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Creep trajectories for beech during moisture changes under load

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Tensile creep experiments during concurrently changing humidities have been performed on Beech. There appears to be a "threshold compliance" level below which any change of moisture content, whether sorption or desorption, causes an increase in creep. Above this compliance level the creep appears to follow creep trajectories which form a shallow trough shape, for either humidification or dehumidification, when plotted with compliance as ordinate and moisture content as abscissa. The level of the threshold appears to vary with the instantaneous stiffness level of the material, measured at uniform moisture content. The mechano-sorptive creep below the threshold compliance could be explained in terms of the stress bias during hydrogen-bond breaking and remaking.

1. Introduction

More than 20 years ago, Armstrong and Kingston [1] reported that the creep of wood under load increased dramatically during moisture content changes and that during either sorption or desorption the final creep compliance was greater than would be expected at either the lower or the higher moisture content. This phenomenon has been labelled "mechano-sorptive" creep by Grossman [2].

Since that time a number of workers [3–7] have investigated the phenomenon and progressed towards a qualitative description of it. However, partly because of the variable nature of the material, little progress has been made towards either: (i) a quantitative description that could eventually lead towards design data, or (ii) a theoretical explanation. It should be noted that these two goals are somewhat interdependent, since a theoretical explanation would help in deciding what measurements need to be made for a full quantitative description. So far, even the qualitative description is incomplete.

A full review of observations of mechano-sorptive behaviour of wood was given by Grossman [2]. Amongst the observations quoted were (a) excessive bending deflections occurred during moisture cycling under load [5], (b) the final deflection depended mainly on the size of the moisture step and was little affected by its duration [3], and (c) deflections increased with a rise as well as with a drop of moisture content, but with some exceptions [3]. The exceptions are that whilst the first moisture increase and all reductions in moisture content cause increases in deflection, the second and all later moisture increases tend to produce some recovery of deformation [8]. However, Norimoto and Yamada [9] and Bryan and Schniewind [10] claimed the opposite for particle boards; namely that humidifying increased the deflection while drying produced recovery.

An approach to the quantitative description of mechano-sorptive creep has been made by Ranta Maunus [11]. He proposed the use of dimensionless "hydroviscoelastic constants" to quantify the ratio of change of compliance to change of moisture content. In order to describe the phenomenon, three different values were needed: a^- quantified the effect of moisture reductions, a^{++} quantified the effect of first moisture increases at any moisture level, and a^+ quantified any subsequent moisture increases at the same moisture level. All of the hydroviscoelastic constants were assumed to be constant, i.e. independent of moisture level and other factors. The creep strain,

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ϵ, in a constant-load creep test, could therefore be quantified by the equation

$$\epsilon = \sigma_0 \left[J + \sum_{i=1}^{n} a J_0 (u_i - u_{i-1}) \right] \qquad (1)$$

where σ_0 is the constant applied stress, J is the cumulative compliance that would be expected at the constant moisture contents obtained during the test (i.e. an integrated value of the normal mechanical creep), n is the number of changes between moisture content values of u_{i-1} and u_i, a is a coefficient taking the value of a^-, a^{++} or a^+ according to the type of moisture content change, and J_0 is the "instantaneous" elastic compliance at 0% moisture content.

More recent work [12] has shown that the hydroviscoelastic constants are not constant for Beech but that they are dependent on strain. At low stress levels, for the relative-humidity range 30 to 60% the value of a^- was found to decrease with strain increase whilst the value of a^+ was found to increase. The result was that the value of $(a^+ - a^-)$, or the effective increase in creep during a complete moisture cycle, gradually approached zero as the overall strain level increased. If such behaviour were to apply at all moisture content levels the result would be a limit to the possible amount of mechano-sorptive creep since the creep associated with the a^{++} constant (related to first moisture increases) would be exhausted when 100% r.h. was reached.

This paper describes more detailed investigations of the relations between the hydroviscoelastic constants and the levels of moisture content and strain at constant temperature. As with the previous work the tests were made on high-accuracy tensile creep machines, rather than bending creep machines, in order to simplify the interpretation of the results. For the same reason, relatively small stresses were used, in order to remain within the linear viscoelastic range.

This paper also gives results of some tests on the effect of stress on moisture diffusion in Beech. This was done in order to investigate suggestions that mechano-sorptive creep might be partly explained by the effects of stress on moisture diffusion rates or on the equilibrium moisture contents.

The effect of stress on the equilibrium moisture content was studied by Barkas [13], who developed a thermodynamic theory that enabled the effect of stress to be calculated, but he dismissed the effect of longitudinal stress as negligible and so did not measure it. Subsequent workers [14] made some measurements with longitudinal stress on softwoods and claimed that their results agreed with the Barkas theory. Barkas had predicted that the moisture content would increase, following the application of a tensile stress σ_L, by δ_m, where

$$\delta_m = \frac{V \alpha_L \sigma_L}{v \left(\frac{\partial h}{\partial m} \right)_p} \qquad (2)$$

where V is the specific volume of the wood, α_L is the dimensionless longitudinal expansion of the wood due to moisture change alone, v is the specific volume of the vapour under a vapour pressure h, and $(\partial h / \partial m)_p$ is the slope of the sorption isothermal. Inserting values measured on the Beech used in this project gave values of moisture increase of 0.012% at 30% r.h., 0.019% at 60% r.h. and 0.028% at 80% r.h., for an axial stress of 10 N mm^{-2}. Such small changes in moisture content appear unlikely to have much effect on mechano-sorptive creep.

The effect of stress on the diffusion rate does not appear to have been measured in wood, although it is generally expected that a tensile stress may increase the sorption rate in wood due to the increase in free volume. Such an expectation is supported by consideration of the energy balance, but the effect of a tensile stress on desorption rates is less certain because the two effects would oppose each other. The results described here are mainly exploratory, since the effects were found to be so small that they appeared unlikely to make an important contribution to mechano-sorptive creep.

