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Longitudinal moisture-shrinkage coefficients of softwood at the mechano-sorptive creep limit *

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Summary. An adaptor for the conversion of a high-accuracy tensile creep machine to compression loading is described. It was found that a stable mechano-sorptive creep limit could be obtained by a suitable load reduction after moisture cycling; after which further creep and creep recovery just balanced each other. In this stable state the value of the longitudinal moisture-swelling coefficient depended on the strain; being less with tensile strain and more with compressive strain then in the unloaded condition. These differences in the swelling coefficient could explain the apparent recovery during subsequent sorptions in mechano-sorptive creep in bending. Such a hypothesis was strongly supported by numerical comparisons of strains in bending, tension and compression.

Introduction

It is known that varying humidity conditions will accelerate the rate of creep of wood under load (Armstrong, Kingston 1960). Since deflection is usually the limiting factor in timber designs, any acceleration is evidently an important consideration. In spite of its importance and the fact that it has been known for thirty years, a full explanation and description of the phenomenon, known as 'mechano-sorptive creep' (Grossman 1976), has not yet been achieved.

The classical description of the phenomenon of mechano-sorptive creep consists of three parts: (a) an increase of creep strain during any desorption, (b) an increase of creep strain during the first sorption at any moisture level, and (c) a decrease of creep strain during any subsequent sorption at the same moisture levels as in (b), e.g. Hearmon and Paton (1964). This latter decrease has always caused difficulties in developing a theoretical explanation of mechano-sorptive creep.

A recent published note (Hunt, Shelton 1987) showed evidence that a stable limiting state of creep could be obtained quickly by a suitable (unspecified) load-humidity history. At this stable state under tensile loading, it was found that the longitudinal dimensional movement rate, as shown in a graph of strain versus moisture content, was consistently lower than in the original unloaded state. Since the mechano-sorptive creep in tension is normally obtained by subtracting from the

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actual strain a correction based on the unloaded dimensional movement, previous creep data evidently contained an unexpected error. Moreover the magnitude of the error could be sufficient to account for the apparent tensile creep decrease during subsequent sorptions. In reality successive moisture cycles could cause a continuous increase in tensile creep until the creep limit was approached. It was further postulated at the time, that if a stable state of creep could be obtained under compressive loading, the longitudinal dimensional movement rate might be *greater* than in the original unloaded state. If this could be shown to be true, then it could explain the apparent decrease in creep during subsequent sorptions under bending, which is the mode of testing that has generally been used by researchers in the past. This would allow the simplification of the phenomenon of mechano-sorptive creep to a first-order system; namely a continuous increase towards a creep limit with all moisture increases, regardless of direction. Mechano-sorptive creep might then fit an equation of the type

$$\varepsilon = \varepsilon_L (1 - \exp(-a \sum_{i=1}^{n} \delta u)) \tag{1}$$

where ε_L is the strain at the creep limit under a given stress, δu is the absolute value of any moisture change and a is a suitable coefficient.

In order to obtain accurate creep measurements in compression, an adaptor was designed to be attached to standard tensile-creep machines. This was used to study mechano-sorptive creep and the stable-state creep limit in compression.

The scope of this paper is then:

1) To give details of compression-loading adaptors for tensile-creep machines which have been described previously (Darlington, Saunders 1970).

2) To give experimental details of an accelerated method of obtaining and verifying a stable-state creep limit.

3) To show that, at a creep limit under compressive loading, the longitudinal dimensional movement was greater than in the unloaded state.

4) By quantitative comparison between dimensional movements of matched test pieces at stable-state creep limits under tensile, compressive or bending loading to show that the above theory is reasonable.

A general comparison of mechano-sorptive creep in tension, compression and bending will be given in a later paper.

Experimental details

Tests were made on scots pine (*Pinus sylvestris*) of cross section 8 mm radial by 3.2 mm tangential. The pieces were carefully prepared to avoid any surface damage, and the samples were checked for compression wood.

