JOURNAL OF MATERIALS SCIENCE 21 (1986) 2088–2096

The mechano-sorptive creep susceptibility of two softwoods and its relation to some other materials properties

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This paper describes a new design of bending creep machine for accurate measurements of mechano-sorptive creep. Tests on two species of pine showed that at low stresses bending and tension gave similar results. It is shown that the mechano-sorptive creep susceptibility correlates with the mean microfibrillar angle of the S2 layer in a continuous relation that includes two species of pine, including one which showed evidence of compression wood; thus giving further evidence of the importance of inter-microfibril stresses in the S2 layer in mechano-sorptive creep. Accordingly, mechano-sorptive creep susceptibility also correlated continuously with elastic compliance; thus encouraging the possibility of the selection of non-susceptible material by machine stress grading. These two correlations also diminish the main obstacle to research on mechano-sorptive creep, the excessive variability of the material and the consequent difficulty of matching of samples.

1. Introduction

In common with other hydrophilic materials, wood creeps more under stress at a high moisture content than at a low moisture content. However, wood creep appears to differ from that of synthetic polymers, in suffering anomalous creep behaviour under changing moisture conditions. This anomalous creep behaviour is often termed "mechano-sorptive" creep.

Typically there are three aspects of mechano-sorptive creep. Firstly, during any decrease of moisture content the creep deflection increases. Secondly, during any increase of moisture content, at moisture levels reached for the first time since the load was applied, the creep deflection increases much in excess of that expected due to the moisture level alone. And thirdly, during moisture increases at levels reached for the second or subsequent times since the load was applied, the creep deflection decreases. This type of behaviour has been known since 1960 when Armstrong and Kingston [1] first reported it. Since then a large number of papers has been published on the subject (for example, see the extensive review by Grossman [2]).

A method of quantifying mechano-sorptive creep was proposed by Ranta Maunus [3] using the following equation

$$\varepsilon = \sigma_0 \left[J + \sum_{i=1}^{n} aJ_{00}(u_i - u_{i-1}) \right] \qquad (1)$$

where ε is the strain at a constant stress σ_0, J_{00} is the instantaneous elastic compliance at 0% moisture content, J is the integrated cumulative creep and elastic compliances that would be expected as a function of the elapsed time at the moisture contents sustained during the test, n is the number of step changes between moisture contents u_{i-1} and u_i, and a is known as the hydroviscoelastic constant and has three distinct values: a^- for decreases in moisture content, a^{++} for first moisture increases at any moisture content level and a^+ for subsequent moisture increases. More general forms of this equation could be in terms of the total compliance:

$$J_{\text{total}} = J + J_{00} \sum_{i=1}^{n} a(u_i - u_{i-1}) \qquad (2)$$

or in terms of dimensionless, or relative creep:

$$\varepsilon_{\text{rel}} = J/J_{00} + \sum_{i=1}^{n} a(u_i - u_{i-1}) - 1 \qquad (3)$$

where the relative creep is expressed as the ratio of the creep to elastic compliances and is composed of a "normal" creep term and a mechano-sorptive creep term. The hydroviscoelastic content is seen to be dimensionless but having the meaning of change in relative creep per unit of moisture content change. It must be emphasized here, that this theory is based on the assumption of a fundamental difference, without interaction, between normal and mechano-sorptive creep. Such a difference is not universally accepted.

This classical view of mechano-sorptive creep needs to be modified slightly in the light of results recently presented by the author [4] who, in attempting to quantify the mechano-sorbtive creep of beech, found that the hydroviscoelastic constants depended upon the levels of moisture content and of creep compliance (or strain). Although an attempt was made to quantify the mechano-sorptive creep of beech, it was plain that there were many difficulties to be overcome before a design code could be written.

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There are two main areas in which the study of mechano-sorptive creep must progress. These are the development of a theoretical explanation based on the structure of wood, and the development of design procedures to enable codes of practice to be drawn up.

A number of theoretical explanations have been proposed, but none have fitted all of the known facts. Little progress appears to have been made since the review of Grossman [2]. The most useful explanation appears to be the effect of stress bias during hydrogen-bond breaking and re-making during moisture changes. Since hydrophilic synthetic polymers also have hydrogen bonding but do not suffer mechano-sorptive creep, the difference must be related to the structure of the wood; and possibly to the wood microfibrils, the elementary strands of cellulose molecular chains, being arranged at preferred orientations to the principal stressing (grain) direction. Such bonds would then be stressed in shear and tension, at a magnitude determined by the microfibrillar orientation relative to the stressing direction. Although the orientation of the microfibrils is different for different layers of the cell wall, for convenience the mean microfibrillar angle of the main structural S2 layer will be referred to in this paper. Since the mean microfibrillar angle is also related to other properties such as magnitude of orthotropic shrinkage [5, 6] and elastic modulus [7], this theory suggests that susceptibility of wood to mechano-sorptive creep might correlate positively with the reduction in Young's modulus, the increase in longitudinal swelling and the decrease in transverse swelling that are associated with larger microfibrillar angles. Since the microfibrillar angle is also known to correlate with the growth-ring position [8], the above theory suggests that mechano-sorptive creep susceptibility should also correlate with growth-ring position within a single tree.

Whilst the above theory, based on the effect of stress bias on hydrogen bonding, is probably part of the explanation, it must be modified to account for recovery observations [9–12], for the phenomenon not being observed during moisture diffusion [13], and for the differences between the first and subsequent moisture increases.

The main priority in developing design procedures is to gather data for softwoods, which are much more widely used than hardwoods such as beech. This work must involve the stress grading and selection of the materials to be used. The author's previous work [4] on beech indicated the wide variation of creep properties, even between test pieces cut from the same piece of wood. During the current work on two species of softwoods (pines) even larger variations were observed, especially between the two species; one extreme giving about six times the response of the other. It was quite clear, then, that two essential preliminaries to any development of a design procedure were:

1. the establishment of a creep-testing procedure to quantify the susceptibility of a piece of wood to mechano-sorptive creep (ideally using a minimum time for the test); and
2. the correlation of other material properties with the measured susceptibility, with the goal of finding a simple property measurement that can be used to grade a material for its mechano-sorptive creep susceptibility (in the same way that stiffness measurements can be used to grade wood for strength properties).