2. Experimental details

The tensile creep tests were made on small clear test pieces of Beech (*Fagus Sylvatica*) of cross-section 8 mm in the tangential direction and 3.17 mm in the radial direction. The gauge length was 50 mm and the remaining dimensions have been given previously [15]. The three creep-testing machines have been described [16], and are capable of giving an accuracy of ± 0.4% at the 0.1% strain level. These three machines were housed in an environmental chamber which controlled the temperature to within ± 0.1° C and the relative humidity to ± 1% r.h. Some idea of the precision of the results can be obtained from the consistency of the experimental points of Fig. 1.

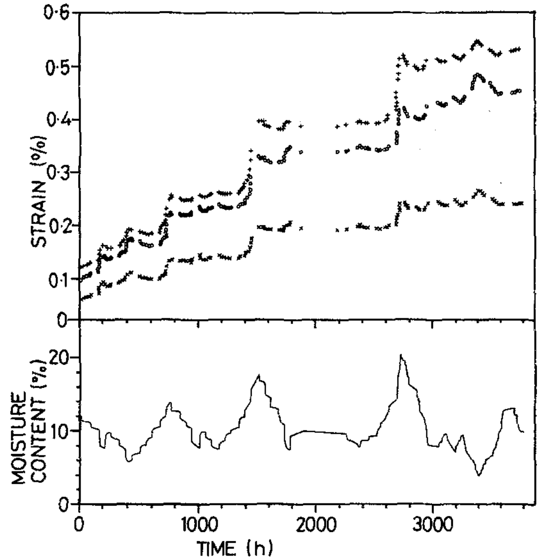

Figure 1 Complete results of creep tests at 6 (×), 9 (○) and 12 (+) N mm^{-2}, strain and moisture content as a function of time.

The chief test described here and known as test number 31, was designed to combine all of the findings of previous exploratory tests. The test stresses for this test, which remained constant throughout, were 6, 9 and 12 N mm^{-2}, representing approximately 6, 9 and 12% of the instantaneous breaking stress, on the three testing machines respectively. Previous tests had shown these values to be within the linear viscoelastic range for Beech at intermediate values of relative humidity [15]. To amplify and confirm these findings, the results of the previous exploratory tests have been included here. These were all performed at stresses of 10 N mm^{-2} and are designated as tests numbers 13, 17, 25, 28 and 29 respectively. Moisture contents were obtained from weighing measurements on four Beech pieces of the same dimensions as the gauge length of the creep test pieces (8 mm by 3.17 mm), and with their ends sealed. The temperature was kept constant at 23.5° C throughout the tests.

2.1. The material and its variability

One of the main difficulties in obtaining quantitative data on mechano-sorptive creep is the variability of the material. The approach in this project has been to prepare a large number of test pieces and make a preliminary 24-hour test at 60% r.h. on each piece followed by recovery for a minimum of one month. The philosophy of such an approach was discussed in a previous paper [15]. Since tensile-creep measurements involve differences between the dimensional changes of loaded and of matched unloaded test pieces it was necessary also to make preliminary calibrations of dimensional changes during moisture changes without load, on each test piece used.

For each experiment, the three test pieces were chosen to have very similar creep compliances after 5 sec and 24 h. Those for the main test described here, test number 31, were taken from a group of stiffer test pieces; having a mean of 24-hour creep compliance of 0.9 times the standard deviation below the mean (see Fig. 2), whilst those for the exploratory tests all had compliances above the mean. However, in spite of this matching procedure, creep compliance curves often diverged significantly at longer times or with humidity changes, as can be seen by comparing the experimental results given below. In an attempt to overcome this problem the experiment was designed so that most of the conclusions obtained would depend less on comparisons between test pieces; and more on comparisons between the results from the same test piece at various stages of the experiment. Individual conclusions will be discussed in this context below.

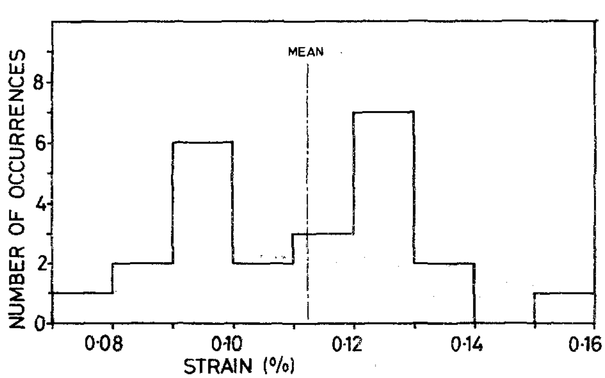

Figure 2 Histogram of results of preliminary tests for matching test-pieces, showing creep after 24 h at 10 N mm^{-2}. Standard deviation was 0.0175% strain.