Testing was done at 23.5 °C in a closely-controlled environmental chamber that has been described previously (Hunt, Darlington 1978). Measurements of move-

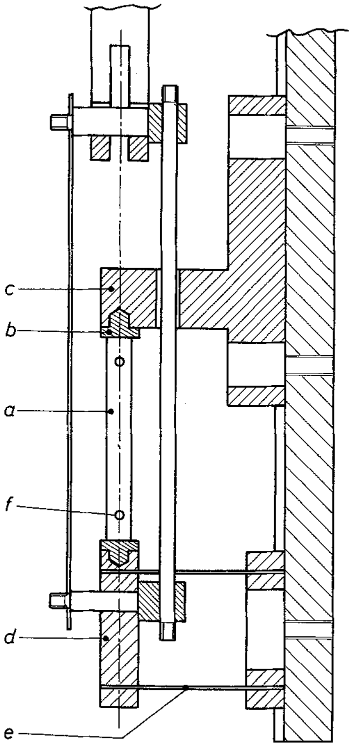

Fig. 1. Sectional view of compression adaptor for tensile creep machines: *a* test piece, *b* end plates, *c* and *d* fixed and movable plattens, *e* spring guides and *f* extensometer locations

ment were made directly with super linear variable capacitance (SLVC) transducers. Tensile and bending tests were done on machines that have been described (Darlington, Saunders 1970; Hunt 1986). All test results were corrected for variation in elastic compliance and for dimensional changes as described in Hunt and Shelton (1987).

Compression loading was applied on the tensile machines previously described, but using adaptors as shown in Fig. 1. The intention was to obtain compression creep results of an accuracy comparable with that obtainable with tensile machines. This is especially important since most of the previous published compression-creep results have been made with less accurate mechanical extensometers (e.g. Armstrong, Kingston 1962; Armstrong 1972; Bazant, Meiri 1985). The test piece (*a*) has a T-shaped cross section fabricated from two 8 mm by 3.2 mm pieces bonded with epoxy resin to reduce the buckling effect. The total test-piece length was 64 mm; the gauge length being 51 mm. The test piece was bonded to end plates (*b*) that fitted into the fixed (*c*) and movable (*d*) plattens. Parallel spring guides (*e*) ensured that the movement of the movable platten was axial. Deflections were measured with a scissor-type extensometer that located on the centroidal axis (*f*) of the test piece with fine needle points. Preliminary tests of elastic compliance showed that this apparatus gave results of similar accuracy to those of the tensile machines.

Results

Achievement of the creep limit

If wood under load is subjected to continuous moisture cycling, the increase in creep per cycle reduces on each cycle, so that the total mechano-sorptive creep may tend towards a creep limit. Such a limit can be predicted quantitatively provided that a sufficiently large number of cycles have been made. This has been done in the case of a seven-week seven-cycle creep test on five pieces of european spruce (*Picea abies*). The relative humidity was cycled between 30% and 84%. The plotting of the natural logarithm of the increase in strain per cycle δ_ε against the cycle number N, gives approximately a straight line. This gives an equation of the form

$$\delta_\varepsilon = \mathrm{a} \exp(-\mathrm{b}\mathrm{N}) \qquad (2)$$

which can be summed to infinity to give a limiting strain of a (1/(exp (b) – 1)).

It is also known that moisture cycling will not only cause an increase in creep under load but will also accelerate recovery when the load is removed (Arima, Grossman 1978). This suggested a means of accelerating the achievement of a creep limit, namely partial unloading, so that creep and recovery balance each other.

The initial investigation was made with a set of twelve test pieces in bending. These were loaded to give a surface bending stress of 7.5 N mm^{-2}, or approximately 7% to 10% of the instantaneous fracture stress. They were loaded at 7% moisture content, then given a slow (two-weeks) cycle to 16.5% and back to 7%. They were then partially unloaded to give six pairs of test pieces with stresses of 7.5, 6.2, 5.0, 3.7, 2.5 and 1.2 N mm^{-2} respectively. They were then subjected to two more similar two-weeks cycles to 16.5% and back to 7% moisture content. The overall change of compliance during the second of these subsequent cycles was measured and plotted as a function of fractional load reduction, as shown in Fig. 2. The fitted straight line gave a zero compliance change for a load reduction to 51% of the original load.

