] indicated that recovery of the compression set of wood decreases with increasing press temperature and time. The mechanical properties of hot-pressed wood increase with increasing compression and decrease with increasing press temperature and time. Inoue et al.[10] found that the compressive deformation of wood can be permanently fixed by heating or steaming at high temperature. Tabarsa and Chui[11] demonstrated that the hygroscopicity of wood was affected primarily by heat, and the differences in mechanical properties were small between 150 and 200°C.

Mechanosorptive (MS) creep is a deformation due to an interaction between stress and MC change.[12] In many situations where wood is subjected to applied stress and MC change, the wood undergoes MS deformation that may result in great deformation or early failure of wood. The rheological behavior of wood and wood composites during moisture changes has been widely studied. So far, however, no investigation has been conducted on the bending creep behavior of hot-pressed wood under cyclic moisture change conditions.[13,14] Total deformation of hot-pressed wood under moisture change contains elastic deformation and MS deformation:

$$D_T = D_E + D_M \tag{1}$$

where D_T is total compliance (MPa^{-1}), D_E is elastic compliance (MPa^{-1}), and D_M is MS compliance (MPa^{-1}).

The objectives of the study were to (1) examine the bending creep behavior of hot-pressed sugi wood during cyclic moisture changes; (2) investigate the effects of MC change on elastic and MS compliance; and (3) evaluate the relation between MS compliance and thickness swelling.

Materials and methods

Manufacture of hot-pressed specimens

Defect-free boards with dimensions 320 (L) × 40 (T) × 15 (R) mm and 320 (L) × 40 (T) × 20 (R) mm were cut from air-dried sapwoods of sugi (*Cryptomerica japonica* D. Don). These boards were stored in an air-conditioned room at 20°C and 65% relative humidity (RH) and conditioned to 13% MC. For each size board, three groups with five boards each were prepared for hot-pressing. One group of specimens with dimensions 320 (L) × 10 (T) × 10 (R) mm was not hot-pressed and was used as the control. To eliminate the effects of wood density differences on the performance of hot-pressed wood, these groups were arranged in terms of wood density so the means and standard deviations of density in all groups were similar.

The hot-pressing parameters in the study and their levels were nominal compression (33% and 50%) and press temperature (140°C, 170°C, and 200°C). Totally, six combinations of parameters were given. Each group of boards was hot-pressed under a specific combination of parameters using a laboratory hot-press. The compression force was applied in the radial direction of boards. Press stops were used to ensure that the final thickness (10mm) was reached. Pressure (1.5MPa) was maintained at the final thickness for 20min. After hot-pressing each board was cut along its length to produce three 10mm wide test specimens, so the dimensions of each specimen were 320 (L) × 10 (T) × 10 (R) mm. All specimens were stored in an air-conditioned room until they reached equilibrium moisture content (EMC). The modulus of rupture (MOR) and modulus of elasticity (MOE) were then measured for each of six groups of hot-pressed specimens.

Elastic compliance test

The mass and dimension of the specimens for examining the effect of MC on elastic compliance were determined at 20°C and 65% RH, and their elastic deflection under a load 25% of the short-term breaking load was measured. Subsequently, the specimens were transferred to a chamber conditioned at 20°C and 95% RH using saturated potassium sulfate solution; and the RH was cycled. In total, three cyclic RH changes between 65% and 95% were made, with 24h for each sorption. The specimens were removed from the conditioning chamber at measured time intervals. Their mass, dimension, and elastic deflection were measured immediately, and the specimens were then placed back in the conditioning chamber. After cyclic moisture sorption, the three specimens were oven-dried and their oven-dried mass and dimensions were measured.

Creep test

The creep test was performed in a chamber placed in the air-conditioned room at 20°C and 65% RH. A load corresponding to 25% of the short-term breaking load was applied on the T-L face of the creep specimen to create four-point bending. In this study deflection 12s after load application was defined as the initial elastic deflection. The deflection was measured with a dial gauge with an accuracy of 0.01mm. The thickness swelling of the load-free specimen was continuously measured with another, similar dial gauge. The mass change of the MC specimen was constantly monitored by a digital balance (accuracy up to 0.001g) placed outside the conditioning chamber with an attached specimen hanger passing into the chamber. After load application, the RH condition in the chamber was maintained at 95% using saturated potassium sulfate solution for 24h. The salt solution was then removed from the chamber, and the RH level was maintained at 65% for 24h. In all, three cyclic RH changes between 65% and 95% were made. The test was replicated once for each group of specimens.

