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Progress in the analysis of creep in wood during concurrent moisture changes

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In analysing wood creep during moisture changes, various adjustments can be made to the data, including corrections for density and for dimensional changes. Provided that the variation of elastic compliance with moisture content is known, the elastic compliance can be separated from the total compliance to give a "reduced" creep compliance. Elastic compliance data can be formed into a graphical chart based on moisture content and the compliance at a single known moisture content. Good correlations have been obtained between reduced creep compliances for various modes of moisture change and the unloaded axial movement coefficients β_L. If β_L could be considered as a measure of a number of internal "events", related to hydrogen bonding, and taking place during moisture changes; then the number of these events might also be related to moisture-induced creep changes.

Nomenclature

J	compliance
J_E	elastic compliance
J_R	reduced compliance
J_0	elastic compliance of wood at 7% moisture content
dJ^{++}/du	rate of change of compliance with moisture during humidification through moisture levels reached for the first time, after loading at low moisture content
dJ^{--}/du	rate of change of compliance with moisture during dehumidification through moisture levels reached for the first time, after loading at high moisture content
dJ^{+}/du	rate of change of compliance with moisture during humidification at levels already previously reached since loading
dJ^{-}/du	rate of change of compliance with moisture during dehumidification at levels already previously reached since loading
u	moisture content
β_T	unloaded movement coefficient in the tangential direction
β_L	unloaded movement coefficient in the longitudinal direction
θ	mean microfibril angle of the S2 layer of the cell wall

1. Introduction
1.1. Methods of presentation of data and corrections needed

Traditionally, creep is presented graphically as strain or compliance plotted against time. In the case of a hygroscopic material such as wood, creep during moisture changes involves a third variable, moisture content. This raises difficulties, and although both moisture content and strain can be plotted as "histories", with time as the horizontal axis, it has been shown [1] that more useful information can be obtained by plotting strain or compliance against moisture content. This is justified partly by the observations of Armstrong and Kingston [2] and Schniewind [3] that whilst normal creep, under constant moisture conditions, depends on the time variable, mechano-sorptive creep does not; mechano-sorptive creep being the additional creep that occurs during moisture content changes in wood [4], and depending only on the amount and direction of the moisture change.

Whilst time and moisture content are usually the independent variables, the basic dependent variable is that of bending deflection or tensile extension, which is then usually converted to strain. Since the strain response, at least at low stresses, is mainly linear in terms of stress, the strain is often divided by the stress to give compliance, J. An alternative parameter for the purpose of data presentation is the "relative creep", defined as (total strain−elastic strain)/elastic strain. The problem here lies with the definition of the value of the elastic strain, since its magnitude is a function of the moisture content. The value is often taken as the elastic strain observed at the start of the test, but this makes comparison of tests difficult, especially if the moisture content is one of the variables of the test.

In the study of creep of wood in changing humidities, an alternative method of presenting strain or compliance is to subtract from the measured compliance the previously-measured elastic compliance at the current moisture content. This gives a parameter that is referred to in this paper as "reduced compliance", J_R, i.e. $J_R = J - J_E(u)$, where J is the total measured compliance, and J_E, the elastic compliance, is a function of u, the actual moisture content at the time of measuring the compliance. When the reduced compliance is plotted against the moisture content, the main differences, compared with the total compliance, are (a) that the creep begins at a reduced compliance of zero, and (b) that the slope of the curve dJ/du is less steep during humidification but more steep during dehumidification. The slope dJ/du is, of course, one of the fundamental parameters relating to mechano-sorptive creep.

The use of reduced creep can be considered as a first step towards the isolating of mechano-sorptive creep. It could be argued that the second step should be the estimation of the "normal" (i.e. not mechano-sorptive) creep during moisture cycling, and then the subtraction of this from the total creep; the remainder being the value of the mechano-sorptive creep alone. However, in the present state of knowledge this second step cannot be justified, since it is not known whether normal creep, which is time dependent, and mechano-sorptive creep, which is independent of time, are basically the same or different phenomena. It is much easier to justify the separation of the elastic compliance, since it is easily demonstrated to be reversible, and can even be reversibly measured during a creep test without showing any effect on the creep curve.

Another variable that needs to be considered is the density of the wood. It is usually considered that the density is a measure of the amount of wood substance present per unit volume. It is therefore also a measure of the number of structural components per unit area that are available to support the applied load; in other words the effective stress. Partly for this reason, the results in this paper have been presented as compliance rather than strain, and the density variation between samples was allowed for by a type of normalization process. This process consisted of multiplying the compliance values by the factor (specific gravity of the test piece/0.5), the value 0.5 being an approximate mean specific gravity for the samples used.