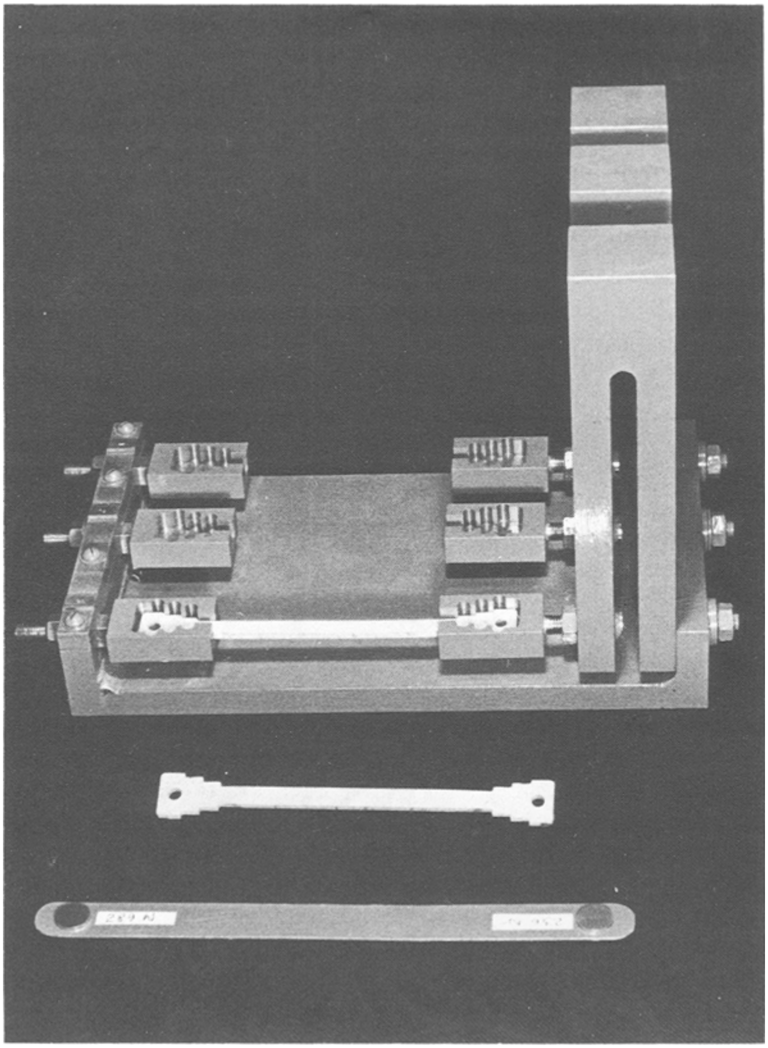

Figure 3 Apparatus for measuring the effect of tensile stress on moisture sorption and diffusion.

In view of the variability of the material it could be argued that tests on only three test pieces, each at a different stress, are not sufficient to draw conclusions. However, all of the conclusions obtained, except for the effects of stress, had also been obtained in the previous exploratory tests.

2.2. Effect of stress on moisture diffusion

Measurements of the effect of tensile stress on the moisture diffusion rates were made using the apparatus shown in Fig. 3. This consisted of a number of quick-release tensioning fixtures which allowed a test piece to be released, weighed and re-tensioned within less than 30 sec. The stepped test piece was tensioned by placing it in the stepped grips shown, then tightening the nut on the left of the apparatus until the calibrated feeler gauge would just fit into the space within the heavy "fork" springs on the right. A number of different feeler gauges were prepared for different loads. The test piece was released by loosening the nut. The unloaded control test pieces were placed in a similar fixture alongside.

3. Results

3.1. Creep tests

All creep results have been zero-load corrected, i.e. the dimensional changes of the unloaded control test piece, multiplied by a calibration factor, have been subtracted from those of the loaded test pieces.

The results of the main creep test are shown in Fig. 1, plotted as strain against time, together

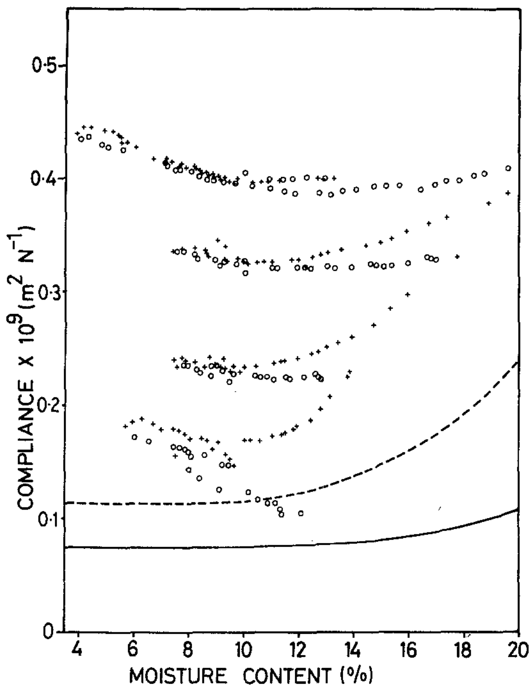

Figure 4 Creep compliance as a function of moisture content at 6 N mm^{-2}: humidifying (+), dehumidifying (○). The lines represent estimated compliance at constant moisture content, based on matched test pieces: instantaneous (——), after one week (– – – –).

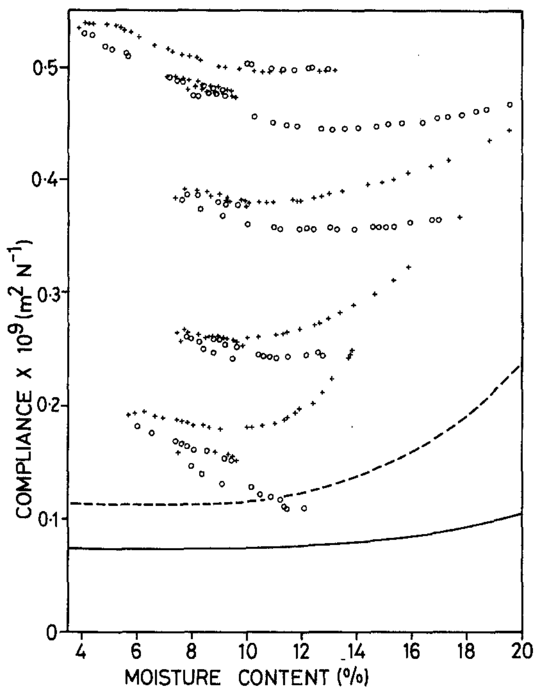

Figure 5 Creep compliance as a function of moisture content at 9 N mm^{-2}: humidifying (+), dehumidifying (○). The lines represent estimated compliance at constant moisture content, based on matched test pieces: instantaneous (——), after one week (– – – –).

with the moisture content values. Although these show the complete results, interpretation is difficult. Previous workers [3, 7] have stated that whilst normal creep depends on the time variable, mechano-sorptive creep does not. In an attempt to simplify the interpretation of the results in respect of mechano-sorptive creep they were therefore plotted as compliance against moisture content in Figs. 4, 5 and 6 for the stresses 6, 9 and 12 N mm^{-2} respectively. For comparison are also shown estimated compliances for normal mechanical creep at constant moisture contents, based on separate tests on matched test pieces. Further simplification was made by separately plotting the "dehumidifying" and "humidifying" results such as are shown in Figs. 12 and 13 for the 12 N mm^{-2} test only.