The scope of this paper, then, is as follows:

(a) to study the qualitative mechano-sorptive creep behaviour of samples of two species of softwoods, one of which was very susceptible and the other of which was very resistant to mechano-sorptive creep. The independent variables were moisture content and compliance levels;
(b) to present a procedure for quantifying the differences between the two samples;
(c) to show how the above procedure was used to measure, for the resistant and the susceptible samples, the effect of the microfibrillar angle of the test piece on the mechano-sorptive creep susceptibility;
(d) to present some correlations of mechano-sorptive creep susceptibility with other properties which are themselves dependent on microfibrillar angle or growth-ring position for both species: elastic compliance and dimensional changes with moisture-content changes.

The following symbols are used in this paper: J^* is the mechano-sorptive creep compliance in general, whilst J^{++}, J^+ and J^- are mechano-sorptive creep compliances specifically associated with the hydro-viscoelastic constants a^{++}, a^+ and a^-, respectively, and with the corresponding types of moisture change (units are $m^2 N^{-1}$). This allows the Ranta Maunus equation to be re-written for the total compliance,

$$J_{\text{total}} = J + \sum_{i=1}^{n} \frac{dJ^*}{du}(u_i - u_{i-1}) \qquad (4)$$

where J^* takes the value J^{++}, J^+ or J^- according to the type of moisture change. This form of the equation has the advantage that it is not necessary to know the value of J_{∞}. However, this form of the equation makes no allowance for stress dependence of dJ^*/du; but provided that the stress remains constant, this causes no problem. The results presented below appear to show that at low levels of stress (below about 10% of the breaking stress) the stress level does not greatly affect the values of J_{total}.

2. Experimental procedure

The creep tests were performed in an environmental chamber that has been described [14]. The temperature was maintained at $23.5 \pm 0.1°$C throughout. The relative humidity, which could be varied, was controlled within $\pm 1\%$.

Five creep machines were used simultaneously; three tensile and two bending. The tensile machines have been described [14].

A section through a bending-creep machine is shown in Fig. 1. This uses four-point loading, with knife-edge bearings to accurately define the 80 mm length of the bending region. The knife edges (A), transducer holder and vibrator are all mounted on a massive metal frame (F) whose parts are accurately

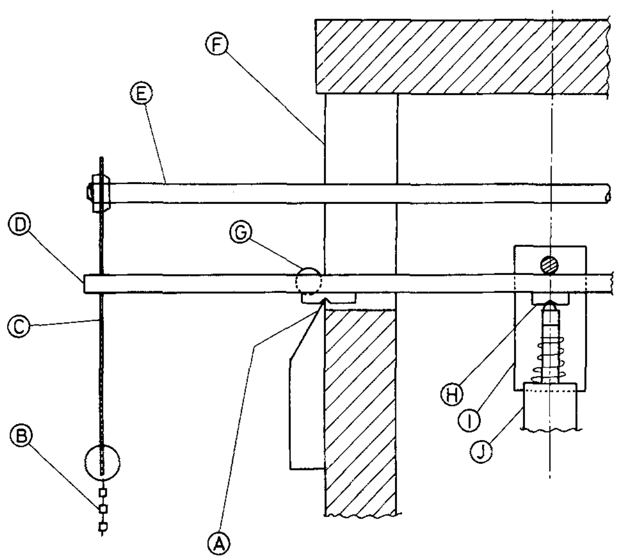

Figure 1 Section through bending creep machine.

aligned and located. Deflections are measured with a SLVC transducer (J) whose end bears against a pad (H) to prevent any indentation of the test piece (D). A vibrator is operated just prior to taking a reading in order to prevent any sticking of the transducer and to ensure improved accuracy. The force of the transducer spring is balanced by a static balancing weight (I). The load is hung on a rigid bar that hangs on a chain (B) from the load applicators (C), which are made from 0.5 mm thick sheet and accurately spaced 160 mm apart by a spacer rod (E). Centring of the test piece within the load applicators, the transducer-spring balancing weight and the frame fork above the knife edges, is achieved with high-pile velvet pads; those (G) for the frame being adjustable. This gently centres the test piece without applying pressure when the test piece swells at high moisture contents. Trial tests of these machines using metal test pieces gave an accuracy of about $\pm 0.25\%$ at the 0.1% strain level.

Two species of softwoods were used for these tests: ponderosa pine (*Pinus ponderosa*) and Scots pine (*Pinus sylvestris*). The Scots pine showed evidence of compression wood, the abnormal wood that forms on the compression side of a leaning tree. This wood has a number of structural and chemical differences from normal wood, including a larger mean microfibrillar angle. In this case the Scots pine had relatively high microfibrillar angles ranging from 26° to 33°, compared with from 17° to 25° for the ponderosa pine. Both materials had similar densities of around $500\,\mathrm{kg\,m^{-3}}$, the Scots pine being about 8% heavier. The annual-ring counts were between 5 and 10 per cm for both species. Test pieces for bending creep, for tensile creep and for moisture content measurements all had a cross section of 8 mm (radial) by 3.17 mm (tangential), so that moisture content changes should take place at the same rate. The moisture content samples had their ends sealed with aluminium foil. The tensile-test gauge length was 50 mm and the other dimensions have been given previously [15]. Great care was taken to avoid compressing the wood in the gauge length; at no stage of preparation was it held in any clamp or vice. The stress for all creep tests was $7.5\,\mathrm{N\,mm^{-2}}$, or around 10% of the instantaneous fracture strength.

Dimensional change measurements were made with SLVC transducers on pieces of the same species, of the same cross-sectional dimensions and of length either 85 or 180 mm. The samples were all held and measured between parallel faces to ensure accurate alignment; the axial measurement samples also had their ends held in locating jigs after carefully sanding their ends flat and square. All axial moisture–expansion coefficients were measured before creep testing. Radial and tangential coefficients and microfibrillar angles were measured after creep testing. Prior to all creep tests the necessary dimensional changes and deflections were pre-calibrated so that the creep results could be corrected for dimensional changes under zero load. Microfibrillar angles were measured by the X-ray technique described by Meylan [16], using samples that were 1 mm thick in the radial direction and consisting mainly of latewood taken from the centre of each creep test piece. The path of the X-ray beam was in the radial direction.