Calculations

Thickness swelling of hot-pressed wood was calculated as:

$$TS = \left[\frac{T_1 - T_0}{T_0}\right] \times 100\% \tag{2}$$

where TS is the thickness swelling (%), T_1 is the thickness at a given MC level (mm), and T_0 is the thickness at the reference RH level (mm) (The reference RH was 65% in this study.)

Compliance of the specimen under bending stress can be expressed as:

$$D = \frac{4bh^3y}{Pa(3l^2 - 4a^2)} \tag{3}$$

where D is compliance (Pa^{-1}), b is the width of the specimen (m), h is the depth of specimen (m), y is the deflection of the

Table 1. Summary of the properties of hot-pressed specimens

Compression (%)	Temperature (°C)	SG	MOE (GPa)	MOR (MPa)	EMC (%)
33	140	0.45 (0.03)	11.4 (1.6)	81.1 (2.9)	10.3 (0.1)
	170	0.45 (0.03)	10.5 (3.0)	83.7 (7.9)	10.2 (0.1)
	200	0.45 (0.03)	10.8 (2.1)	78.1 (4.7)	9.8 (0.0)
50	140	0.62 (0.03)	14.3 (3.3)	110.1 (5.4)	10.1 (0.0)
	170	0.60 (0.04)	13.6 (1.9)	102.3 (8.0)	9.9 (0.1)
	200	0.60 (0.03)	14.1 (1.1)	104.7 (6.1)	9.6 (0.1)
Control		0.33 (0.01)	8.9 (0.6)	71.1 (4.2)	13.1 (0.0)

Values in parentheses are standard deviations
SG, specific gravity, based on oven-dry mass and volume at 65% relative humidity; MOE, modulus of elasticity; MOR, modulus of rupture; EMC, equilibrium moisture content

specimen under bending stress (m), P is the load (N); a is the load span (m) (0.1 m in this study), and l is the span (m) (0.3 m in this study).

In the creep tests the measured deflection of the loaded specimen contained a thickness swelling due to MC change, which was determined in terms of the measurement of the load-free specimen. During the calculation for total compliance, the total deflection of the loaded specimen was calculated by adding the magnitude of thickness swelling of the specimen to the measured deflection. As in Eq. (1), MS compliance D_M was calculated by subtracting the elastic compliance D_E from the total compliance D_T. The details of the calculation are described in previous papers.[15,16]

Results and discussion

Table 1 shows the properties of hot-pressed specimens at 20°C and 65% RH. It can be seen that the specimens with greater compressive strain had larger specific gravity, MOE, and MOR. In comparison, temperature had a weak influence on specific gravity, MOE, and MOR. The EMC of hot-pressed specimens appeared to be lower than that of the untreated wood (control), and it decreased with increasing press temperature. A similar behavior has been observed in hot-pressed wood of white spruce.[11]

Moisture content, thickness swelling, total compliance

Figure 1a shows the MC of hot-pressed specimens during cyclic RH changes between 65% and 95%. The magnitude of the MC change of hot-pressed specimens appeared to be smaller than that of the control, probably owing to the different specific gravity and hygroscopicity of the specimens.

As shown in Fig. 1b, the thickness swelling of specimens increased during moisture adsorption and decreased during desorption. The thickness of the specimens did not return to their initial stage during moisture desorption because moisture-related thickness swelling of hot-pressed wood consists of two components: swelling of wood itself (recoverable) and release of compression stress from the pressing operation (unrecoverable). The thickness swelling increased with the moisture cycle, which led to increases in