Attention should be drawn to a number of factors.

1. The shapes of the curves are different from those that would result if the hydroviscoelastic constants a^-, a^+ and a^{++} were truly constant: in which case the hypothetical plots of Fig. 7 would result for arbitrarily chosen values of the constants. It should be noted that the slopes of

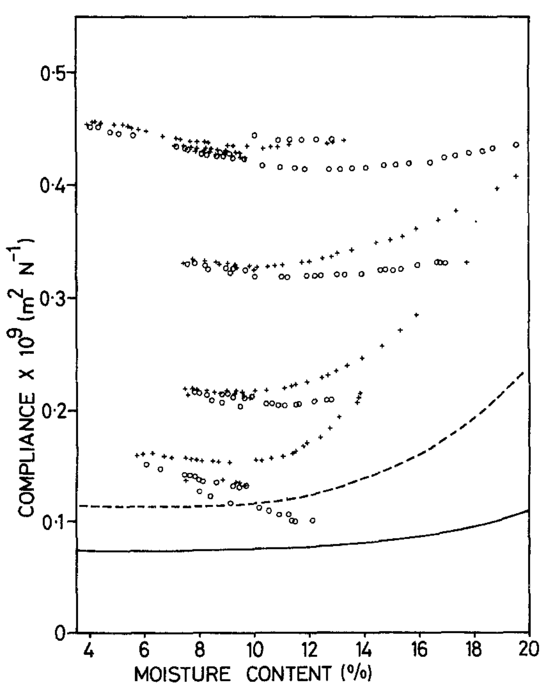

Figure 6 Creep compliance as a function of moisture content at 12 N mm^{-2}: humidifying (+), dehumidifying (○). The lines represent estimated compliance at constant moisture content, based on matched test pieces: instantaneous (——), after one week (– – – –).

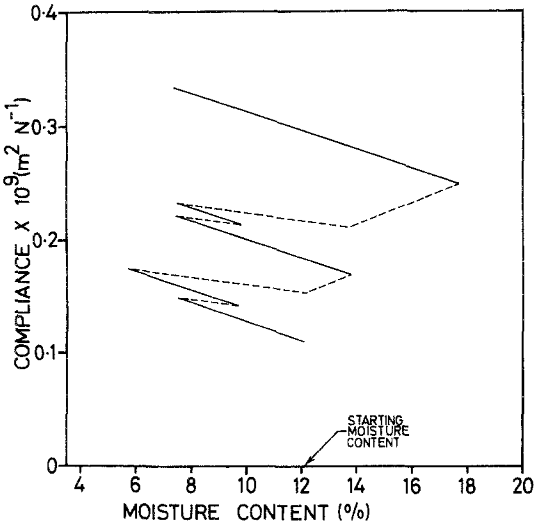

Figure 7 Hypothetical plots of compliance against moisture content that would have resulted if the values of a^-, a^+ and a^{++} were constant at $a^- = -15$, $a^+ = -5$ and $a^{++} = 14$: humidifying (– – – –), dehumidifying (———).

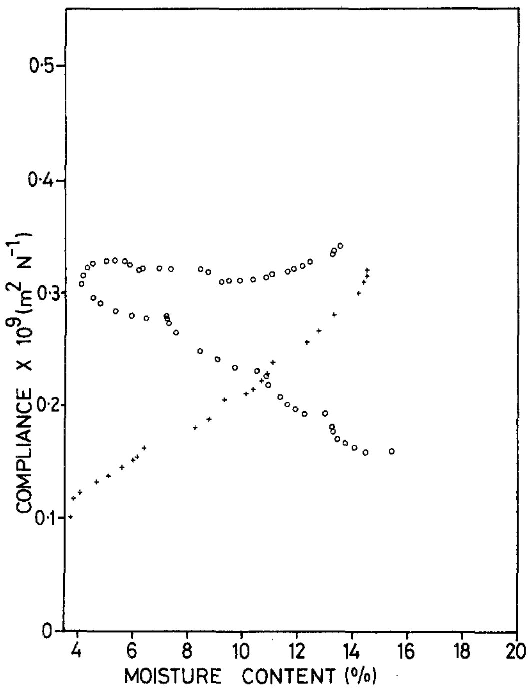

Figure 8 Mean creep compliance as a function of moisture content during triplicate exploratory tests 13 (+) and 17 (o). Preliminary tests at constant moisture content showed a large compliance.

curves of compliance against moisture content are proportional to the values of a^-, a^{++} or a^+, as appropriate. The results of Figs. 4 to 6 show that whilst dehumidifying caused an increase in creep at moisture contents below about 10% it caused a decrease at moisture contents above this value. Comparison with Fig. 7 shows that whilst the value of a^- was negative, as previously assumed, below this moisture content, it was positive at high moisture contents, and furthermore its value varied with moisture content and with strain. The results of Figs. 4 to 6 show that whilst humidifying caused a decrease in creep at moisture contents below about 11% it caused an increase at moisture contents above this value. Comparison with Fig. 7 shows that whilst the value of a^+ was negative, as previously assumed, below this moisture content, it was positive at high moisture contents, and furthermore its value varied with moisture content and with strain.