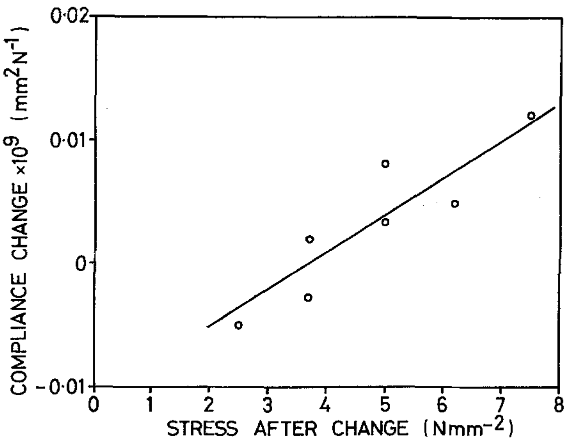

Fig. 2. Compliance change during second humidity cycle after stress change from 7.5 N/mm^2

The criterion for considering that the creep limit has been reached has been the achievement of a closed loop on a strain versus moisture content graph to within an error of less than 25 microstrain. The figure of 51% load reduction has been used for at least 50 subsequent tests on pieces from the same wood sample, and has proved to be satisfactory. These tests have involved other conditions such as reducing the load at high or low humidity, cycling up to 18% or 23% moisture content, other modes of loading, the use of multiple cycles and with test pieces of widely varying elastic compliances. During one experiment, the laboratory was accidentally flooded, relative humidity approached 100% for 24 hours, all power was shut off for a week with no environmental control and readings were suspended for 3 weeks. However the incident happened shortly after the creep limit had been reached; and subsequent readings showed no departure from the strain versus moisture loop begun before the flooding. Generally the achievement of a creep limit has been most positive with tensile loading and least positive with compression loading, with bending intermediate.

Anybody attempting to use the procedure on other samples or species would be advised to re-determine a suitable load-reduction value for their own sample.

Effects of strain on the longitudinal movement coefficient

Because of the variability of wood as a material, it is useful to design experiments in order to obtain the maximum amount of information from any given test piece, rather than to rely too much on comparisons between test pieces. Where matching of test pieces was needed, it was based on the elastic compliance, as previously described (Hunt 1986). Loading measurements were made in tension, compression and bending; whilst measurements were also made of relative humidity, moisture content and length changes under zero load. The outline of the experiment, to determine the effect of creep strain on the longitudinal movement coefficient, was as follows:

1) At least one full slow conditioning cycle, humidification – dehumidification (90%–30%–90% rh), was used to stabilize the material and to relieve stresses of unloaded test pieces.

2) Still unloaded, a slow two-weeks humidity cycle was made with five step changes in each direction of relative humidity. Dimensional and moisture content measurements were made at suitable intervals.

3) Test pieces were loaded at a stress of 7.5 N mm^{-2}, held for 24 h, and then given a one-week humidity cycle.

4) The loading was reduced by 49% to give stresses of 3.855 N mm^{-2} and then the pieces were given a one-week humidity cycle to achieve a stable state of creep at this stress.

5) The pieces were again given a two-weeks cycle, as in 2) above.

6) Steps 3 to 5 were repeated, but with the stress being increased to a higher value and then later reduced to 7.5 N mm^{-2} to achieve a stable state at this stress.

The experimental conditions are summarised in Fig. 3.

