Creep of nylon-6,6 during concurrent moisture changes

David G. Hunt
Department of Mechanical and Production Engineering, Polytechnic of the South Bank, Borough Road, London SE1, UK
Michael W. Darlington
Department of Materials, Cranfield Institute of Technology, Cranfield, Bedfordshire, UK
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Dimensional changes of nylon-6,6 during moisture changes under zero load and under applied tensile loads have been measured. These moisture changes included both simple sorption or desorption and humidity cycling. The anomalous creep behaviour that had been observed with wood was not found, but on the contrary it was found that the creep behaviour in changing humidities could be approximately predicted from creep data at constant stress and humidity. The method of prediction assumed that the instantaneous mean moisture content controlled the behaviour. This relatively simple approach was compared with a lengthy 'explicit' method and found to give almost identical results.

INTRODUCTION

A previous paper[1] has described apparatus for the accurate measurement of creep of nylon-6,6 under conditions of constant stress, temperature and moisture content. A second paper[2] described a method of superposing the resulting creep curves to form a single basic master curve for infinitesimal strains that could be used to predict creep at any value of constant stress or moisture content within the range studied. The master curve was plotted as the logarithm of compliance against a distorted logarithmic-time scale designated θ; and a separate plot gave the value of a shift parameter as a function of moisture content. This shift parameter, designated a, gives the amount by which a frame of reference representing the effective start of the creep test (*Figure 1*) must be moved along the θ, or time scale, at any given uniform moisture content. The creep compliance master curves are slightly higher at higher stresses, and therefore there is a correction factor for stresses as a function of θ. This results in a set of derived master curves for various constant stresses that allow for the slight viscoelastic nonlinearity.

In service, the moisture content of a part is not normally held constant; on the contrary it normally fluctuates as a result of daily and seasonal changes in the ambient relative humidity. Therefore, the decision was made to study the effect of such fluctuations by undertaking a series of creep tests in concurrently changing air humidities and then seeing whether the resulting measured creep behaviour could be correctly predicted from the master curve.

A further reason for interest in the creep of nylon during concurrent moisture changes was to compare its behaviour with that of wood, which is also hygroscopic, polymeric, and swells with increasing moisture content. Wood has been found to creep much faster while its moisture content is changing than while it is constant at either the upper or the lower limit of the moisture change[3]. It was felt that such behaviour in a polymer used for structural purposes would necessitate a serious reappraisal of its design parameters, not only because changing humidities are normal in service conditions, but also because this could represent 'unsafe' behaviour, i.e. the resulting compliances could be outside the range measured in the constant-humidity tests that would normally be used to obtain values for design.

Two types of moisture changes are considered. First a simple step-sorption and step-desorption, in which the test pieces were conditioned at a given relative humidity and then during the creep test the relative humidity was suddenly changed to a new value and held constant. Second, test pieces were subjected during a creep test to a relative humidity that cycled between two values, to give more the type of conditions that would be met in practice.

The changes occurring in a nylon test piece during relative humidity changes are somewhat complicated. The material gains or loses moisture – the final moisture content tending to an equilibrium level in constant environmental conditions. Because the moisture takes time to diffuse through the material, the moisture content varies with position and time.

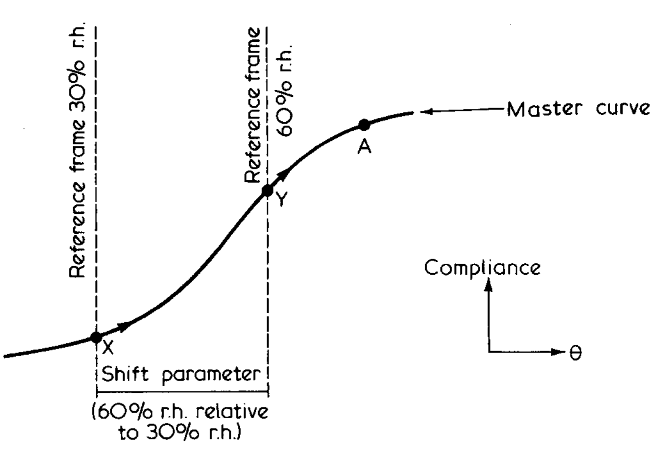

Figure 1 Use of a master creep-compliance curve for the prediction of creep at various moisture contents (arrows indicate the 'start' of creep tests at 30% r.h. and 60% r.h. respectively)

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As an increase in moisture content causes swelling under equilibrium conditions, the moisture gradient induces differential strains. These differential strains result in internal stresses whose magnitudes depend on a modulus that decreases with time and also decreases with increasing moisture content. Moreover, these are biaxial stresses with associated triaxial strains that vary both with time and position in the test piece. Such behaviour occurs even in the absence of an external applied load.