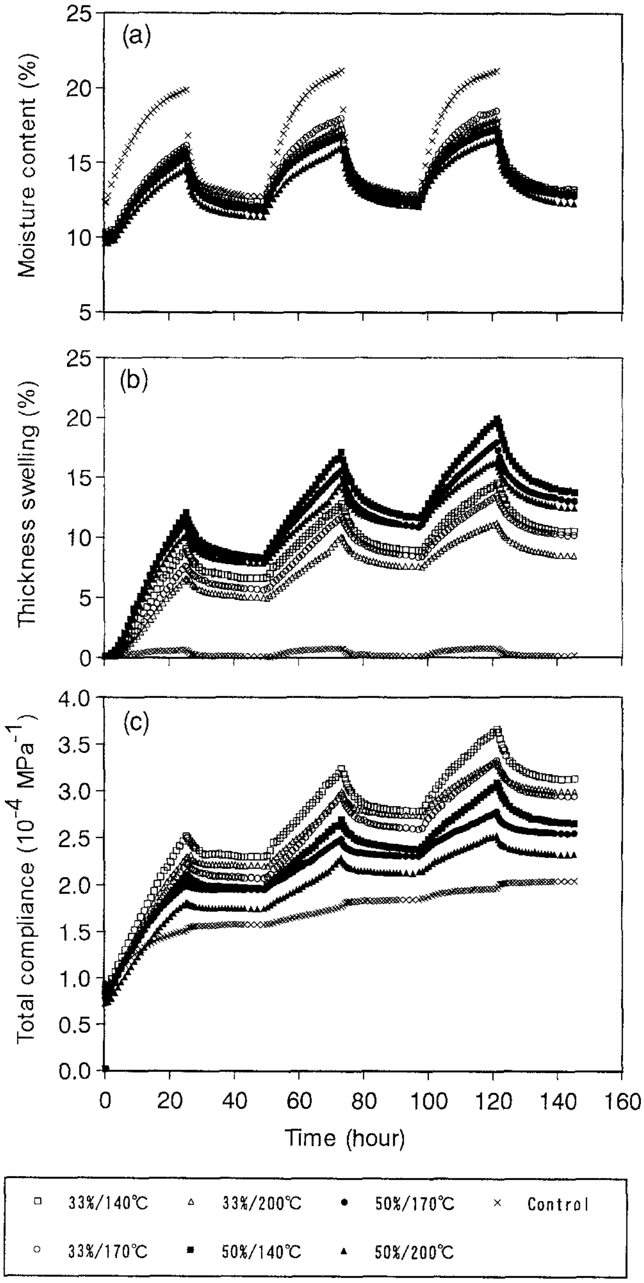

Fig. 1. Moisture content (**a**), thickness swelling (**b**), and total compliance (**c**) as a function of sorption time

the dimensions of the hot-pressed specimens by the end of the cyclic moisture sorption. Release of compression stress occurs at high RH, and this part of the swelling is not recovered when the specimen returns to a drier state. It can be seen that the thickness swelling under 50% compression was greater than under 33% compression, suggesting that thickness swelling increased as compression increased.

As shown in Fig. 1c, the total compliance of hot-pressed specimens with similar behavior increased during the cyclic moisture changes. Total compliance behavior was closely related to the MC and thickness swelling changes, implying a significant effect of MC and thickness swelling. For each specimen, the total compliance increased markedly during moisture adsorption and decreased during desorption. The behavior is quite different from that of the control, for which total compliance increased during both adsorption and desorption. Similar results have been found with particleboard, hardboard, and plywood.[17,18] These findings suggest that hot-pressing treatment not only modifies the mechanical properties of wood but also changes its rheological behavior.

Relation between thickness swelling and MC

Figure 2 shows the thickness swelling of hot-pressed specimens as a function of MC during adsorption and desorption. It can be found that the thickness swelling increased as the MC increased during adsorption, and it decreased as the MC decreased during desorption. A linear fit between thickness swelling and MC for all six conditions led to the following relations:

$$\mathrm{TS} = K_{SW}\,\mathrm{MC} \quad (4)$$

$$\mathrm{TS} = K_{SH}\,\mathrm{MC} \quad (5)$$

where TS is thickness swelling (%), K_{SW} is the swelling coefficient for the relation between thickness swelling and MC during adsorption (%/%), and K_{SH} is the shrinkage coefficient for the relation during desorption (%/%).