2. Whilst humidification to a moisture content level above that previously reached during the test followed the pattern shown in Fig. 7, it is difficult to detect an abrupt change in slope at the point where the previous highest moisture content was passed. In other words there appeared to be no difference between the values of a^+ and a^{++} at that point. It should also be noted that the slope of the curve during humidifying, i.e. the value of a^{++}, appeared to increase at higher moisture contents, although part of this increase was caused by the contribution to Equation 1 of the J term, i.e. the contribution of the normal mechanical creep to the integrated value of J.

3. Whilst the above observations applied to compliances above 0.15×10^{-9} m^2 N^{-1}, this compliance appeared to be some kind of threshold, below which all moisture content changes, whether sorption or desorption, caused an increase in compliance. Whilst this can only be observed during the first dehumidification in Figs. 4 to 6, and more plainly in Fig. 13; the results of previous exploratory tests given in Figs. 8, 9 and 10 show more clearly the increase in compliance following any moisture change below a compliance level of about 0.25×10^{-9} m^2 N^{-1} changing to the present behaviour above this value. Justification of this statement and an explanation of the two different threshold values will be discussed below. There also seems to be some between-sample variation in the a^- values: in this experiment the mean value of a^- was -13.65; in the exploratory experiments, using test pieces of lower modulus, the mean value of a^- was -21.7.

4. It is of interest that minima in the curves appear to have occurred at a moisture content

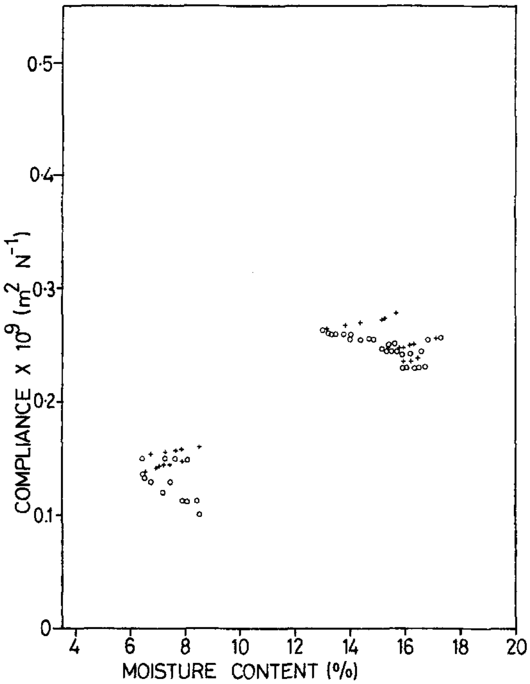

Figure 9 Mean creep compliance as a function of moisture content during triplicate exploratory tests 25 (starting at 8.6% moisture) and 28 (starting at 16.5% moisture): humidifying (+), dehumidifying (o). Preliminary tests at constant moisture content showed a large compliance.

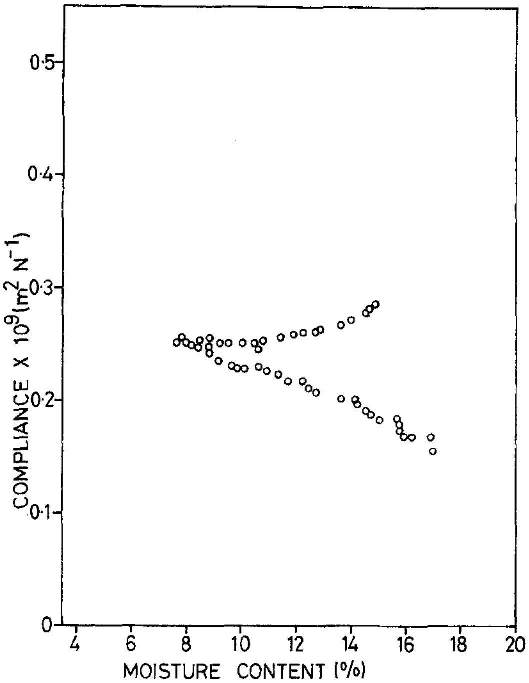

Figure 10 Mean creep compliance as a function of moisture content during triplicate exploratory test 29. Preliminary tests at constant moisture content showed a large compliance.

around 10% during dehumidification and around 11% during humidification.

5. At higher values of compliance, cycling between 30 and 50% r.h. (7.5 and 10.5% moisture content) did not appear to increase the compliance level appreciably (except for the piece stressed at 9 N mm^{-2}). This agrees with previously reported results [12]. At the highest compliance levels, even a cycle down to 3.8% moisture content did not cause a substantial increase in permanent compliance.

6. On the other hand, at high values of compliance, cycling just above the minimum of the curves (i.e. between 10 and 13% moisture content) did cause an increase in the compliance level, although this was well below the moisture content for the a^{++} regime.

7. For the first few weeks of the experiment, as can be seen from the moisture content graph of Fig. 1, the experiment was conducted by means of "step" changes of relative humidity followed by waiting until equilibrium had apparently been reached. Creep readings were taken at intervals from the start of this change, in order to define the creep curves. However, examination of the compliance against moisture content curves of Figs. 4, 5 and 6 suggests that all points fitted approximately on the curves, whether equilibrium had been reached or not. This observation, coupled with the uncertainty of the nature of moisture equilibrium (see [17]) led to the decision during the experiment to change slightly the relative humidity after each reading without attempting to reach equilibrium. This allowed the gathering of far more information within the same period of time; but the maintenance of constant relative humidity at the extremes of cycles allowed a further check that equilibrium did not affect the results (the time to reach 50% of moisture equilibrium was measured as about 2.5 h).