Finally, there is the problem of dimensional changes that occur concurrently with the moisture changes during the test. In the case of tensile creep, although width and thickness changes affect the gross stress, they could also be considered as merely a redistribution of the wood substance, so that the load on an individual structural element remains unchanged. Therefore, no correction is needed for tensile creep, other than the correction for the axial movement ("movement" being the term used to denote the dimensional changes associated with moisture changes of unloaded wood). In the case of bending, the structural elements are being displaced relative to the neutral axis of the beam, thus affecting both the stress and the radius of bending curvature. It can be shown that for small changes, the fractional correction to the compliance J is given by $\delta J/J = 2\delta t/t$, where $\delta t/t$ is the fractional change in thickness. The correction to the slope dJ/du is therefore equal to $2J(\delta t/t)/\delta u = 2\beta_T J$, where β_T is the movement coefficient in the thickness direction as a result of moisture change. The effect on the compliance against moisture content graphs is to increase the slope during humidifying and to decrease it during dehumidifying.

1.2. Elastic compliance as a function of moisture content

Several authors have presented values of elastic modulus as a function of moisture content for various species of wood. For instance [5–7], it has generally been found that the elastic compliance increases with moisture content. In dynamic bending measurements, Kollmann and Krech [8] found that on sorption between 0% and about 4% moisture content the compliance decreased to a minimum, but thereafter increased, up to moisture contents beyond the fibre saturation point. Their results also showed an increase in compliance with decreasing density, to a slightly greater extent than could be explained by the relative reduction in the amount of load-carrying material.

The work described in a previous paper [9] has indicated a correlation within a wood sample, between susceptibility to mechano-sorptive creep and various material characterizing parameters such as the basic elastic compliance of the test piece. It was therefore considered to be of interest, not only to measure the rate of increase of elastic compliance with moisture content, but also to see how this rate of increase was affected by a suitable material-characterizing parameter. The parameter chosen was the elastic compliance at 7% moisture content: that at 0% moisture, although more scientifically basic, being considered difficult to measure and of less practical interest.

1.3. Analysis of past results using reduced creep compliance

The purpose of analysing results of creep tests is to formulate general rules, so that the amount of creep can be correctly predicted in any given set of loading and humidity conditions. This is a first stage towards the development of design rules. One means of characterizing mechano-sorptive creep is to obtain numerical values of dJ/du, the rate of change of compliance with moisture content, which is a development of the hydroviscoelastic constants of Ranta Maunus [10].

The classical type of mechano-sorptive creep has been described by Grossman [4]. In this, the creep compliance always increased during desorption, and it also always increased during the first sorption at any moisture content level; but with subsequent sorptions, such as during humidity cycling, the strain always decreased. However, some recently published work on mechano-sorptive effects in a hardwood, beech [1] and on two softwoods, pines [9] showed some differences between the hardwood and the softwoods. The softwoods behaved more nearly according to the classical description of mechano-sorptive creep, and although the rates of change of compliance with moisture content, dJ/du, were not constant within any of the three mechano-sorptive creep regimes, it was possible to assign rough numerical values to them, as least within certain moisture content bands. The hardwood, on the other hand, appeared to behave in such a way that it was very difficult to assign consistent numerical values to dJ/du and it did not even appear to follow the classical rules of mechano-sorptive creep. A method of analysis using a graphical system of trajectories was suggested.

Comparison between the elastic compliance and moisture content characteristics also showed marked differences between pine and beech. These suggested that subtraction of the elastic from the total compliance to give a reduced compliance J_R, could remove much of the difference between the creep curves of the two materials, thus making analysis easier.

1.4. Correlation between mechano-sorptive creep susceptibility and unloaded axial movement coefficient

It has been suggested, above, that a suitable numerical characterizing parameter of mechano-sorptive creep could be the value of dJ/du under the conditions of the test. On comparing the slopes of the graphs of reduced compliance against moisture content (dJ_R/du) and of unloaded axial dimensional change against moisture content (β_L), some similarities were noted. This is to be expected, since both mechano-sorptive creep deflections and unloaded dimensional changes are thought to be associated with breaking and re-making of hydrogen bonds. For instance, during sorption, both the creep compliance and the unloaded movement curves with respect to moisture have been found to have steep slopes in the 7 to 10% moisture range decreasing to shallow slopes at around 16 to 18% moisture content. During desorption, the slopes were again shallow at the higher moisture contents but steeper at the lower moisture contents; although the slope of the compliance curves changed sign from sorption to desorption. It was also pointed out that there was a rough correlation between the mechano-sorptive creep susceptibility, as quantified by the various dJ/du values, and the mean β_L over a moisture range of about 8 to 18%. It was therefore considered to be of interest to compare the slopes using numerical analysis, both for sorption and desorption.