Any attempt at prediction of creep with concurrent moisture changes must therefore consider four separate simultaneous effects: the continuously-changing moisture gradients, the continuously-changing stresses, the continuously-changing moisture-induced dimensional changes and the variation from the centre to the surface of the bar.

The present paper describes the following programme of work:

(1) creep measurements at constant stresses but in changing relative humidities;

(2) determination of equilibrium dimensional changes with moisture content;

(3) confirmation of the absence of the type of anomaly observed during the creep of wood with concurrent moisture changes;

(4) the prediction of creep strains in changing relative humidities from:

  (i) measured and calculated moisture contents;
  (ii) basic creep data obtained at constant stresses and constant humidities;
  (iii) the use of Boltzmann Superposition for changing stresses;
  (iv) measured equilibrium dimensional changes due to moisture content changes alone.

Previous work

The prediction of moisture changes in nylon has been established by a number of workers[4–7] who found that moisture in nylon-6,6 obeys Fick's laws of diffusion, and that stress has very little effect on the diffusion rate[4]. The diffusion coefficient appears to depend mainly on the moisture concentration and slightly on the thickness of the material. The mean moisture content of a test piece at any time during a creep test can therefore be satisfactorily determined by weight measurements on an unstressed control piece of the same dimensions, and internal moisture contents can be calculated by the Crank–Nicholson finite-difference method. Alternatively, by previously measuring the diffusion coefficient as a function of moisture content and thickness, the internal moisture contents can be calculated directly from a knowledge of the relative humidity history.

The effect of various levels of constant moisture content on the elastic and creep properties of nylon-6,6 has been studied by a number of workers[1,8–10]. Measurements at 23.5°C showed that below about 30% r.h. and for short times, the material is below the glass transition and is fairly stiff, whilst above about 60% r.h. it is above this transition, and its modulus is reduced to about 33% of its value in the dry state.

The effect of changing stress on the creep of polymers is generally predicted in the linear viscoelastic region by means of Boltzmann Superposition. This has been used successfully with a number of polymers, for example polypropylene[11].

The equilibrium dimensional changes with moisture content changes under zero load have been established on nylon-6,6 by several authors[4,12,13].

The prediction of concurrent dimensional changes during humidity changes either with or without an external applied stress has been studied on polymers other than nylon-6,6. The pioneers were Kishimoto and Fujita[14], who studied the simpler problem of introducing moist air during relaxation tests of nylon-6, using the concept of a moving boundary between the moist and the dry regions. They were followed by Machin and Rogers[15], who developed the method further to predict creep during sorption or desorption of various organic solvent vapours in poly(n-butyl methacrylate). Their calculations were based on the assumption of two layers; one at the initial solvent content and one at the final solvent content, and each having its own constant shift factor. These two layers were separated by a moving boundary, so that the relative thickness of the two layers was continuously changing with time. The equilibrium and compatibility equations of stress analysis were then applied to these hypothetical layers to give an analytical expression for creep, based on the assumption that the shift factor for the final solvent content should be applied from the moment that the vapour concentration was changed. For each of these layers considered individually, the effect of the assumptions is that of a continuously changing stress, because the proportion of the total load supported by each layer is continuously changing. Machin and Rogers ignored the effects of internal stresses resulting from the natural expansion or shrinkage of the polymer caused by the vapour alone; and they assumed that the diffusion coefficient was constant. However, in spite of the assumptions made, the calculations agreed well with the experimental results. A similar method was used for prediction of creep in the early stages of water sorption in glass-filled nylon-6,6 by Smith[8] with good results.

EXPERIMENTAL

The materials and apparatus used have been described in a previous paper[1]. The test pieces were of ICI Grade A 100 nylon-6,6 with an estimated crystallinity of 36% and a birefringence of between $3(10^{-3})$ and $4(10^{-3})$. These were moulded as 0.125 in thick bars, but were machined from both top and bottom surfaces down to 1 mm and the dumb-bell-shaped test pieces were cut out on a router. The pieces were placed in an atmosphere of 90% r.h. for 3 weeks to accelerate any slow structural changes that might result from humidification, and then in the test humidity for at least 6 months before testing (except in the case of the humidity cycling tests, when the conditioning time was only 3 months).

Creep tests were made on accurate creep machines that were capable of limiting the errors in the modulus to within ±0.4% at the 0.1% strain level. These machines were housed in an environmental chamber maintaining the temperature within ±0.1°C, and the relative humidity within 1% or better.