8. Comparison of Figs. 4, 5 and 6 suggests that at these relatively low stress levels, the stress value had a fairly small effect on the mechano-sorptive creep, although no confirmatory tests have been made to check this conclusion. It may be noted that the highest compliance levels were for the 9 N mm^{-2} stress with the lowest for 6 N mm^{-2}.

9. Particularly noticeable at the start of each of the humidifying half-cycles of Fig. 6 is that the

first two points did not follow the downward trend of the next part of the curve. This will be discussed below.

10. An analysis of six exploratory triplicate moisture-cycling creep tests supports all of the above observations (except for (8), the effect of stress level), with the proviso of (3) that the level of the postulated threshold compliance level below which the traditional mechano-sorptive creep behaviour applied, may need to be adjusted upwards for the less stiff test pieces used in the exploratory tests.

3.2. Diffusion tests under stress

The results of triplicate exploratory measurements of the effects of stress on diffusion rates are shown in Fig. 11. The differences in the values of the diffusion coefficients, stressed and unstressed, were obtained from the slopes of the graphs of fractional moisture change plotted against the square root of time [18], during unsteady-state diffusion with small moisture intervals. The slopes were determined at 50% moisture change, i.e. well within the straight middle section of the sigmoid curves. This method was considered to give the most accurate results, in view of the slight differences in the equilibrium moisture changes of the stressed and unstressed pieces. The approximate r.m.s. error of the results, weighted according to the size of the r.h. change, has been estimated as ±0.0152. As the theory suggests, the tensile stress appears to increase the diffusion rate for sorption, an overall mean being +2.0%. For desorption, however, no definite conclusions can be reached, although the results give a mean increase of + 0.8%.

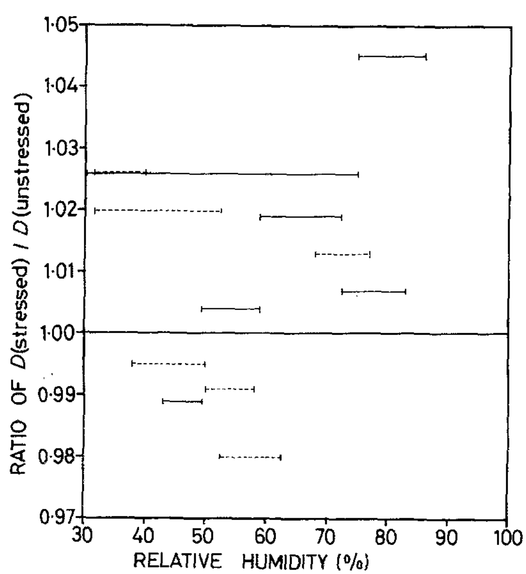

Figure 11 Effects of a tensile stress of 10 N mm^{-2} on the ratio of the moisture diffusion coefficients, stressed to unstressed, at various r.h. levels. The ends of the horizontal bars indicate the two r.h. values between which unsteady-state diffusion took place: sorption (———), desorption (– – – –). The level of each bar is the mean of three tests.

4. Discussion of results

4.1. Progress towards design data

Whilst design against mechano-sorptive creep must eventually be summarized in rules of extreme simplicity, the first step towards such a goal should be the ability to quantify this type of creep in any given conditions.

If the postulated compliance threshold exists, then below this compliance level, the two hydroviscoelastic constants a^{++} and a^- could be used in the normal way according to Equation 1. However, consideration of the results of Figs. 4 to 6 shows that above the threshold compliance, analytical calculations based on the hydroviscoelastic constants would require the development of mathematical expressions of the constants as a function of moisture content and compliance. This would be difficult.

A simpler alternative to such an analytical approach is a graphical approach. For instance, Figs. 12 and 13 give sets of "creep trajectories" for a stress of 12 N mm^{-2} during humidification and dehumidification respectively. These are sets of regularly-spaced curves drawn by a computer to fit the data obtained in the experiment. Fig. 14 combines the two types of trajectories into a single chart. For any known moisture cycling of a loaded test piece it should be possible, by following parallel to the appropriate trajectories, to obtain an approximate graphical solution of compliance as a function of moisture content, and therefore as a function of time.

The above method does not use the concept of hydroviscoelastic constants. If these constants were to be used within a graphical method then separate contour plots of a^-, a^+ and a^{++} would be required as a function of moisture content and compliance. For many purposes differential plots would be more useful, i.e. $(a^+ - a^-)$ and $(a^{++} - a^-)$, since long service could be better considered as a series of moisture cycles rather than as individual step changes. These differential values would then need to be converted to actual compliance changes

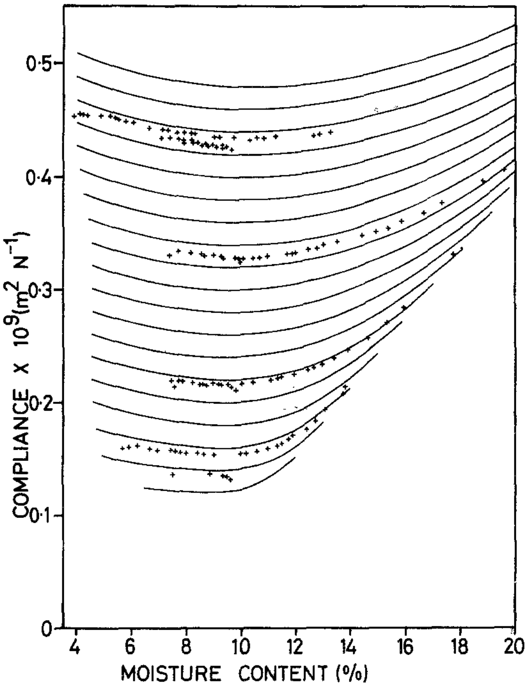

Figure 12 Creep trajectories, humidifying at 12 N mm^{-2}, superimposed on data points.