1.5. Scope of this paper

In view of the above discussion, the scope of this paper is as follows: (1) to present a family of elastic compliance against moisture content curves for a spread of stiffnesses of the same species. Then, using these elastic compliance values, (2) to take some creep results that have already been published on beech [1], and on a species of pine [9], and to re-present them in the form of reduced compliance as a function of moisture content; (3) to study the correlation between axial creep compliance changes and unloaded axial dimensional changes as a function of moisture content.

2. Experimental details

2.1. Materials

The material used for the elastic compliance measurements was ponderosa pine (*Pinus ponderosa*). The compliance was measured in bending. Similar measurements were also made on scots pine (*Pinus sylvestris*) in bending and on beech (*Fagus sylvatica*) in tension, using the same test pieces that were used for the actual tests described earlier [1, 9]. Since the elastic compliance measurements take place over a very short time, it was felt to be acceptable to use the same test pieces, provided that most of the creep recovery had taken place.

Density variations within the species were within a range of $\pm 4\%$.

2.2. Apparatus and methods

The bending creep machines, the tensile creep machines and the environmental chamber have been described [9, 11]. The procedure for measuring the elastic compliance was to measure the unloaded deflections, and then to load to give a maximum stress of approximately 7.5 N mm^{-2}, or approximately 7.5% of the instantaneous breaking stress. The deflections were measured at 10, 20, and 30 sec, the piece was unloaded, and the deflection was measured again after a further 10 min. The results were processed to estimate the deflection 10 sec after loading, and this was taken as the elastic deflection at that stress.

3. Results

All of the results quoted below have been corrected for density variations by the normalization process described in Section 1.1, and for dimensional changes taking place during the test.

3.1. Elastic compliance measurements

The elastic compliance of the ponderosa pine samples is given in Fig. 1. together with the linear regression

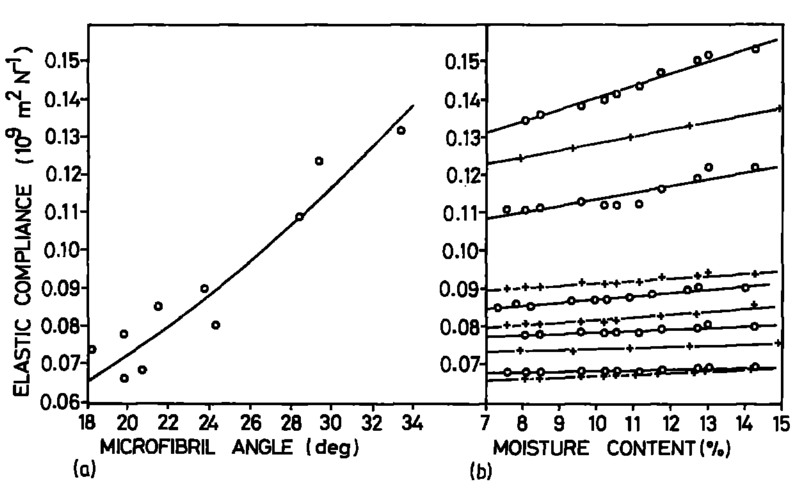

Figure 1 Elastic compliance at 7% moisture content as a function of (a) microfibril angle, and (b) elastic compliance as a function of moisture content for ponderosa pine. Experimental results and fitted curves.