As suggested and discussed in a previous paper [4] the amount of information obtained within a given time was increased by not attempting to reach complete equilibrium before each reading was taken. In any case, the requirements for complete equilibrium are not fully known, althought the time required could be very large indeed [17]. For this reason, it was felt that it would be more cautious to take readings at various delays after step relative-humidity changes. Observation of the smoothness of the curves would then allow judgement to be made on whether sufficient time had elapsed. This procedure was adopted in the work described here.

The procedure adopted was to make a step change in relative humidity, wait for a minimum of 2 h and then take a reading. Overnight a longer period of approximately 16 h allowed the test pieces to move closer to equilibrium, whilst at the end of each half-cycle, at least 48 h was allowed for equilibrium to be approached. These times may be compared with the time measured for 50% of equilibrium to be reached, of approximately 1.67 h. The effect of not achieving full equilibrium can be discerned on some of the graphs, although the effect is small. The effect of incomplete equilibrium shows up as a series of short concave-upwards "scollops", of which the cusps lie on the first points obtained in the mornings, after at least 16 h at constant relative humidity. An example can be seen in Fig. 2, in which the fifth, eighth and ninth points on the first dehumidification were obtained in the mornings. On the first humidification (crosses), the second, fifth, eighth, eleventh and fifteenth points were obtained in the mornings.

In an attempt to obtain smoother curves, one set of creep results was plotted against both the axial and the thickness unstressed dimensional changes. They were slightly smoother, but the improvement was too small to justify the departure from the important variable of moisture content. The relative humidity was kept constant for 24 h after the load was applied, in order to allow the initial creep to take place.

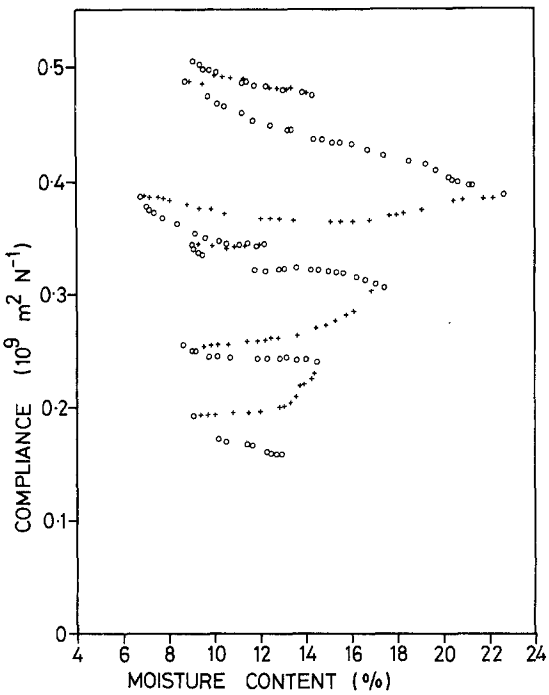

Figure 2 Compliance against moisture content for Scots pine in tension at 7.5 N mm^{-2} (mean of three): (○) dehumidifying, (+) humidifying.

3. Results

3.1. Qualitative effects of moisture content and compliance levels

The results of the two similar moisture-history experiments for the two species are given in Figs 2 to 7. Figs 2 and 3 give mean compliances plotted against moisture content for Scots pine in tension and bending, respectively. Fig. 4 gives mean relative creep for bending only. Figs 5 and 6 give mean compliances for ponderosa pine in tension and bending, respectively, whilst Fig. 7 gives mean relative creep for bending only. The important observations are given below.

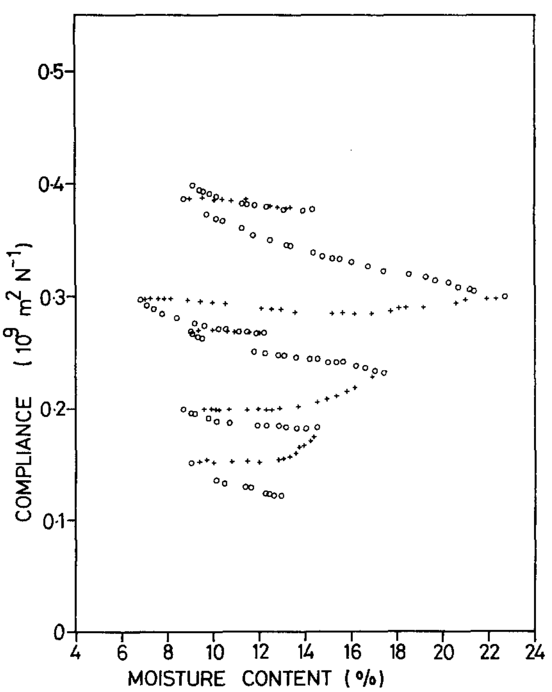

Figure 3 Surface compliance against moisture content for Scots pine in bending at 7.5 N mm^{-2} (mean of two): (○) humidifying, (+) dehumidifying.

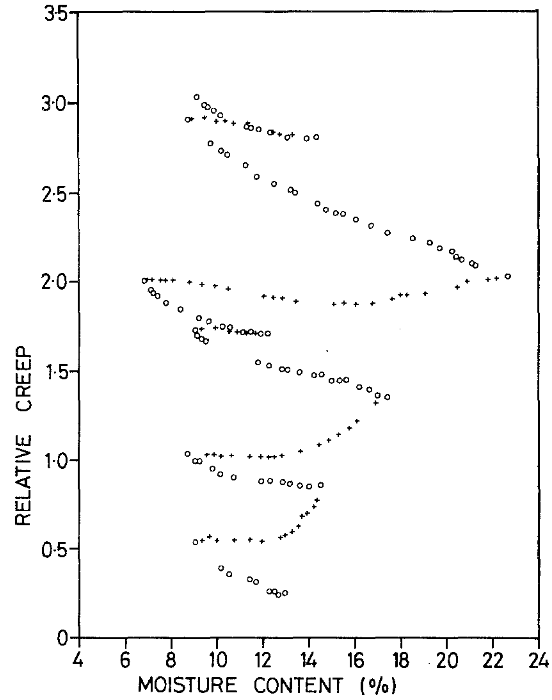

Figure 4 Relative creep against moisture content for Scots pine in bending at 7.5 N mm^{-2} surface stress (mean of two): (○) dehumidifying, (+) humidifying.