The average values for K_{SW} and K_{SH} are given in Table 2. The specimens hot-pressed under 50% compressive strain had higher swelling and shrinkage coefficients (from 1.82 to 2.26 and from 1.10 to 1.64, respectively) than did those under 33% compressive strain (from 1.16 to 1.64 and from 0.72 to 1.13, respectively). The thickness swelling of hot-pressed specimens depended on the release of internal stress from the press operation. The internal stress in the specimens under 50% compressive strain was larger than that under 33% compressive strain. In addition, the specimen with higher density had a greater thickness swelling.[19]

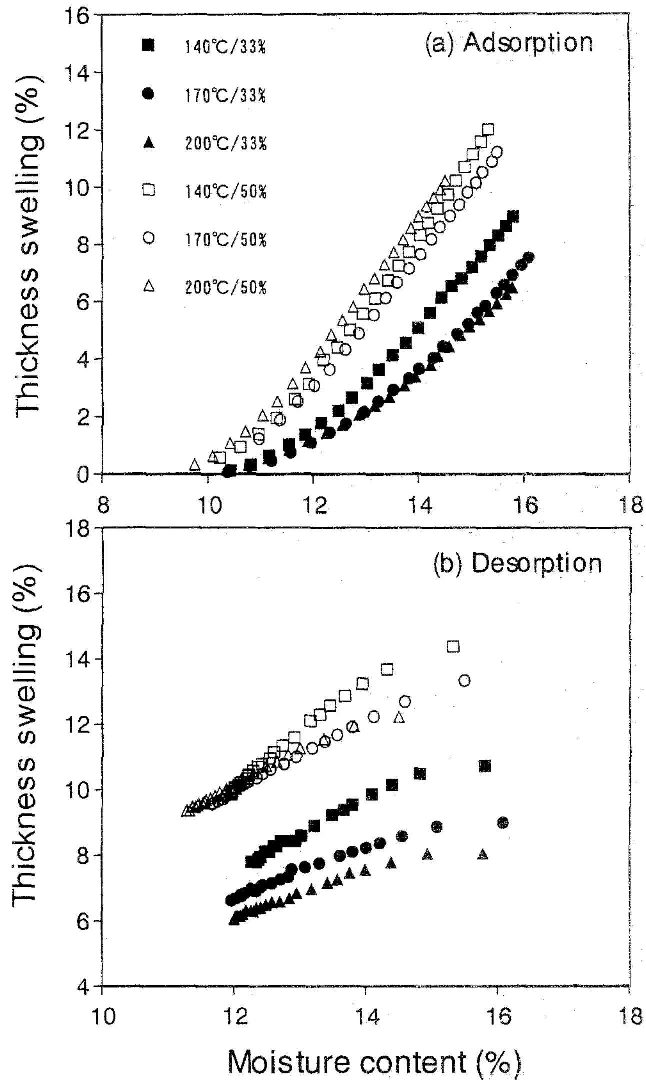

Fig. 2. Typical plots showing thickness swelling as a function of moisture content during adsorption (**a**) and desorption (**b**)

Table 2. Summary of thickness swelling and shrinkage coefficients and the elastic and mechanosorptive parameters

Compression (%)	Temperature (°C)	K_{SW} (%/%)	K_{SH} (%/%)	K_E (10^{-5}MPa^{-1}%$^{-1}$)	K_M (10^{-5}MPa^{-1}%$^{-1}$) AD1	AD2	AD3	DE1	DE2	DE3
33	140	1.64	1.13	0.22	2.42	1.94	1.70	−0.58	−0.98	−1.16
	170	1.28	0.78	0.19	1.95	1.51	1.11	−0.29	−0.61	−0.72
	200	1.16	0.72	0.18	1.99	1.27	0.99	−0.11	−0.39	−0.51
50	140	2.26	1.64	0.52	2.63	2.02	1.90	−0.22	−0.76	−1.16
	170	1.89	1.22	0.48	2.26	2.03	1.96	−0.59	−0.97	−1.39
	200	1.82	1.10	0.41	2.48	1.64	1.41	−0.24	−0.60	−0.80
Control		0.08	0.08	0.13	0.72	0.09	0.02	0.22	0.22	0.22