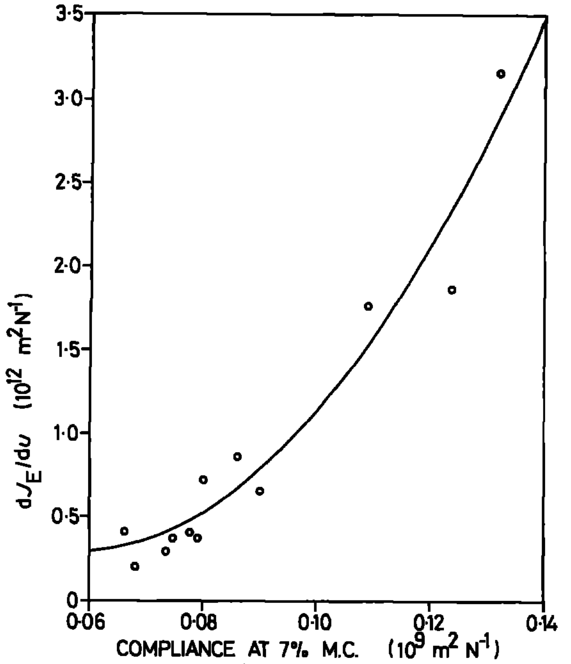

Figure 2 Slopes of elastic compliance against moisture content, dJ_E/du, from Fig. 1 as a function of elastic compliance at 7% moisture content, J_0, showing fitted curve.

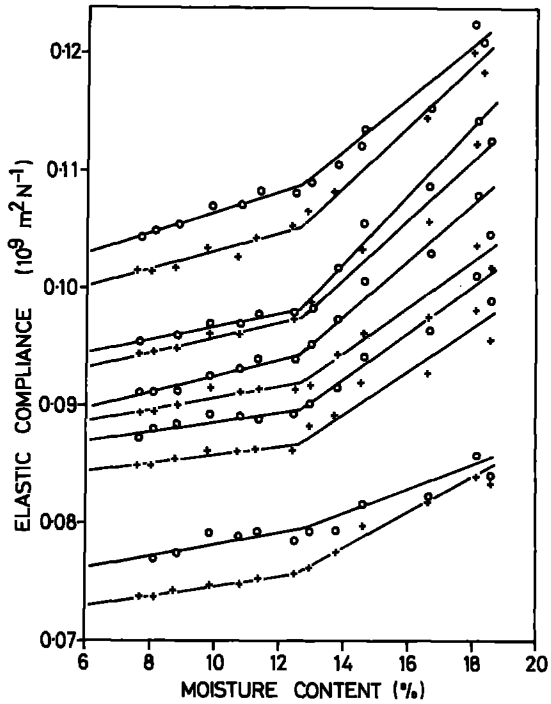

Figure 4 Some sample measurements of elastic compliance as a function of moisture content for scots pine: experimental points and fitted lines.

lines and the mean microfibril angles of the S2 layer (the main structural layer within the cell wall). The regression lines of Fig. 1 form a group the trend of which is to steeper slopes for higher values of elastic compliance. Taking the elastic compliance at 7% moisture content as a base (J_0), a relationship between the slope dJ_E/du of the fitted curves and J_0 was plotted as Fig. 2, which also shows the fitted quadratic curve. Values taken from the fitted curve could then be plotted as a chart, or family of lines, as Fig. 3. From this chart, the measurement of elastic compliance at any known moisture content within its range, allows an estimate to be made of the elastic compliance at other moisture contents.

It may be noticed that the points for the ponderosa pine pieces were quite suitable for linear regression. Some similar measurements were made on samples of scots pine and of beech, as shown in Figs 4 and 5, respectively. In both cases the slope of dJ_E/du can be seen to be greater at higher moisture contents, so that a single straight-line fit would be unsatisfactory. Although a family of quadratic curves could be successfully fitted to each set of data, it was felt that, in view of the scatter of results, it would be more

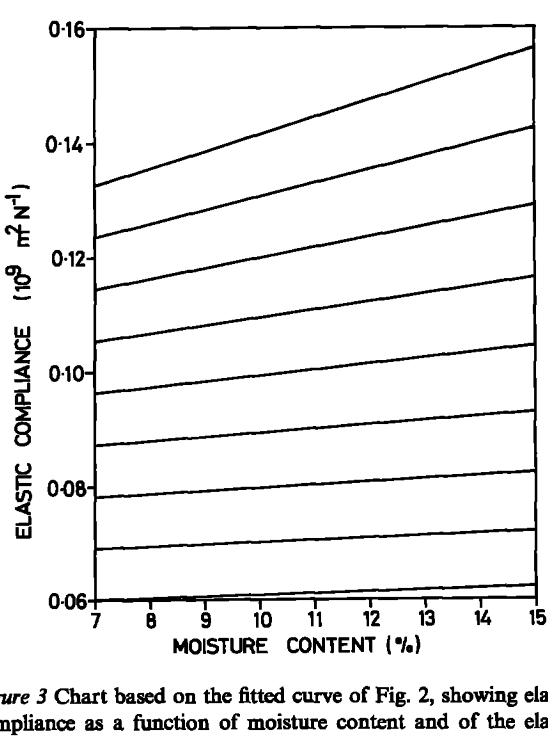

Figure 3 Chart based on the fitted curve of Fig. 2, showing elastic compliance as a function of moisture content and of the elastic compliance at 7% moisture content.