(a) The Scots pine had a much higher elastic compliance and higher initial creep at constant moisture content than the ponderosa pine. At all stages of the moisture cycling the Scots pine showed higher compliances and relative creep values than the ponderosa pine. These differences could be species differences or they could be associated with the compression wood of the Scots pine. One of the important differences between normal wood and compression wood is the larger microfibrillar angle of the latter. This possibility was therefore followed up in the experiments described below, in which the microfibrillar angle of ponderosa

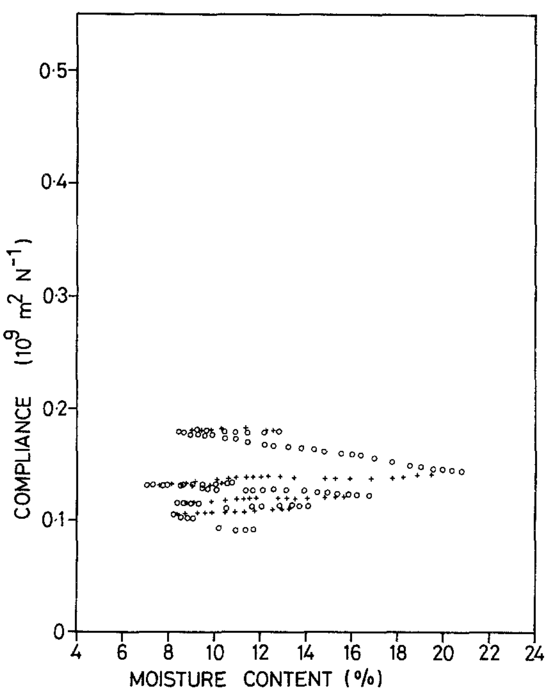

Figure 5 Compliance against moisture content for ponderosa pine in tension at 7.5 N mm^{-2} (mean of three): (○) dehumidifying, (+) humidifying.

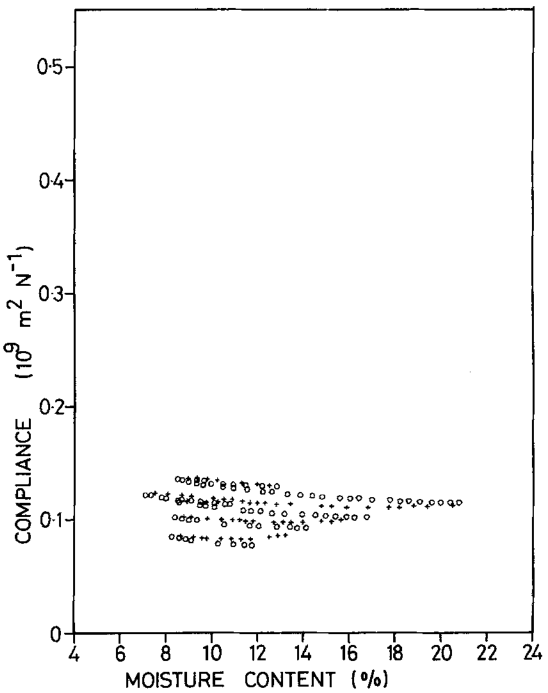

Figure 6 Surface compliance against moisture content for ponderosa pine in bending at $7.5\,\mathrm{N\,mm^{-2}}$ (mean of two): (O) dehumidifying, (+) humidifying.

pine was varied by taking test pieces from different positions in the tree.

(b) The compliance values and also the relative creep values (not shown) were similar for bending and for tension. If anything there was a slight trend towards the tensile tests having larger elastic, normal creep and mechano-sorptive creep compliances than the bending tests; but with the relatively few test pieces used, there was no statistically significant difference between the results of the two modes of stressing. The similarity between the normal creep compliances in tension and bending at this stress level of $7.5\,\mathrm{N\,mm^{-2}}$

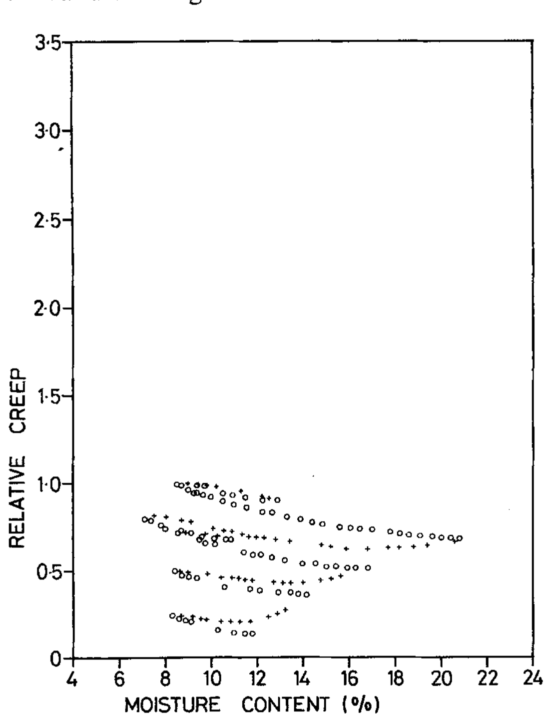

Figure 7 Relative creep against moisture content for ponderosa pine in bending at $7.5\,\mathrm{N\,mm^{-2}}$ surface stress (mean of two): (O) dehumidifying, (+) humidifying.

was confirmed by testing some well-matched test pieces for a period of 2 weeks at constant humidity. Comparison of the mean of three tensile with the mean of two bending tests gave differences of 2% for the ponderosa pine and 3% for the Scots pine. This suggests two conclusions: firstly that the material is roughly viscoelastically linear at stresses of $7.5\,\mathrm{N\,mm^{-2}}$ and below [18, 19]; and secondly that at these low stress levels the normal creep compliance (and possibly the mechano-sorptive creep compliance) in tension is the same as that in compression (since there is no shear stress in four-point bending), thus modifying the conclusions of Armstrong and Kingston [9]. The latter made their deflection measurements with a cathetometer, and as far as can be ascertained, such measurements have not been repeated with the more accurate measuring apparatus now available.