Figure 4 shows typical results of total dimensional change versus moisture content for zero load and for tension, compression and bending at the limiting

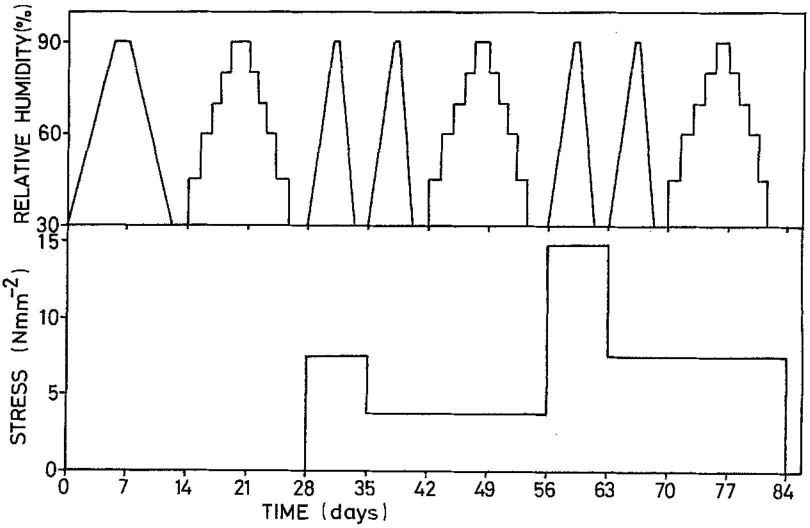

Fig. 3. Experimental load and humidity conditions for the main experiment

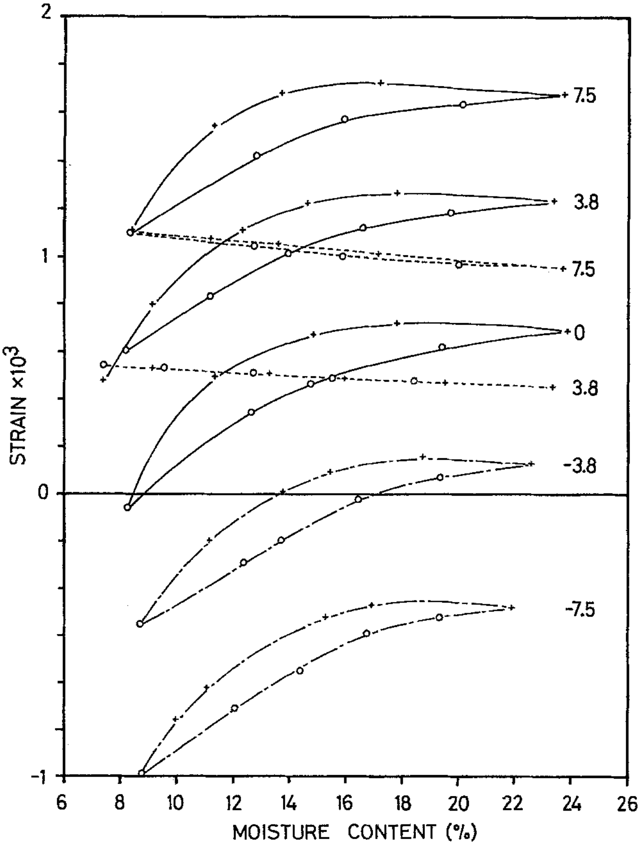

Fig. 4. Typical strain-moisture loops at various stress levels (N/mm^2), as indicated. Tension ———, bending - - - - - - , compression — · — · . Points shown are 24 hour equilibrium points

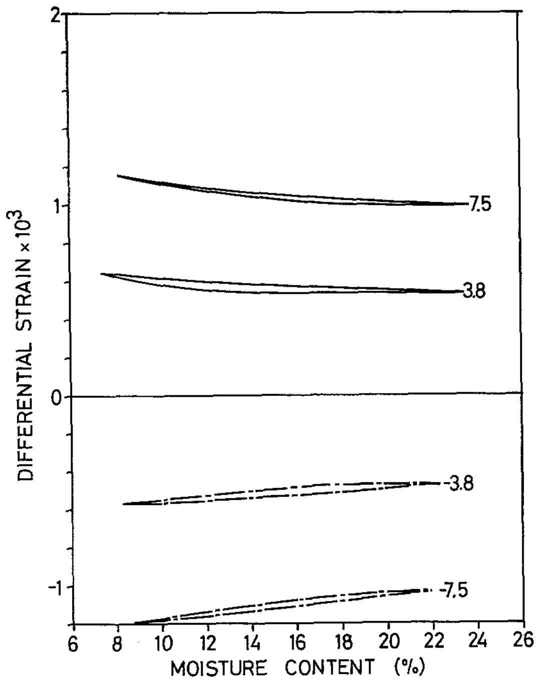

Fig. 5. Typical strain difference loops taken from Figure 4: differences between stable-state loop and zero-load loop. Note the similarity with the bending creep loops of Fig. 4. Tension ———, compression — · — ·