Some additional tests were made on thin 50 μm test pieces cut from the centre of similar 0.125 in moulded bars and with their plane parallel to that of the thicker 1 mm test pieces. These were tested on a specially-adapted creep-testing machine described previously[1].

RESULTS AND DISCUSSION

Tests on 1 mm thick pieces

Creep with concurrent sorption was measured by conditioning the test pieces at 30% r.h. and starting the creep test

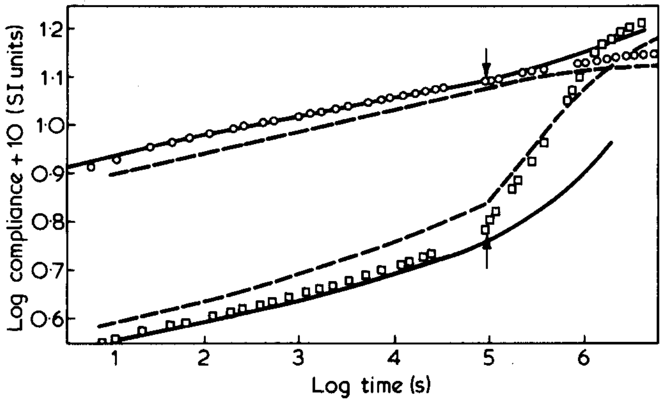

Figure 2 Experimental points and predicted curves (dashed) for creep during sorption from 29.5% to 61% r.h. (□) and desorption from 60 to 29% r.h. (○). (Solid curves are for constant relative humidity: upper, 61%; lower, 31%; stress, 4 MN m^{-2}. The start of sorption or desorption is indicated by arrows)

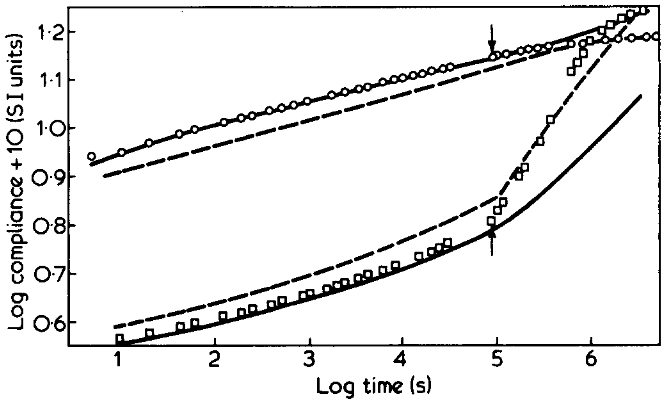

Figure 3 Experimental points and predicted curves (dashed) for creep during sorption from 29.5 to 61% r.h. (□) and desorption from 60% to 29% r.h. (○). Solid curves are for constant relative humidity; upper, 61%; lower, 31%. Stress, 8 MNm^{-2}. The start of sorption or desorption is indicated by arrows

at that condition. After 24 h, the air humidity was suddenly changed to 60% r.h. and held constant at that level for the remainder of the test. The creep test with concurrent desorption was made by the reverse procedure, starting the creep test at 60% r.h. reducing to 30% r.h. after 24 h. The results, corrected for zero-load dimensional changes, are shown in *Figures 2–4* for stresses of 4 MN m^{-2}, 8 MN m^{-2} and 12 MN m^{-2} respectively. Sorption and desorption creep curves are compared with those made on matched samples at constant upper and lower humidity levels. An idea of the magnitude of the zero-load corrections can be obtained from the following figures: for the 4 MN m^{-2} stress, the total uncorrected strain before the start of sorption was 0.246%, and after sorption, 1.180%. For the control test piece the values were 0.004% and 0.531% respectively. Whilst these relatively large zero-load corrections could cause serious errors with poorly-matched test pieces, checks on repeatability with this material showed that the samples were uniform and well matched. It may be noted that the estimated times for 98% equilibrium moisture changes, based on the weight changes of matched unstressed test pieces are for sorption 1 865 h or $\log_{10} t = 6.83$ (where t = time, s), and for desorption 2 070 h, or $\log_{10} t = 6.87$. As can be seen, with desorption beginning after 24 h, the creep curve nearly levels off, only continuing to rise very slowly. With sorption it begins to rise rapidly and approaches the level of the creep curve at uniform 60% r.h.