(c) The creep results were much closer to the classical mechano-sorptive creep behavior than were those of the beech tests described in the author's previous paper [4]. Desorption resulted in a creep increase at all moisture content levels. The creep showed a sharp rate of increase when the moisture content during sorption reached a higher level than had previously been reached during the test. During sorption at lower moisture content levels the creep slightly increased or decreased according to the material and conditions.

(d) Another important difference that could be seen between the two species was the effect on the creep compliance of moisture cycling between about 14% and 8% moisture content. Whilst the Scots pine during one full cycle showed an overall increase or "ratcheting" effect of around $1.1 \times 10^{-3}\,\mathrm{mm^2\,N^{-1}}$ moisture at low compliance to about $0.34 \times 10^{-3}\,\mathrm{mm^2\,N^{-1}}$ moisture at high compliance, the ponderosa pine hardly did so at all (around $0.14 \times 10^{-3}\,\mathrm{mm^2\,N^{-1}}$, or less). The same trend could be observed amongst individual test pieces, the more susceptible ones having a larger $(\mathrm{d}J^+/\mathrm{d}u - \mathrm{d}J^-/\mathrm{d}u)$ value.

The differences between the two species, described above, can be discerned in both the relative creep graphs of Figs 4 and 7 and in the compliance graphs of Figs 2, 3, 5 and 6. However, since the differences were more marked in terms of compliance, and since compliance is more useful for design against creep, the remainder of the results in this paper will be presented in terms of compliance.

3.2. Standardized procedure to quantify mechano-sorptive creep

Having observed marked qualitative differences between the two species of wood, it was necessary to develop a standardized procedure to quantify them.

The decision was made to include the three main modes of moisture change, associated with the constants a^{++} a^+ and a^-, and to use a standardized relative humidity range of 30% to 82% r.h. This humidity range was chosen for convenience in testing and because it covers most of the r.h. values that apply in practice.

Since it was not known whether there would be interaction between the a^{++} and the a^- modes of

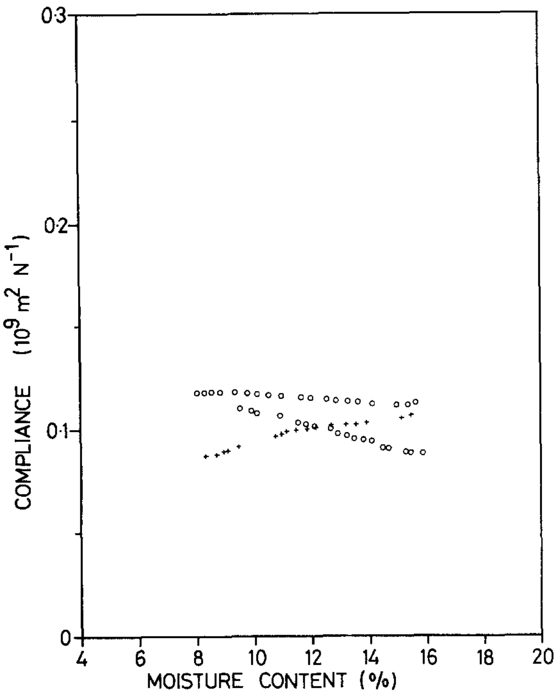

Figure 8 Surface compliance against moisture content for ponderosa pine in bending (mean of two), using separate procedures on separate samples: (+) humidifying, (o) dehumidifying followed by humidifying.

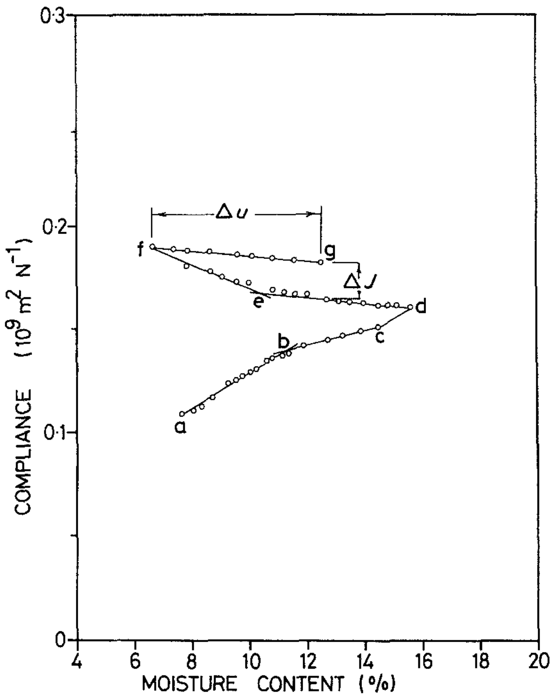

Figure 9 As for Fig. 8 but using a unified procedure.

moisture change, these changes were made initially on separate pieces. The dual procedure adopted was then:

1. One set of pieces was equilibrated at 30% r.h. and then loaded at constant humidity for 24 h. The r.h. was then increased by a small step and held for a minimum of 2 h before a deflection reading was taken; this then being repeated several times. 8 h after the first increase the r.h. was kept constant for 15 h before another reading was taken; then next day the step increases of humidity were continued. The entire test lasted 1 week, with the r.h. remaining at 82% for 48 h before the final reading was taken.
2. A second set of samples was equilibrated at 82% r.h. and the above procedure was repeated, except that the r.h. was gradually reduced until it reached 30% at the end of the first week. During the second week the r.h. was gradually raised to 82% again. The results of both of these tests are included in the correlations given in the next section.

For later tests it was decided to combine the two tests into one, starting with humidification, so that the dJ^*/du value for each of the three modes of moisture change could be obtained from each test piece. The justification for this decision is that, at least for the ponderosa pine test pieces, Fig. 7 suggests that the slope of the creep against moisture content curve was little affected by the compliance level. However, the correlations given below suggest that the value of dJ^-/du is not the same for a first dehumidification as for a later one.