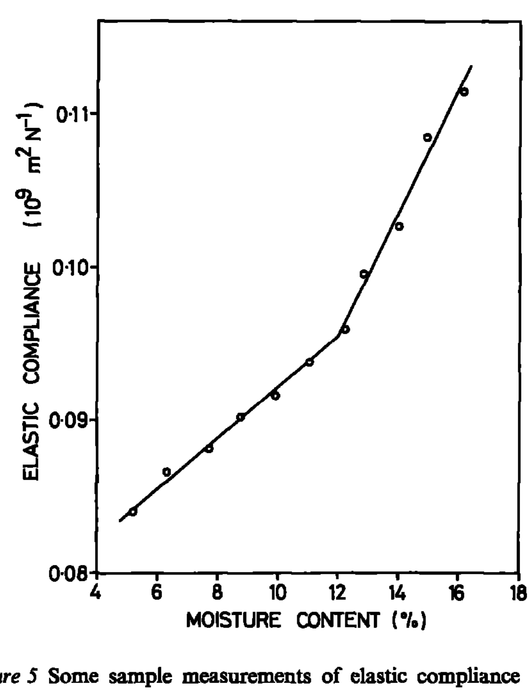

Figure 5 Some sample measurements of elastic compliance as a function of moisture content for beech: experimental points and fitted lines.

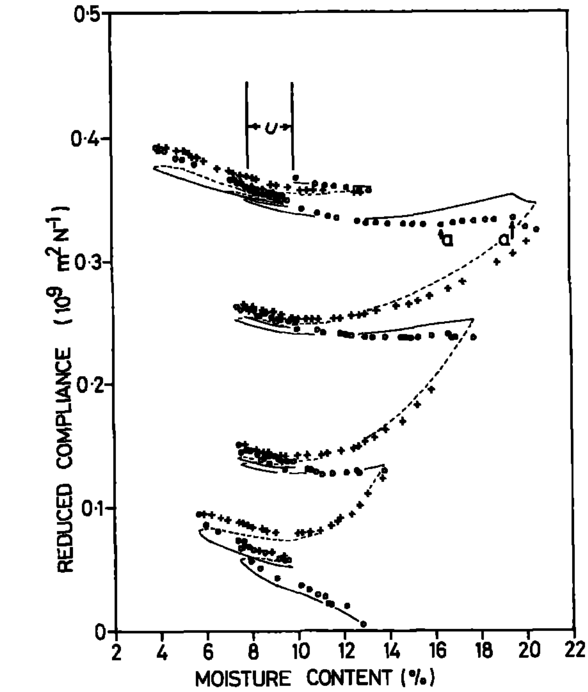

Figure 6 Creep compliance as a function of moisture content during moisture cycling of beech at 12 N mm^{-2} taken from [1]: lines are unprocessed results, humidifying (---), dehumidifying (——); reduced creep points, humidifying (+), dehumidifying (O).

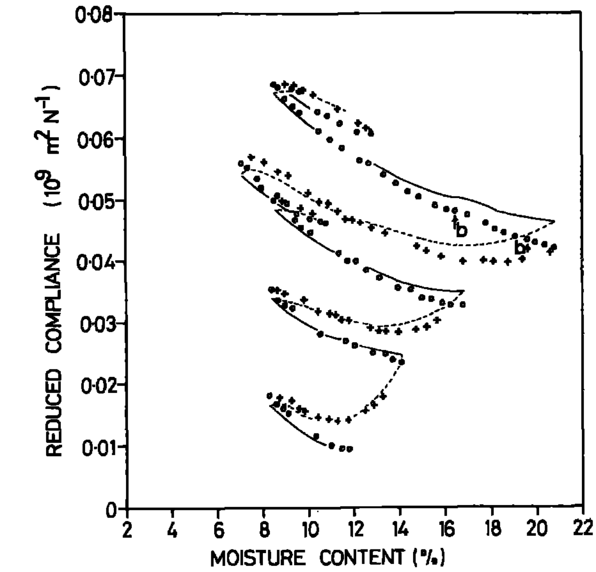

Figure 7 Creep compliance as a function of moisture content during moisture cycling of ponderosa pine at 7.5 N mm^{-2} taken from [9]: lines are unprocessed results, humidifying (---), dehumidifying (——); reduced creep points, humidifying (+), dehumidifying (O).

conservative to fit two straight lines to each set of points, a change in slope being discernible at about 12% moisture content. The resulting fitted curves gave families of lines for the scots pine as follows: up to 12.6% moisture, the slope was $0.0157J_0 - 0.749(10^{-6})$; above 12.6% moisture, the slope was $0.0502\ J_0 - 2.326(10^{-6})$.