Besides creep tests with the relatively simple sorption or desorption, a set of creep tests was performed with concurrent humidity cycling. This started at 61% r.h. for 24 h followed by one week at each of 31%, 61%, 31%, and then to equilibrium at 61% r.h. It should be noted that 1 week at a given air humidity only allows about 50% change towards the new equilibrium moisture content. Although the simpler sorption or desorption tests are easier to analyse quantitatively, it was hoped that this humidity-cycling test would show qualitatively any anomalous behaviour that might be observed during creep with concurrent moisture changes. The reason for starting the test with desorption was because the normal expectation would be that this would cause a decrease in the creep-strain rate, and therefore any anomalous increases in the strain rate, such as have been observed with wood[3] should have been easily noticed. Humidities of 30% and 60% r.h. were chosen because the viscoelastic transition occurs in nylon at equilibrium with a humidity between these two values. The results, corrected for zero-load dimensional changes, are shown in *Figure 5*. Qualitatively they are similar to those for simple sorption and desorption, and they do not show the anomalies observed with wood.

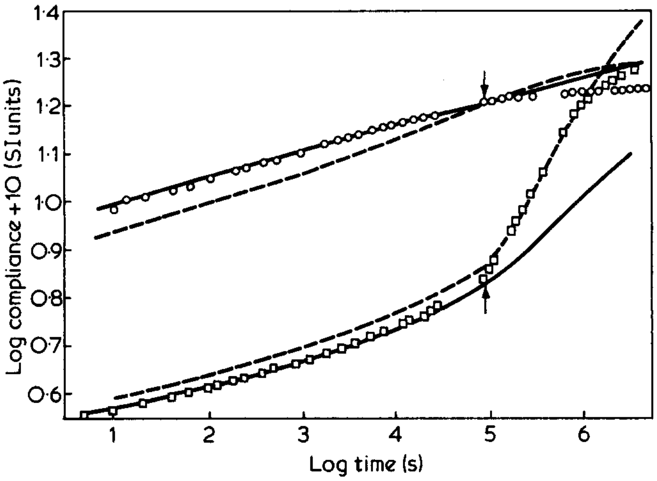

Figure 4 Experimental points and predicted curves (dashed) for creep during sorption from 29.5% to 61% r.h. (□) and desorption from 60% to 29% r.h. (○) (solid curves are for constant relative humidity: upper, 61% lower, 31%. Stress 12 MN m^{-2}. The start of sorption or desorption is indicated by arrows)

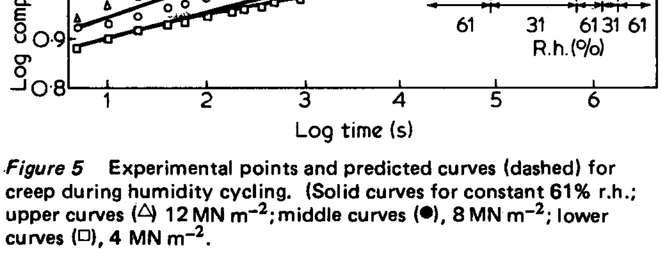

Figure 5 Experimental points and predicted curves (dashed) for creep during humidity cycling. (Solid curves for constant 61% r.h.; upper curves (△) 12 MN m^{-2}; middle curves (●), 8 MN m^{-2}; lower curves (□), 4 MN m^{-2}.

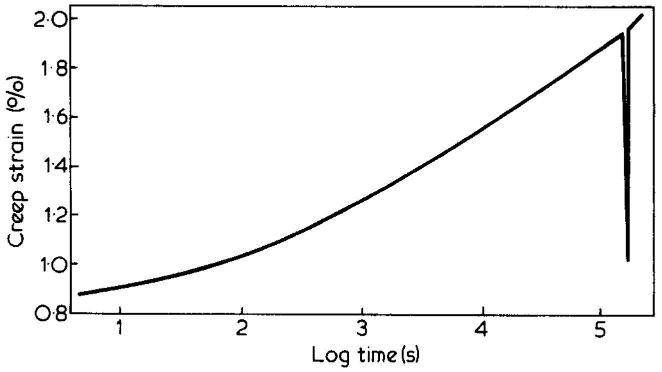

Figure 6 Creep of 50 μm thick test pieces at 61% r.h. and a stress of 8 MN m^{-2}. At $\log_{10}t$ 5.24, the relative humidity was reduced to 9% for 4 h, and was then returned to 61% r.h.

Tests on 50 μm pieces

As the above tests did not show any unexpected results, it appeared likely that the creep during moisture changes could probably be predicted by the ordinary theory. To support and to elaborate this conclusion, some further tests were made on very thin, 50 μm thick, test pieces. Although the accuracy of the dimensional-change measurements on such thin pieces was slightly less than for the 1 mm pieces, the more rapid rate of reaching the equilibrium moisture content enabled a number of additional measurements to be made, as described below.