Some typical mean results for the tests described above are given in Fig. 8 for two sets of test pieces, and in Fig. 9 for a unified set. The main difference between the two procedures is that in the dual procedure of Fig. 8, the dehumidifying of the newly loaded test piece gave a constant slope, whilst in the unified procedure of Fig. 9 dehumidification gave a curve, with a higher slope at low humidities. These differences applied to every single test piece.

3.3. Correlations between mechano-sorptive creep susceptibility and some other materials parameters

Amongst the independent variables (materials properties) tested were growth-ring position; microfibrillar angle; the mean dimensional change coefficient in the axial direction (α_L) during shrinkage; the values α_L/α_R and α_L/α_T (where α_R and α_T are the dimensional change coefficients in the radial and tangential directions, respectively); and the "elastic" compliance (J_{100}) measured 100 sec after loading.

The first step in correlating mechano-sorptive creep with other properties was to reduce a typical creep curve such as that shown in Fig. 9 to a set of numerical parameters. Referring to Fig. 9, in which the parameter dJ^*/du is represented by the slope of the curve, it can be seen that the first humidification has three obvious sections ab, bc and cd; the dehumidification has two sections de and ef; whilst the second humidification has one section fg. It was possible to distinguish such regions on every creep curve obtained, although the author accepts that this interpretation is open to argument (for instance it could be argued that the dehumidification follows a smooth curve of constantly changing slope). The section cd has not been investigated, but may possibly be related to the effect of the longer time allowed at high humidity before the start of dehumidification.

For purposes of correlation, the mechano-sorptive creep susceptibility was reduced to the following parameters: the maximum value of dJ^{++}/du (section ab in Fig. 9), the minimum value of dJ^{++}/du (section bc), the mean value of dJ^-/du (section df), and the total increase in compliance during one complete cycle of

TABLE I Correlation coefficients for various combinations of mechano-sorptive creep coefficients with other physical properties

Mechano-sorptive creep rates	Microfibril angle, θ	Elastic compliance, J_{100}	Length expansion coefficient, α_L	Length to radial expansion ratio, α_L/α_R	Length to tangential expansion ratio, α_L/α_T
dJ^{++}/du (max)	0.858	0.837	0.669	0.657	0.633
dJ^{++}/du (min)	0.952	0.886	0.705	0.664	0.668
dJ_2^-/du (mean)	0.879	0.919	0.782	0.652	0.760
dJ_1^-/du (mean)	0.896	0.986	0.926	0.886	0.907
$(\Delta J^+ - \Delta J_2^-)/\Delta u$	0.858	0.920	0.698	0.597	0.705
$(\Delta J^+ - \Delta J_1^-)/\Delta u$	0.870	0.984	0.925	0.886	0.918

desorption and sorption divided by the size of the moisture interval ($\Delta J^*/\Delta u$ from Fig. 9). This latter value depends on the size of the moisture interval chosen, so for comparison purposes it was restricted to the approximate interval 7% to 13% moisture. To avoid confusion, this will be called $(\Delta J^+ - \Delta J^-)/\Delta u$ in this paper.

Every one of these combinations showed a significant correlation, not only within a species, but including both species of softwood. The results of some of the more useful correlation attempts are given in Table I, which lists correlation coefficients for the varous combinations. It can be seen that the best correlations are with the microfibrillar angle and the elastic compliance; these being statistically significant at well below the 0.1 % level in every case. Those for α_L/α_R and α_L/α_T are statistically significant at about the 1% level. The more statistically significant correlations are also shown graphically. Fig. 10 gives the correlation of the two dJ^{++}/du values with microfibrillar angle, whilst Fig. 12 gives dJ^-/du and $(\Delta J^+ - \Delta J^-)/\Delta u$ with microfibrillar angle. Figs 11 and 13 give correlations with the elastic compliance J_{100}. Several points can be noted from these graphs.

(a) The general trends are for higher microfibrillar angles and for larger elastic compliances to give higher

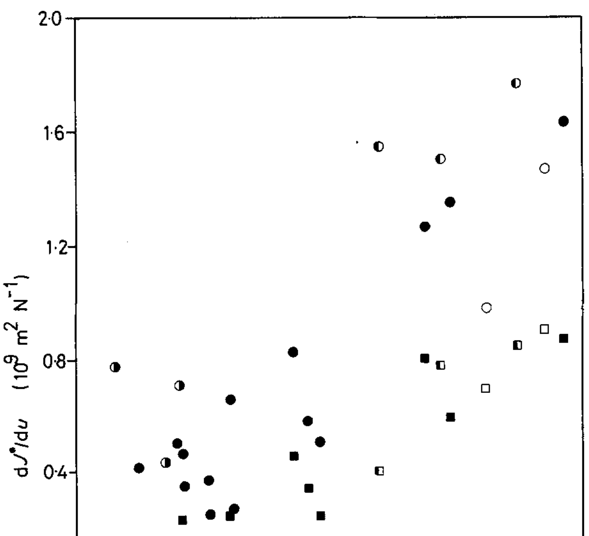

Figure 10 Correlations between dJ^{++}/du and microfibrillar angle: circles, maximum values at low humidity; squares, minimum values at high humidity; (○□) Scots pine bending (◑◨) Scots pine tension, (◐◧) ponderosa pine tension (●■) Ponderosa pine bending.

mechano-sorptive creep parameters. In some cases the values for the Scots pine are scattered amongst those for the ponderosa pine, although the former were generally more susceptible.

(b) The graphs of Figs 12 and 13 clearly distinguish between the effects of initial dehumidification after loading at a high humidity, and the effects of dehumidification following an initial humidification. This somewhat parallels the differences between the first and later humidifications, designated by Ranta Maunus a^{++} and a^+, respectively. For convenience of reference in this paper, the appropriate parameters will be designated J_1^- and J_2^- for the first and subsequent dehumidifications, respectively; and by ΔJ_1^- and ΔJ_2^- for the respective differentials during complete cycles. These differences can be observed, but were not further investigated, in the beech results given previously [4]. The ratios of dJ_1^-/du to dJ_2^-/du can be seen to be around 2 to 1 in Figs 12 and 13, whilst the ratios of $(\Delta J^+ - \Delta J_1^-)/\Delta u$ to $(\Delta J^+ - \Delta J_2^-)/\Delta u$ are of the same order. Similar results can be observed qualitatively in Figs 2 to 7. This means, then, that it is necessary to consider not three, but four, different types of mechano-sorptive creep.