K_{SW}, thickness swelling coefficient; K_{SH}, shrinkage coefficient; K_E, elastic parameter; K_M, mechanosorptive parameter; AD1, AD2, and AD3, adsorption 1, adsorption 2, and adsorption 3, respectively; DE1, DE2, and DE3, desorption 1, desorption 2, and desorption 3, respectively

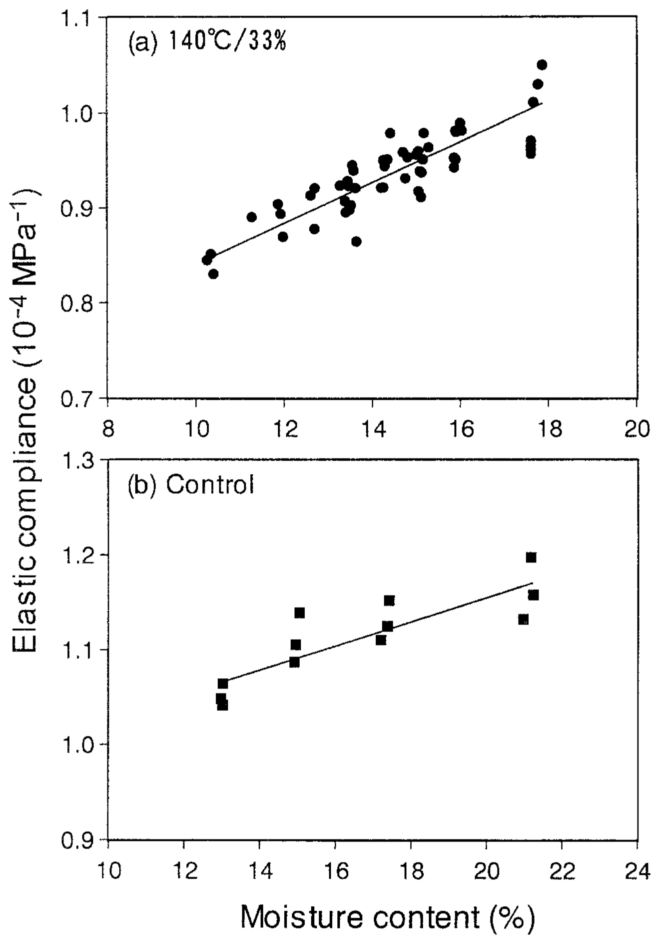

Fig. 3. Typical plots showing elastic compliance as a function of moisture content for hot-pressed specimens (**a**) and controls (**b**). Lines show the linear fit of the data

For compressive strain, in general, the swelling and shrinkage coefficients (K_{SW} and K_{SH}) decreased as the press temperature increased. This finding is similar to the observations of Suematsu et al.[7] and Tabarasa and Chui.[11]

Relation between elastic compliance and MC

Figure 3 shows a typical plot of elastic compliance as a function of MC for hot-pressed specimens. Elastic compliance increased as the MC increased. All hot-pressed specimens followed a similar relation with MC over the given MC change. A linear fit between elastic compliance and MC for all six conditions led to the following relation:

$$D_E = D_{E0} + K_E \text{ MC} \quad (6)$$

where D_{E0} is the elastic compliance at some standard MC (MPa^{-1}), and K_E is the elastic parameter for the relation between elastic compliance and MC ($MPa^{-1}\%^{-1}$).

Regression analysis was used to fit Eq. (6) to obtain the elastic parameter (K_E). The results for K_E are also listed in Table 2. The specimens hot-pressed under 33% compression had a smaller elastic parameter ($0.18–0.22 \times 10^{-5} MPa^{-1}\%^{-1}$) than did those pressed under 50% compression ($0.41–0.52 \times 10^{-5} MPa^{-1}\%^{-1}$). The elastic parameter decreased as the press temperature increased. A negative consequence of thickness swelling is the reduction of strength properties of hot-pressed specimens. As the MC increased, elastic compliance increased with thickness swelling, and thus the elastic parameter K_E increased with thickness swelling.

Relation between MS compliance and MC change

Figure 4 shows typical plots for the relation between MS compliance and MC change. With increasing MC change, the MS compliance of hot-pressed specimens increased in adsorption and decreased in desorption. The first adsorption led to greater MS compliance than did the subsequent adsorption. However, the MS compliance of the control increased linearly with increasing MC change during the first adsorption and all desorption while it showed a slight increase during the subsequent adsorption.