3.2. Re-analysis of past test results using reduced creep

Using the elastic compliance against moisture content data described in the previous section, some past creep data have been re-analysed. Fig. 6 shows data from a moisture-cycling experiment on beech in tension [1]; from which the elastic compliances have been subtracted to give reduced creep compliances. For easy comparison, superimposed on the reduced creep compliance points are the curves showing the total compliance, but with a suitable zero shift. A similar presentation of results for ponderosa pine in bending from [9] is given in Fig. 7.

The important observations in Figs 6 and 7 are that subtraction of the elastic compliance decreased the slopes during humidification but increased them during dehumidification. Because the elastic compliance of the beech changed rapidly with moisture content at higher moisture levels, as shown in Fig. 5; the downward slope of the compliance curve during dehumidification was therefore almost eliminated by the conversion to reduced compliance.

3.3. Slope of reduced compliance against moisture content curves as a function of unloaded movement coefficients

In a previous paper [9] it was pointed out that the changes in slope dJ/du of creep compliance against moisture content curves were somewhat parallel with changes of slope of movement against moisture content curves of unloaded test pieces (i.e. movement coefficient β_L).

In this section, actual values of dJ_R/du are compared with actual values of β_L at various moisture content values, and for both humidification and dehumidification. Fig. 8 gives rates of change of compliance with moisture content, dJ_R^{++}/du, during the first humidification after application of the load as a function of the movement coefficient β_L at the same moisture content during humidification. Fig. 9 gives the same parameter but during the first dehumidification, dJ_R^{--}/du as a function of β_L during

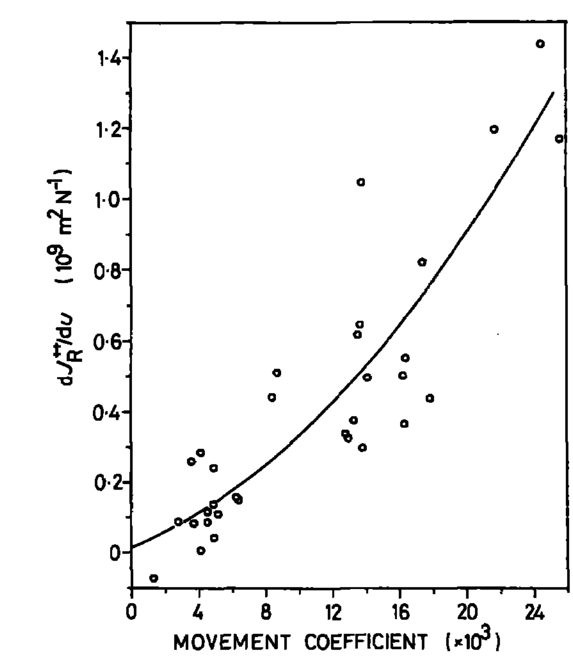

Figure 8 Rates of change of reduced compliance with moisture content dJ_R^{++}/du during the first humidification after loading of ponderosa pine pieces as a function of the axial movement coefficient at the same moisture content.

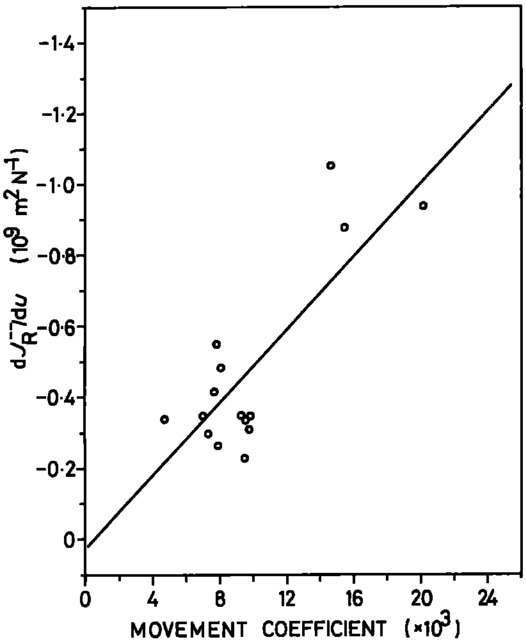

Figure 9 Rates of change of reduced compliance with moisture content dJ_R^{--}/du during the first dehumidification after loading of ponderosa pine pieces as a function of the axial movement coefficient at the same moisture content.