(c) The results presented in Figs 10 to 13 supported the conclusion that the mechano-sorptive creep compliances in bending and tension were of a similar magnitude. Although there were insufficient tests to apply statistical analysis, the tension points lie in the same general band as the bending points, but possibly towards the upper side.

4. Discussion

It is of interest to compare Fig. 9, having six separate regions with their characteristic slopes, with a typical axial zero-load dimensional change curve, as shown in Fig. 14, for the same moisture-content range. During humidification, the slope in Fig. 14 is high at low moisture content, smoothly decreasing to a low value at high moisture content. During the subsequent dehumidification the slope starts low and gradually increases, although it is generally much more uniform than during humidification. One essential difference is between the smooth curves of Fig. 14 and the quite marked "knee" during humidification of Figs 8 and 9, which knee occurred at around 11% moisture content in every piece measured.

It is tempting to try and relate the different regions to different mechanisms of moisture bonding, such as postulated by Kollmann [20] and Newns [21]. Such a mechanism could also be a basis for explanation of the

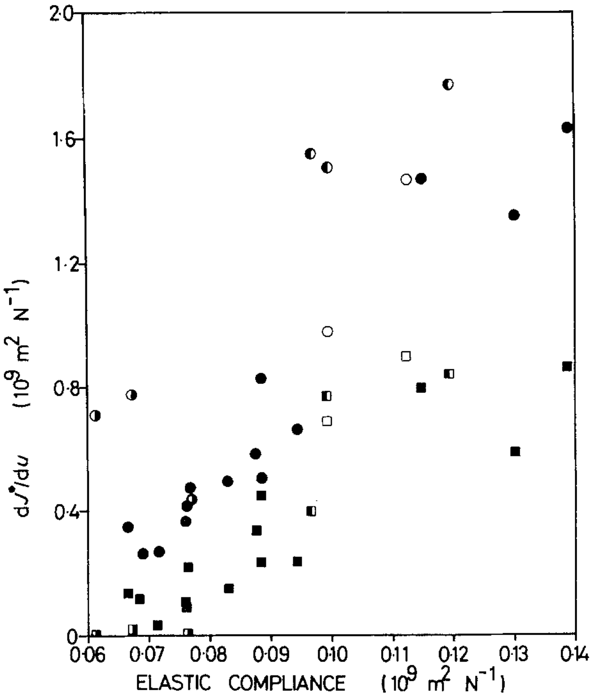

Figure 11 Correlations between dJ^{++}/du and elastic compliance J_{100}: circles, maximum values at low humidity; squares, minimum values at high humidity; (○□) Scots pine bending, (◐◧) Scots pine tension, (◑◨) ponderosa pine tension, (●■) Ponderosa pine bending.

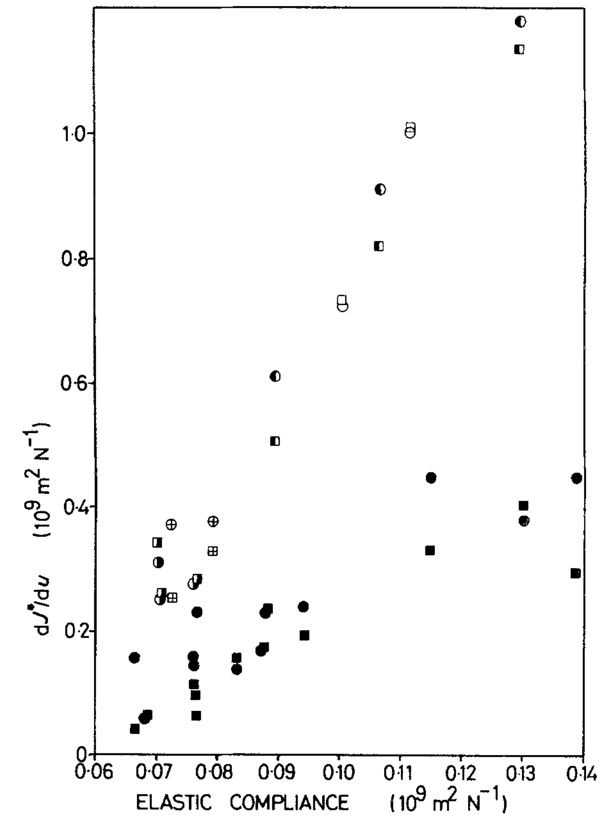

Figure 13 Correlations between dJ^-/du (circles) or $(\Delta J^+ - \Delta J^-)/\Delta u$ (squares) and elastic compliance J_{100}: (○□) Scots pine bending, (◐◧) Scots pine tension. (◑◨) ponderosa pine tension, (⊕□) ponderosa pine bending, all started at high humidity, (●■) ponderosa pine bending started at low humidity.

cd region of Fig. 9, which should not be considered too seriously without further investigation. The latter region could also be a "time" effect; time having been largely ignored in the measurements described above.