A linear fit between MS compliance and MC change led to the following relation:

$$D_M = K_M|M| \quad (7)$$

where K_M is the MS parameter for the relation between MS compliance and MC change ($MPa^{-1}\%^{-1}$), and M is the MC change (%). To obtain the MS parameter K_M for each specified sorption, least-squares regression was used to fit Eq. (7), with MS compliance as the dependent variable and MC change as the independent variable. The values of K_M are listed in Table 2.

The MS parameter K_M during adsorption generally decreased with increases in press temperature, and it increased with increasing compression. The absolute value for the MS parameter of the hot-pressed specimens was significantly greater than that of the control. This is due to the fact that, in addition to the MC effect, the larger thickness swelling of the hot-pressed wood might have importantly affected MS compliance. The physical state of wood amorphous polymers changes from glassy to rubbery when they are heated to the glass transition temperature. The tendency for the material to "flow" under sustained pressure and to exhibit permanent deformation upon removal of the pressure increases with the temperature.[20]

When the wood was hot-pressed the hydrogen bonds between the molecules of cell wall polymers were re-formed, and so the deformation was fixed. Much of the MS creep is due to molecular mobility in the amorphous region. During moisture adsorption unrecoverable thickness swelling occurs, and so the re-formed hydrogen bonds between the molecules of cell wall polymers are broken. As a result, molecules or flowing segments in wood substances have mobility; and under external stress, relative displacement between segments may arise, resulting in appreciable deformation in the wood.

During the first adsorption, some of the deformation caused by compression was recovered, so the total thickness swelling considerably increased (Fig. 1b). However, the increase in total thickness swelling of compressed wood