creep state for various stresses. The three bending loops were made on the same test piece, the three tensile loops on another one and the two compression loops on another. For reasons of clarity the zero-load loop for the compression piece was not included on the graph, but it did conform closely to that given. All pieces had been matched by preliminary elastic compliance tests to within ± 5%. It should be noted that the bending values, although plotted in the positive strain region, actually involve both positive and negative strain values. The interest of these graphs lies in the differences in the slopes of the tension and compression loops at the various strain levels: lower slopes at higher strains and vice versa. This is a further development and confirmation of similar data already reported (Hunt, Shelton 1987). Whilst these are quoted as typical results, the same effects have been observed in three out of three compression tests and in nine out of nine tension tests, together with more than 40 bending tests.

The differences between the strain-moisture content loops at various stresses relative to the zero-load loop are shown in Fig. 5, taken from the values of the tests shown in Fig. 4. It is of interest to note the similarity in shape between the tensile loops of Fig. 5 and the bending loops of Fig. 4; and similarly between the tensile and the compression loops, bearing in mind the reversal of the signs of the strains. When the mean slopes of the hysteresis loops such as those of Fig. 4 were plotted against the strain at a reference moisture content of 8%, the graph of Fig. 6 was obtained. Those points that are joined by straight lines are for cases where progressive loading cycles gave slope measurements at three different strain levels, including zero. All other measurements were made at two stress levels; one non-zero

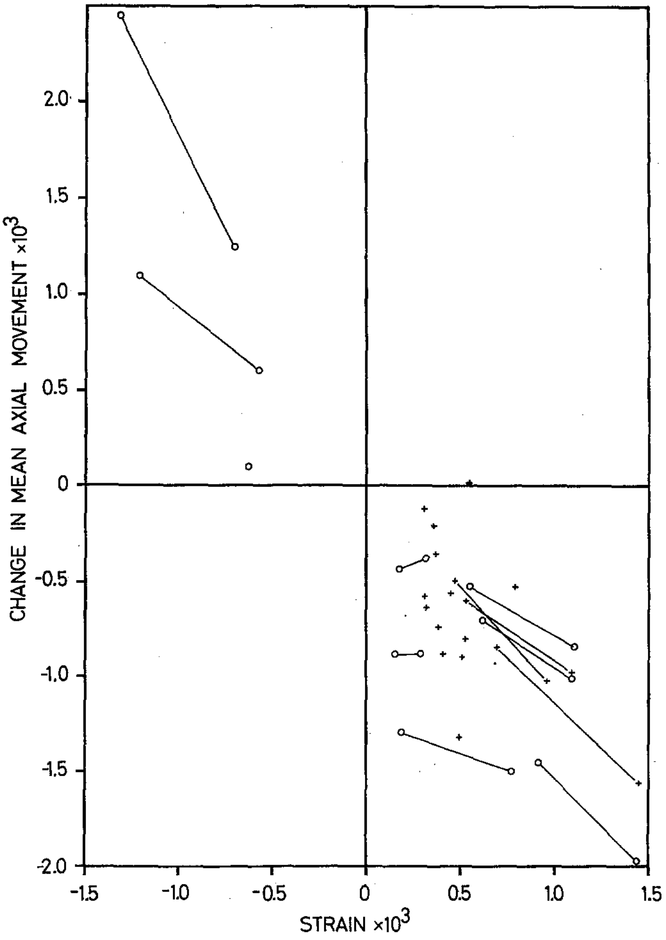

Fig. 6. The effect of strain level on the mean slope of strain-moisture loops. Tension and compression ⊙, bending + (tensile surface values). Lines join points obtained from the same test piece

and one zero stress value. Once again the positive sign chosen for the bending strains is entirely arbitrary. Fitting a straight line by the least-squares method gave the equation: $d\varepsilon/du = -0.013\ (10^{-3}) - 1.215\ \varepsilon$. The results for tension and compression are summarised in Table 1, which gives the longitudinal dimensional movement coefficients as a function of the applied stress.