Of the various correlations presented, all showed positive results. The ratios α_L/α_T and α_L/α_R as independent variables gave less useful correlations, and since these have no physical meaning they will not be considered further. The value of α_L obviously correlates with the microfibrillar angle and so gives good correlation. However, the main significance lies with the correlations with the other two independent variables microfibrillar angle, θ, and the elastic compliance, J_{100}. The microfibrillar angle directly controls the magnitude of the tensile and shear stresses applied to the inter-microfibril boundaries of the S2 layer and hence to its

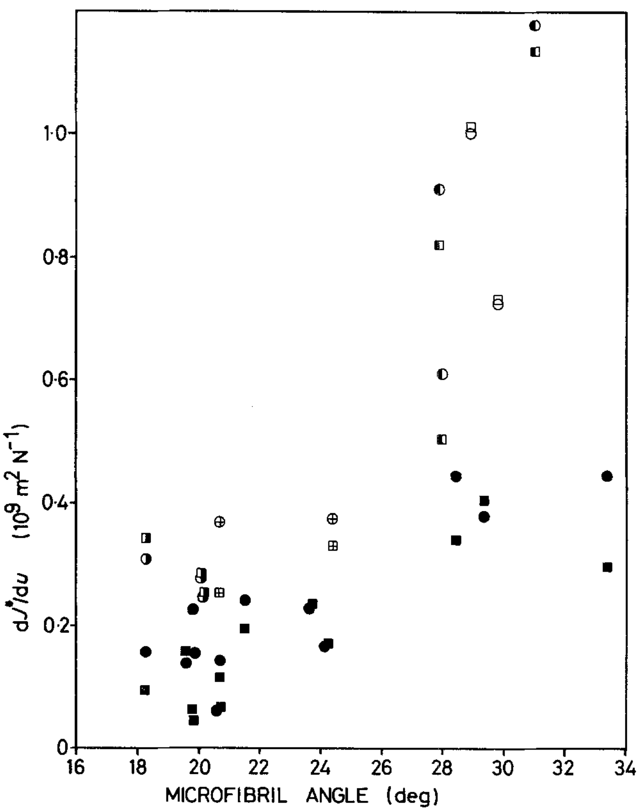

Figure 12 Correlations between dJ^-/du (circles) or $(\Delta J^+ - \Delta J^-)/\Delta u$ (squares) and microfibril angle: (○□) Scots pine bending, (◐◧) Scots pine tension, (◨◑) ponderosa pine tension, (⊕□) ponderosa pine bending, all started at high humidity, (●■) ponderosa pine bending started at low humidity.

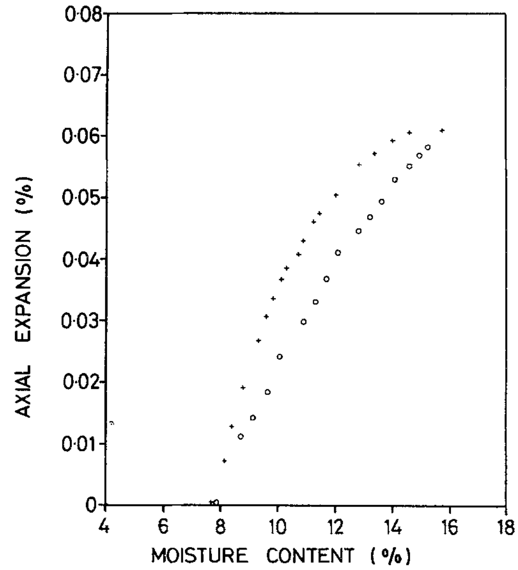

Figure 14 Unloaded dimensional change as a function of moisture content for a ponderosa pine sample.

inter-molecular bonds. The tensile stress is proportional to $\sin^4\theta$ and the shear stress is proportional to $\sin^2\theta \cos^2\theta$. A study of the data given in Figs 10 and 12 suggest that the points would fit better to a $\sin^4\theta$ curve and hence to a perpendicular tensile-stress function, than to a shear-stress function. However, the fit to neither function is good. It may be hoped that this confirmation of the importance of the type of inter-microfibril stress in the S2 layer in mechano-sorptive creep may eventually, by consideration of their respective orientation distributions, lead to an explanation of the differences between wood and other hygroscopic polymeric materials in their susceptibility or resistance to mechano-sorptive creep.

Two aspects of correlations were considered to be of particular interest. Firstly, any correlations that showed a continuous function for both species, including the compression wood of the Scots pine, could give a clue to the underlying cause of mechano-sorptive creep. Secondly, it would be useful if a simple measurement could be used as a practical sorting test to determine susceptibility to mechano-sorptive creep.

The importance of the correlation with the elastic compliance is in connection with the use of stress-grading machines for the selection of material. Whilst one of the main functions of a stress-grading machine is to detect strength-reducing defects such as knots, the relatively defect-free higher structural grades might also be usefully sorted for their mechano-sorptive creep resistance by this method.

A further important result of the correlation with elastic compliance is that this appears to diminish one of the chief obstacles to research on mechano-sorptive creep in the past, namely the variability of the material and the consequent difficulty of matching samples. The correlation with elastic compliance allows the possibility of either (a) deliberately selecting material that is fairly closely matched, for replicate tests, or (b) deliberately selecting material that is divergent, so that trends and limiting values can be studied.

The similarity of creep compliances in tension and bending is not entirely unexpected at the low stresses, well below the value at which cell collapse is important. If this can be confirmed, it will be useful in reducing the cost of larger-scale testing programmes in which test pieces of substantial size are used, since bending tests are less expensive than tensile ones.

The evidence that there are at least four types of mechano-sorptive creep: first humidifications, subsequent humidifications, first dehumidifications and subsequent dehumidifications, means that a single standardized testing procedure, such as the one proposed, is incomplete since it only covers three of the four types. For complete coverage, two testing procedures are required; test pieces for the two procedures being matched or related by their elastic compliances: one set of tests being started at low humidity, followed by sorption, desorption and then sorption; and the second set started at high humidity, followed by desorption, sorption and then possible desorption again.

It is not intended to discuss deeply the theoretical implications of the results presented. One reason is that the main aim of this paper was practical; to quantify the mechano-sorptive creep of two softwoods for eventual design purposes. The second reason is that a more detailed analysis of these and some other results will be presented in a later paper and it is hoped that this will shed some light on the theoretical background of mechano-sorptive creep.

Finally, the results of this work on two softwoods should be compared with the previous work by the same author [4] on a hardwood, beech. On the face of it, there appear to be some fundamental differences, both between the mechano-sorptive creep behaviour of the two materials and between the requirements for the reduction of the creep to a parametric form. In the planned later paper, it is proposed to show a modified method of analysis of both sets of data which will eliminate some of the apparent differences and perhaps offer a unified approach to analysis.

Acknowledgement
A grant from the Science and Engineering Research Council for the purchase of equipment for this research is gratefully acknowledged.

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Received 11 February and accepted 14 August 1985