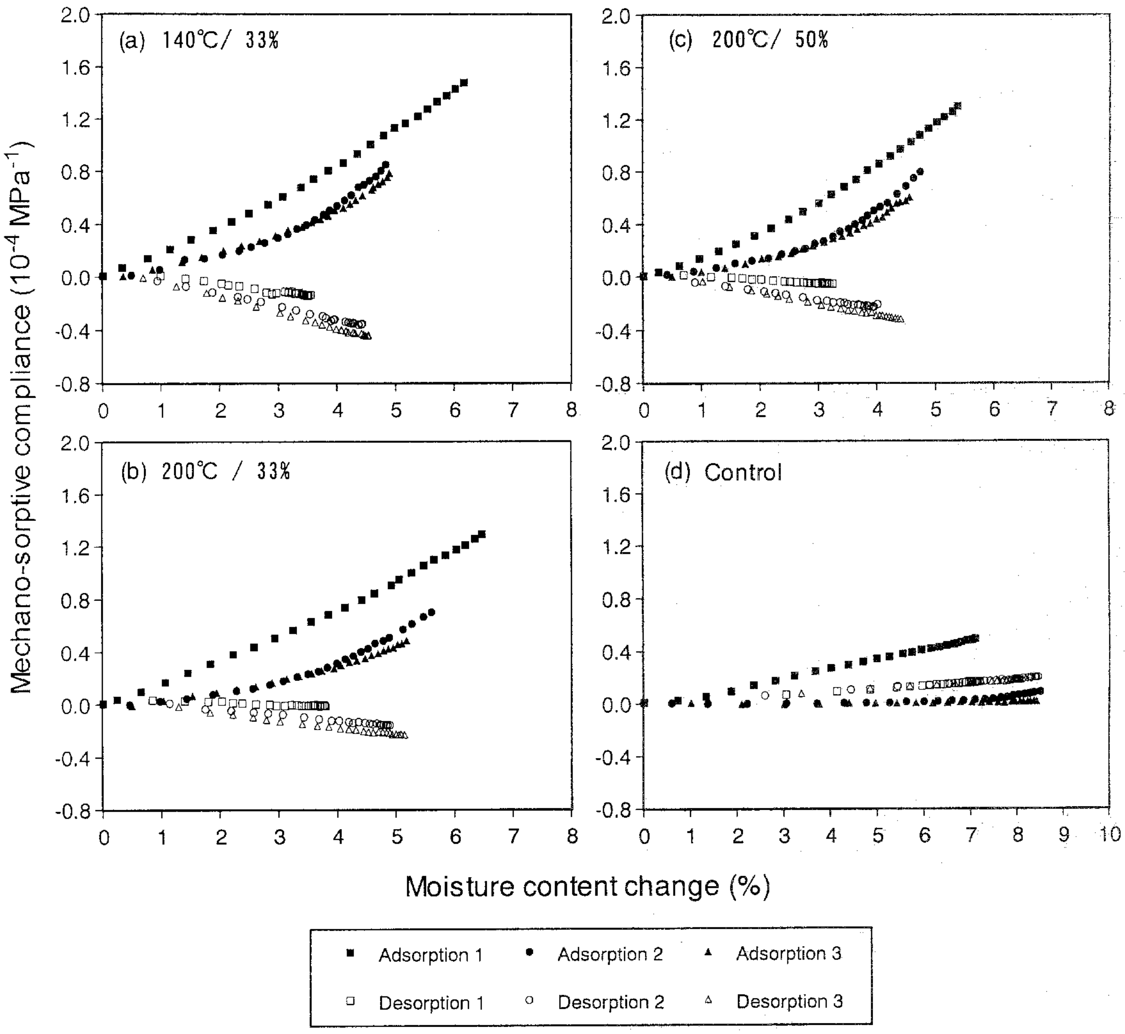

Fig. 4. Typical plots showing the relation between mechanosorptive compliance and moisture content change

during subsequent adsorption appeared to be less owing to its smaller amount of remaining unrecoverable thickness swelling. Therefore, the MS compliance during subsequent adsorption was less than that during the first adsorption.

In contrast to the control, the dimension of the hot-pressed specimens fluctuated markedly during cyclic moisture sorption. As a result, the amount of wood substance per unit volume of specimen also varied owing to the changes in volume; that is, it decreased 9%–15% during adsorption and increased 5%–6% during desorption. This behavior may cause an increase in elastic and MS compliance during adsorption and a decrease during desorption. As shown in Eq. (3), compliance D is directly proportional to bh^3y. During adsorption, depth h and deflection y considerably increased, and so MS compliance increased as well. On the other hand, during desorption the data for MS deflection y revealed a slight increase, but depth h appreciably decreased. As a result, MS compliance during desorption showed a reduction.

As the sorption cycle increased, the absolute value for the MS parameter decreased during adsorption and increased during desorption (Table 2). This implies that the increase in MS compliance tends to be smaller with increasing sorption cycle. The absolute value for the MS parameter (0.11–$2.63 \times 10^{-5}\mathrm{MPa}^{-1}\%^{-1}$) was generally higher than the elastic parameter (0.18–$0.52 \times 10^{-5}\mathrm{MPa}^{-1}\%^{-1}$). This suggests that the total compliance behavior was mainly dependent on the changes of MS compliance during cyclic moisture changes.

Relation between MS compliance and thickness swelling

Figure 5 shows the relation between the MS parameter (K_M) and the thickness swelling coefficient (K_{SW}) of specimens during adsorption. The MS parameter increased as the swelling coefficient increased, with the same MC change. The positive correlation ($r = 0.73$) between K_M and K_{SW} was statistically significant at the 0.01 level. This suggests that MS compliance increases are closely related to the thickness swelling increase. Figure 6 represents the relation between the MS parameter (K_M) and the shrinkage coefficient (K_{SH}) of specimens during desorption. The MS parameter decreased as the shrinkage coefficient increased.