Discussion

It will be very important to obtain accurate long-term creep data to test the existence of a creep limit. The exponential function given in Eq. (2) gave the best fit to the 1176-hour seven-cycle creep tests mentioned above, and also would lead to a

Table 1. Longitudinal dimensional movement coefficients as a function of stress

Test-piece code	Stress N/mm^2	Stress sense	Longitudinal dimensional movement[a] coefficient (× 1000)
67L	0		5.74
	3.8	tension	5.21
	7.5	tension	4.89
66C	0		7.86
	3.8	tension	6.41
	7.5	tension	5.88
66L	0		4.76
	3.8	tension	4.06
	7.5	tension	3.75
64R	0		11.44
	6.3	tension	9.93
64C	0		4.99
	6.3	tension	4.11
64L	0		4.36
	6.3	tension	4.09
66R	0		5.20
	3.8	compression	5.30
67C	0		3.84
	3.8	compression	5.09
	7.5	compression	6.29
67R	0		5.46
	3.8	compression	6.06
	7.5	compression	6.56

[a] Mean value between 8.3% and 22.6% moisture content

creep limit. Gressel (1984, 1986) conducted 500-hour ten-cycle creep tests between 30% and 90% rh at 20 °C on beech and some other wood-based materials. He considered four mathematical functions to fit to his data, including a three-parameter model similar to Eq. (2), which would lead to a strain limit. He eventually, however (Gressel 1986) chose a power function $(\varepsilon_t - \varepsilon_0)/\varepsilon_0 = at^b$ (where a and b are constants, t is time, and ε_t and ε_0 are total and elastic strains respectively). This gave a better fit to his data in general, including plywood and chipboard and some 80,000-hour tests at constant humidity and temperature. On the other hand, the conclusions of Noack and Stöckmann (1969) that wood remains in a 'glassy state' until the beginning of rupture, supports the existence of a creep limit.

The results plotted in Fig. 6 suggest that the change in mean axial movement for the limiting strain loop, $d\varepsilon/du$, is approximately proportional to the strain level, ε_R. If this is correct, then it would be expected that in the case of bending, in which there is a linear variation of strain between the two surfaces, the ratio of $d\varepsilon/du$ to ε_R would be the same as it was for tension and for compression. The results shown in Fig. 6 suggest that this is correct.

If the evidence is accepted that tensile or compressive strains affect the longitudinal movement coefficients, this raises the problem of finding an explanation.

On the molecular level, Murphey (1963) claimed that tension caused an increase in crystallinity, or the degree of molecular ordering and alignment. It is generally considered that the crystalline regions of semi-crystalline polymers are less affected by moisture than the amorphous regions (Crank, Park 1968) so this could also affect movement. However it is not clear whether his interpretation is correct, since it is based only on the observation that the peak levels, when traversing radially across the 002 X-ray diffraction circle, increase as the result of loading. This could equally well be interpreted as a decrease in the microfibril angle (e.g. Meylan 1967). Jentzen (1964), in studying individual pulp fibres, claimed that increased crystallite orientation could be permanently introduced by drying under a tensile load. He found that this produced an increase in the Young's modulus and various other strength properties. Apart from the fact that his individual fibres would have had fewer geometrical constraints than a tracheid within a piece of wood, there is again some question of interpretation. In addition to some measurements that appear to support those of Murphey, there are others that appear to show that there is a reduction of the microfibril angle. Jentzen suggests that the increase in Young's modulus is the result of a more even distribution of stress among the microfibrils.