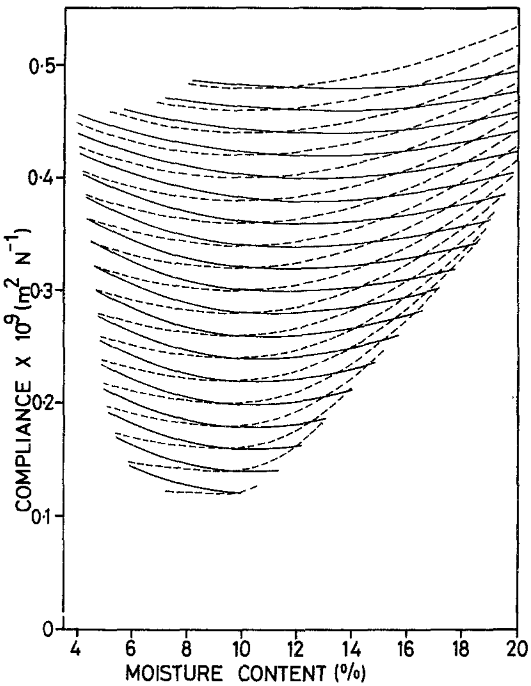

Figure 14 Superposition of humidifying and dehumidifying creep trajectories: humidifying (– – – –), dehumidifying (———).

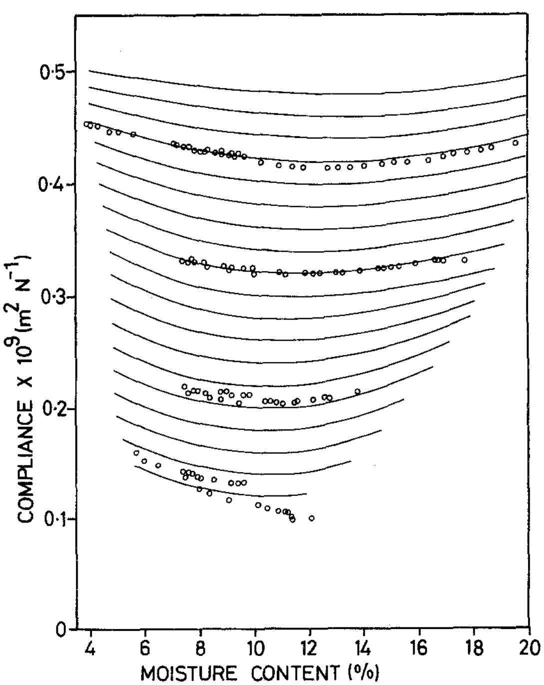

Figure 13 Creep trajectories, dehumidifying at 12 N mm^{-2}, superimposed on data points.

as a function of the moisture content history. The difficulty involved in each of the above steps led to the decision that the creep trajectories would provide a simpler method.

An important consideration for design purposes is the degree of reliability of the creep trajectories. The results of six previous triplicate moisture-cycling experiments at a stress of 10 N mm^{-2} have been plotted to the same scale for comparison. Five of them are reproduced here in Figs. 8, 9 and 10. The conclusions are that the general shape of the creep trajectories were reproduced each time, above a threshold value of compliance, but that in view of the variability of wood it is to be expected that the actual trajectories for one test piece would be different from those of the next piece. The actual extent of the variation in the trajectories can only be determined by a large-scale testing programme.

A trial superposition of the experimental points of test number 17 as plotted in Fig. 8, on the creep trajectories of Fig. 13, showed that the points during humidification cut steeply across the trajectories until a compliance of about 0.25×10^{-9} m^2 N^{-1} was reached, after which the dehumidification points and the subsequent humidification points followed the pattern of the trajectories. This type of behaviour was also observed in other tests, suggesting a threshold compliance below which any moisture change, whether sorption or desorption, causes an increase in compliance, but above which the compliance follows the creep trajectories. The obvious next question is: why is there a threshold compliance of about $0.25 \times 10^{-9}\ m^2\ N^{-1}$ in test number 17 whilst the threshold compliance in the main test (number 31) appears to be $0.15 \times 10^{-9}\ m^2\ N^{-1}$? The explanation probably concerns the sample population from which the tests were taken. The histogram of Fig. 2 shows the results of the preliminary tests on a large number of pieces from which the test pieces were chosen. The test pieces for tests 13, 17 and 29 and others having an apparently higher threshold compliance of $0.25 \times 10^{-9}\ m^2\ N^{-1}$ had also a higher compliance during the preliminary test (of the mean value plus 0.8 times the standard deviation), whilst those for test 31 had lower compliances (the mean value minus 0.9 times the standard deviation), as shown in Fig. 2. It is of interest to compare the results of tests 13 and 17 with the stress trajectories, after making allowance for this difference in a hypothetical threshold. Fig. 15 gives the results of tests 17 and 13, superimposed on the identical creep trajectories of Fig. 14 except that the latter were shifted upwards by $0.11 \times 10^{-9}\ m^2\ N^{-1}$ to higher compliances to allow for the difference in compliance thresholds. It can be seen that the fit is reasonably good.

Another important design question is whether there is a "limiting" strain. In a previous paper the author [12] suggested that there might be. However the evidence of Figs. 4 to 6 suggests a modification: within a range of relative humidities, possibly about 30 to 60% r.h. (6 to 11% moisture) a limit may be reached, but at higher relative humidities the compliance is still increasing with each cycle.