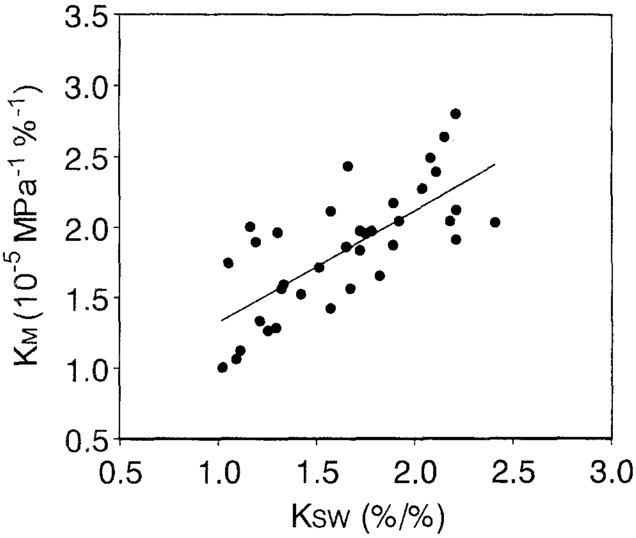

Fig. 5. Mechanosorptive parameter (K_M) as a function of the swelling coefficient (K_{SW}) in adsorption. *Line* shows a linear fit for the data. The regression equation for K_M and K_{SW} with a correlation coefficient of 0.73 is $K_M = 0.52 + 0.80\ K_{SW}$

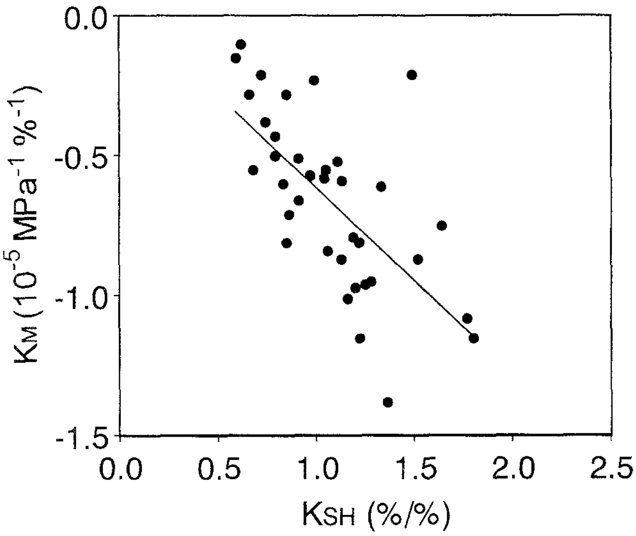

Fig. 6. Mechanosorptive parameter (K_M) as a function of the shrinkage coefficient (K_{SH}) during desorption. *Line* shows a linear fit for the data. The regression equation for K_M and K_{SH} with a correlation coefficient of −0.66 is $K_M = 0.05 - 0.66\ K_{SH}$

The negative correlation ($r = -0.66$) between K_M and K_{SH} was statistically significant at the 0.01 level. This implies that the considerable reduction in the dimensions of the specimens causes the decrease in MS compliance during desorption.

Thus, the MS creep of hot-pressed wood is believed to depend on the changes in cohesive forces between molecular chains and the amount of wood substance per unit volume due to thickness swelling and shrinkage. Studies of moisture effect on the creep behavior of hot-pressed wood should include the effect of thickness swelling. Efforts must be made to reduce the thickness swelling during manufacturing so as to decrease the development of MS creep during a change in moisture conditions. Because MC change is the most obvious factor influencing thickness swelling, protection of hot-pressed woods from moisture uptake during use has some important practical significance for maintaining their quality and performance.

Conclusions

In the six groups of hot-pressed woods, total compliance with similar behavior increased over the course of the cyclic moisture changes; and its behavior was closely related to the changes in MC and thickness swelling. Total compliance increased during adsorption and decreased during desorption. Thickness swelling and elastic compliance increased linearly with the MC and was dependent on press temperature and compression. With increasing MC change, MS compliance increased during adsorption and decreased during desorption. The first adsorption led to greater MS compliance than did the subsequent adsorption, with the same amount of MC change. In general, the elastic parameter K_E and MS parameter K_M increased with compression and decreased as the press temperature increased. The MS parameter K_M was apparently greater than the elastic parameter K_E. The MS parameter K_M increased with the swelling coefficient K_{SW} of hot-pressed specimens during adsorption and decreased with the increasing shrinkage coefficient K_{SH} during desorption. MS compliance significantly increased with thickness swelling owing to exposure to high humidity. Therefore, efforts should be made to reduce thickness swelling during manufacturing and protect the hot-pressed woods from moisture uptake during use. This study provides basic information on the rheological behavior of hot-pressed wood during cyclic moisture changes. Further work is planned to explore creep behavior at various thickness swellings.

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