dehumidification. Fig. 10 gives dJ_R^-/du (for subsequent dehumidification) as a function of β_L during dehumidification. These latter values were all taken from experiments with a standardized moisture history: loading at 30% r.h., increasing the humidity by small steps to 83% r.h., then decreasing by small steps to 30% r.h. again. In the case of dJ_R^{--}/du in Fig. 9, there were not enough experimental points to justify fitting a quadratic curve.

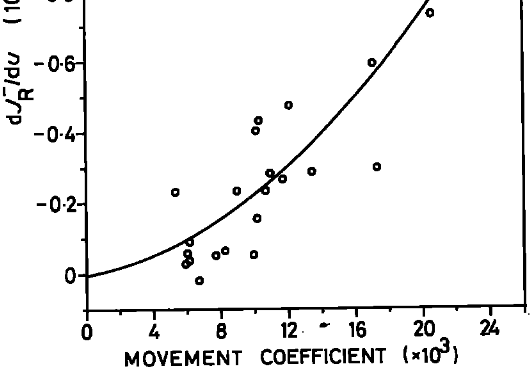

Figure 10 Rates of change of reduced compliance with moisture content dJ_R^-/du during subsequent dehumidification after loading of ponderosa pine pieces as a function of the axial movement coefficient at the same moisture content.

4. Discussion

4.1. Elastic compliance as a function of microfibrillar angle and moisture content

As would be expected [12] wood having higher mean microfibrillar angles in the S2 layer has been shown to have larger elastic compliances. It is also to be expected that material with the higher microfibrillar angles would have higher rates of increase of elastic compliance with moisture content, as shown in Fig. 1. This is because the intermolecular bonds, in which some of the bound water is located, are more highly stressed at higher microfibrillar angles.

The relation between elastic compliance and mean microfibrillar angle θ, has been studied by Cowdrey and Preston [13], who showed that the elastic compliance fits an expression of the type

$$J_E = a_0 + a_1 \sin^2\theta + a_2 \sin^4\theta$$

The least-squares fitted curve of this form shown in Fig. 1 has the coefficients $a_0 = 0.034(10^{-9})$, $a_1 = 0.325(10^{-9})$, $a_2 = 0.0296(10^{-9})$, with a r.m.s. error of $0.0066(10^{-9})$, or about 10% of the smallest J_E value. The relative sizes of these constants are roughly the same as those found by Cowdrey and Preston.

The fitting of linear functions to the elastic compliance against moisture content results of Fig. 1 is not in agreement with the results of Cave [12]. He presented a few results, without any experimental details, which tend to show an increasing slope of compliance against moisture towards higher moisture contents for *Pinus radiata*. This is more in line with the results for scots pine and beech in Figs 4 and 5 of this paper. However, the degree of scatter in the results presented here suggest that linear regression is adequate for the ponderosa pine within the moisture content range chosen.

4.2. Re-analysis of previous moisture-cycling tests, using reduced creep

The results of Fig. 6 show that by plotting as reduced creep compliance, the behaviour of the beech was more similar to that of the softwoods and to the classical theory of mechano-sorptive creep behaviour of wood. For instance, only above about 16% moisture content is there a sign of a decrease in compliance during dehumidification. Furthermore, some recent unpublished results of cycling tests on a sample of european spruce (*Picae abies*), in which the relative humidity was cycled seven times between 30% and 83% r.h., gave slopes at the start of successive dehumidifications that were fairly high (negative) in the earlier cycles decreasing to zero and even slightly positive in the later cycles; thus changing, within the same moisture range and on the same test piece, from a negative slope such as section b–b of Fig. 7 to a positive slope such as section a–a of Fig. 6.