Boyd (1982) proposed a lenticular trellis explanation of viscoelastic and mechano-sorptive creep in which the non-crystalline hygroscopic gel-like matrix material forms lens-shaped pockets between the crystalline microfibril structure. The effect of axial strain would be to change the shape of the matrix pockets and accordingly the local orientation of part of the load-bearing crystalline regions: the result being a difference of behaviour between tension and compression straining. This could form the basis of an explanation, although at present it is not possible to make quantitative comparisons. However, one of the predictions of this theory is that on unloading after compression creep, the change in strain would be slightly greater than it was on loading. Conversely with tension it should be slightly less. With bending it should be unchanged or very slightly greater. The actual measurements in this experiment consistently supported these predictions, but the number of measurements and the small size of the changes were not sufficient to analyse them statistically and so confirm them.

A simplified approach to quantification can be based on the assumption that under a tensile stress any shear between microfibrils will tend to increase their linear alignment, and also decrease the angle between the microfibrils and the longitudinal fibre direction. Conversely, compression will increase the microfibril angle. It is known that the mean microfibril angle of the S2 layer affects the longitudinal movement coefficient. Calculations based on the assumption of a simple helix of microfibrils show that a creep strain of 0.001, if caused entirely by inter-microfibril shear, would cause an angular change of 0°.157 for a microfibril angle of 20° to the grain direction. The change would be 0°.099 for a microfibril angle of 30°. The effect of such small angular changes on the longitudinal movement coefficient can be roughly estimated from the relationship given by Meylan (1972). The results would be changes in the slope at the 10% moisture level of 0.095 (10^{-3}) for a microfibril angle of 20° and 0.245 (10^{-3}) for a microfibril angle of 30°. These may be compared with a typical measured slope change as shown in Fig. 6, of about 1.2 (10^{-3}) for a total strain (including parallel and perpendicular tension and shear) of 0.001. This mechanism therefore does not appear to account for all of the change in movement actually measured. It must be borne in mind, however, that there was considerable scatter at these lower microfibril angles in Meylan's data, and the fitted curve was subject to some error. A large amount of similar scatter was found in the Authors' data so that it was very difficult to fit an accurate expression to it. However an approximate straight-line fit gave a slope change value of about 0.14 (10^{-3}), which agrees with Meylan. On the other hand, the data presented by Jentzen (1964) suggested that the change in the values of the microfibril angle might be as much as ten times the values calculated above. This would make the calculated changes in the movement coefficient comparable to those actually measured.

Another approach is to consider the shape of a typical longitudinal movement versus moisture content curve, such as those of Fig. 4. At higher moisture contents the slope is less steep than at lower ones. The thermodynamic theory of Barkas (1949) predicted that a tensile stress would give a higher equilibrium moisture content. A compressive stress would give a lower one. When the actual moisture contents are calculated or measured as in Hunt (1984) the changes are quite small, ranging from 0.012% to 0.28% over the range 30% to 80% r.h. at a stress of $10\,\mathrm{N\,mm^{-2}}$ in beech. Similar experimental results were obtained by Libby and Haygreen (1967). For this explanation to fit quantitatively to the changes in slope actually measured for this species of softwood, the moisture content would need to be changed by about 0.4% for a stress of $7.5\,\mathrm{N\,mm^{-2}}$ at the 10% moisture content level and by about 2% at the 18% moisture content level.

Conclusions

The achievement of a stable mechano-sorptive creep limit means that there is a real possibility of designing to limit mechano-sorptive creep in softwoods. It also means that some useful dimensional-change measurements can be made in this stable condition that could not otherwise be made. More of these will be described in a later paper.

Tests on the new design of creep compression testing equipment have shown that compression measurements can be made of comparable accuracy to those of tensile tests. Compression and tension measurements at the creep limit then showed that the longitudinal movement coefficient is a function of strain. Quantitative comparison of these changes can then account for the deflection changes in bending test pieces at the creep limit during humidity cycling; and therefore also explain the apparent creep recovery during subsequent humidification. An analysis of the actual creep behaviour in compression during humidity changes will be presented in a later paper.

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