One other problem in design is how to combine normal mechanical creep with mechano-sorptive creep (i.e. how to include the J term of Equation 1). Methods of integration of mechanical creep compliances during moisture changes have been described for synthetic polymers that do not show mechano-sorptive creep [19, 20]. No attempt has been made in this paper to use the integration methods, although creep has been measured at a number of different constant moisture contents. This is because of the variability of the material and the relatively small effects of moisture content on mechanical-creep compliance levels, at least at low and intermediate moisture contents, as can be seen in Figs. 4, 5 and 6.

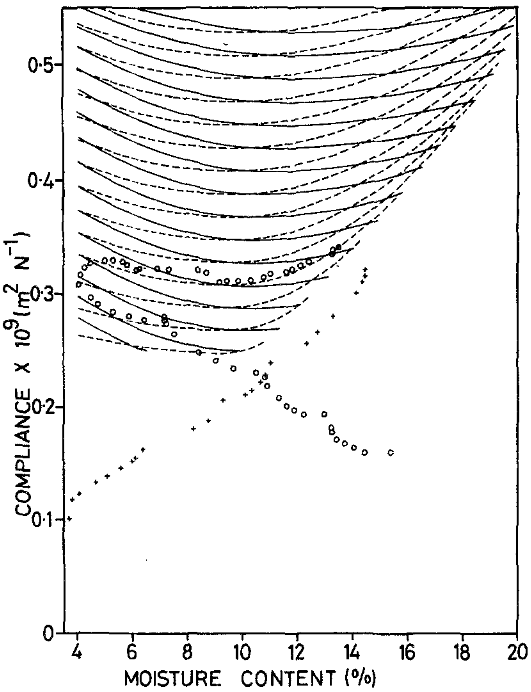

Figure 15 Points of earlier tests 13 (+) and 17 (o) of Fig. 8 on pieces having a large compliance in preliminary tests at constant moisture content; superimposed on the creep trajectories of Fig. 12 shifted upwards $0.11 \times 10^{-9}\ m^2\ N^{-1}$ so that the thresholds coincide: humidifying (– – – –), dehumidifying (——).

In typical service conditions over a long period it seems likely that the mechano-sorptive type of creep will predominate. Nevertheless, it is interesting to compare the total compliances of 0.40×10^{-9}, 0.50×10^{-9} and $0.44 \times 10^{-9}\ m^2\ N^{-1}$ respectively for the three stresses used in the 3793-hour moisture-cycling experiment described above; with that of $0.38 \times 10^{-9}\ m^2\ N^{-1}$ obtained by extrapolation to 3793 h of the mechanical-creep curve of some matched test pieces at a constant moisture content of 19.2% (just below the maximum value obtained in the cycling experiment). The relative closeness of these values suggests that a design "rule of thumb" may eventually specify a total deflection equal to that obtained at a constant moisture content equal to the maximum uniform value expected in service, maintained for the entire service life of the part. Such a suggestion has already been made by Ranta Maunus [11] for certain species of wood, although other authors have presented results at other stresses and moisture cycles which do not support it. Further testing will be required to determine the range of conditions in which such a "rule of thumb" may be applicable.

4.2. Improvements in testing methods

The results presented above suggest some improvements in testing methods compared with those used in the past.

1. Those variables to be controlled and those to be measured must be carefully considered. The creep response was found to depend on both moisture content and compliance level. Regarding the moisture content, the experimental evidence did not indicate whether it was specifically the moisture content or the relative humidity that controlled the response. Since these two are related by hysteresis and therefore moisture history it may be necessary to include moisture history as another variable. Similarly with compliance: there was insufficient evidence to decide whether compliance or strain is the important variable. These two being related by stress, it may be necessary to include the variable stress, even at low levels (within the linear viscoelastic range).

2. The results show the futility of merely cycling the relative humidity and measuring the creep at the extreme ends of each cycle. Depending on the humidity values chosen a variety of different conclusions could be drawn, as described above in the introduction.

3. The evidence suggests that a continuous series of relative-humidity changes at fairly short time intervals with no attempt to reach moisture equilibrium after each step (except at the extreme ends of the cycles) gives better information and more quickly than waiting for moisture equilibrium after each step.

4.3. Progress towards a theoretical explanation

The experimental evidence has raised a number of questions regarding the relation between mechano-sorptive creep and the wood structure.

1. Why does there appear to be a threshold compliance below which all moisture changes cause an increase in creep but above which creep appears to follow the trajectories? And why is this threshold apparently higher for those test pieces that are more generally compliant when tested at uniform moisture content? The creep behaviour below the threshold fits the often-quoted explanation that during the breaking and re-making of hydrogen bonds, which occurs during moisture changes in either direction, a stress bias will favour slippage (for instance, [2]).

2. Why do both types of creep trajectories show a minimum at around 10 to 12% moisture content? What changes in moisture bonding take place at this moisture content?

3. Why does mechano-sorptive creep at low moisture contents involve increase in compliance during desorption but decrease during sorption? A rheological model, but not an explanation, was proposed in a previous paper [12].

4. Why does mechano-sorptive creep at high moisture contents involve increase in compliance during sorption but decrease during desorption? A fraction of the increase could be ascribed to normal mechanical creep.

5. Why do the first few points of the humidifying trajectories fail to conform with the rest of curve (i.e. there appears to be a slight increase in compliance as sorption begins)? Could this be explained by there being two different types of moisture bonding [21, 22] having different diffusion coefficients, so that one type is increasing at the same time as the other is decreasing?

6. Are the changes in response at high compliances controlled by compliance or by strain? A model based on the structure of the wood and wood–water relations would be expected to depend on strain.

5. Conclusions

It is hoped that the observations described here will renew interest in the mechano-sorptive creep phenomenon in wood. In order to utilize the material more efficiently it will be necessary to design wood structures with suitable allowances for mechano-sorptive as well as mechanical creep.

The observations described above have raised a number of questions which can only be answered by further research. This will need to include studies of softwoods and also of the effect of interaction between temperature and moisture-content changes.

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