Measurement of dehumidification slopes within the arbitrary moisture range 8 to 10% gave the values shown in Table I. Two conclusions, supported by similar measurements made on eleven other beech test pieces, may be drawn from these figures. Firstly, at higher compliance levels, the absolute value of dJ_R^-/du was generally less than at lower compliance levels; and

TABLE I Mechano-sorptive creep rates for beech during dehumidification from 10% to 8% moisture, taken from Fig. 6

dJ^-/du ($10^{-9}\,m^2N^{-1}$)	Mean reduced compliance level ($10^{-9}\,m^2N^{-1}$)	Dehumidification from moisture content (%)
−0.84*	0.045	12.8
−0.74	0.060	9.8
−0.47	0.135	13.8
−0.41	0.145	10.0
−0.53	0.250	17.8
−0.48	0.255	10.0
−0.68	0.350	20.6
−0.47	0.350	9.8
−0.48	0.355	9.6

*This value was for dJ^{--}/du.

secondly, that the absolute value of dJ_R^-/du tended to be higher in the cases where dehumidification started from a higher moisture level. Any attempt at quantification of mechano-sorptive creep in the form of parameters, must take these trends into account. Similar measurements were made on the ponderosa pine results shown in Fig. 7, giving the same conclusions.

4.3. Correlation of creep susceptibility and unloaded movement coefficients

The graphs of Figs 8 to 10 show the correlation between various modes of mechano-sorptive creep susceptibility dJ_R/du and unloaded axial movement coefficients β_L. However, these graphs also take into account the different slopes of dJ_R/du and the different movement coefficients in different moisture content regions and different directions of moisture change. In all three graphs, the correlation coefficients are statistically significant at well below the 0.1% level. It is of interest that the fitted curves all pass quite naturally close to zero susceptibility at zero movement coefficient.

As was discussed in Section 4.2, the value of dJ_R^-/du appears to depend on the previous moisture history. The justification for inclusion of Fig. 10 is that the moisture history was the same for all of the test pieces used. Comparison of the dJ_R^-/du with the dJ_R^{--}/du fitted curves, as shown in Fig. 11, gives further support to the idea [9] that in the quantification of mechano-sorptive creep it is important to distinguish between first moisture reductions and subsequent reductions at any moisture level.

A particular interest of the comparison between the dJ_R^{++}/du and dJ_R^{--}/du curves is that they appear to have a similar magnitude, for a given β_L value. In fact dJ_R^{--}/du was slightly greater than dJ_R^{++}/du, but the difference was not statistically significant. For any given piece of wood, β_L may be considered as a measure of a "number of internal events" taking place during a given moisture change; these internal events being hydrogen bond replacements by water molecules in such a way as to cause axial dimensional changes. Since these events are themselves reversible, it would be of particular interest if it could be shown that the amount of mechano-sorptive creep taking place immediately after loading depended only on the number of these internal events occurring, regardless

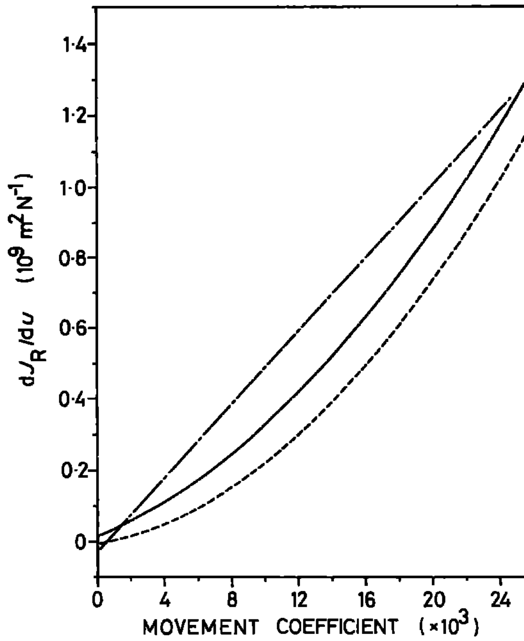

Figure 11 Comparison of the three fitted curves of Figs 8 to 10.

of their direction. This could then be analogous to the time–temperature relations in the creep of other materials, where the creep deflections depend on the number of internal events taking place as a function of time and temperature, commonly in the form [$t \exp(-Q/RT)$], where t is the time and T is the temperature. It must be emphasized that this model must be modified for the later stages of creep, especially after humidity or load reversals: in terms of rheological models, a number of springs would need to be incorporated as well.

The resolution of this matter may well then resolve also the important question of whether mechano-sorptive creep is an entirely separate phenomenon from normal creep. The question is whether the types of internal events associated with moisture cycling are of an essentially similar nature to those associated with time and temperature, so that mechano-sorptive creep is just a means of reaching, in certain conditions more rapidly, the creep strains that would eventually be reached by time and temperature alone.

Whilst such a possibility is of great interest, it must be emphasized that there are still many other unanswered questions on mechano-sorptive creep. In particular, the list must include the effects of stress and any differences between tension and compression and between tension and bending.

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