The time to 50% equilibrium moisture change for 50 μm nylon is about 25 min, and the time to 98% equilibrium is about 4 h or less, and so it was considered to be useful to measure the length changes during a desorption-sorption cycle both at 8 MN m^{-2}, and at zero stress. Accordingly, a set of tests was designed with the following aims: (1) to determine *equilibrium* dimensional changes of the material with moisture changes under zero-load conditions; (2) to establish whether a desorption-sorption cycle between equilibrium moisture content levels under load (ideally to below the transition) causes the creep curve to return to its original level or to a higher level, as in wood. It may be noted that apart from being lengthy, such a measurement would be very difficult in 1 mm thick nylon since further creep would have taken place during the 20 weeks or so of the cycle; and the effect of cycling could only be compared with the creep curve of a matched sample. In this present case, by cycling on the third day of the creep test the compliances before and after cycling could be easily compared; (3) to determine whether length changes during drying are greater under load than under zero load, i.e. whether desorption can cause recovery under load. Such behaviour has been observed in particle boards[16–18]: similar behaviour in nylon would seriously affect the validity of attempts to predict the creep compliance in changing humidities.

Accordingly, four similar 6 day tests were made, in which the test piece was mounted in the machine with a small preload at constant humidity on the first day. On the second day it was subjected to 4 h of desorption to a lower relative humidity followed by sorption to the starting humidity again, which was then held constant. On the third day, the creep test was started by adding a load. On the fifth day the same procedure of four hours desorption followed by sorption was repeated. On the sixth day the test piece was unloaded. All tests gave similar results, of which one set is shown in *Figures 6* and *7* (without zero-load correction to the creep response).

The horizontal $t^{1/2}$/thickness scales of these and subsequent graphs was chosen because, for a given diffusion coefficient and size of relative humidity change, the internal moisture condition is a function of the square root of the time from the humidity change divided by the sample thickness. Moreover, for a step-change in air humidity there is approximately a straight-line relationship between the total moisture content change and $t^{1/2}$/thickness up to about 60% of the equilibrium change, as shown in *Figure 10*, for example. With the graphs plotted on this base it is therefore easier to observe any anomalous departures from the expected behaviour, although in the case of the thin test pieces the response to air humidity change is so fast that an effective step change was not feasible. The chief features of these results are first that after a desorption-sorption cycle the dimensions of both the loaded and the zero-load test pieces returned approximately to their original value, at least well within the experimental errors; and second that the equilibrium dimensional changes under load are nearly the same as those without load, provided that creep strains can be neglected.

Prediction of creep with concurrent moisture changes

The prediction of creep under constant conditions is normally done with a master compliance curve and a moisture-content-dependent shift parameter. For any given moisture content, an imaginary frame of reference such as is shown in *Figure 1* is shifted by the appropriate distance along the horizontal time scale (θ is a function of time) and this gives the point on the master curve at which the creep test effectively starts (i.e. the compliance value at the first measurement after the load is applied).

Such a method can be adapted to simple (i.e. assumed instantaneous) moisture changes. For example, during sorption from 30%–60% r.h., the shift parameter increases, so that the imaginary frame of reference moves to the right on the master curve; thus giving the effect that at any compliance level (e.g. point A, *Figure 1*) the test has effectively been running for a shorter time (A–Y) than it really has (A–X), resulting in a higher creep rate. The opposite effect is expected during desorption. Calculation of creep for the slow (not instantaneous) changes of moisture content that actually resulted from a change in relative humidity were

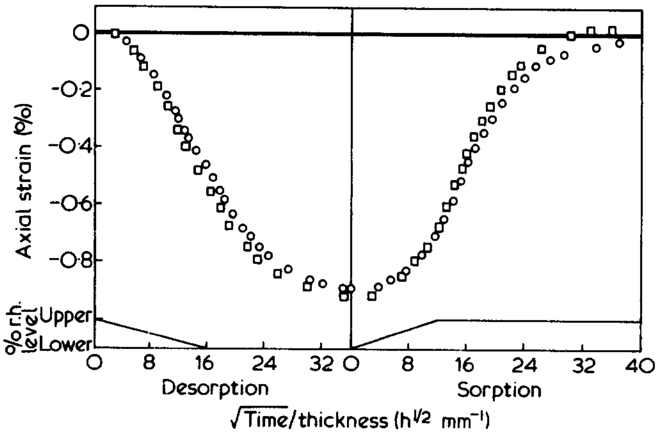

Figure 7 Length changes of a 50 μm test piece during a humidity cycle, both at zero stress (○), and at 8 MN m^{-2} (□). The approximate humidity cycle is shown below, with an upper level of 61% and a lower level of 9% r.h.

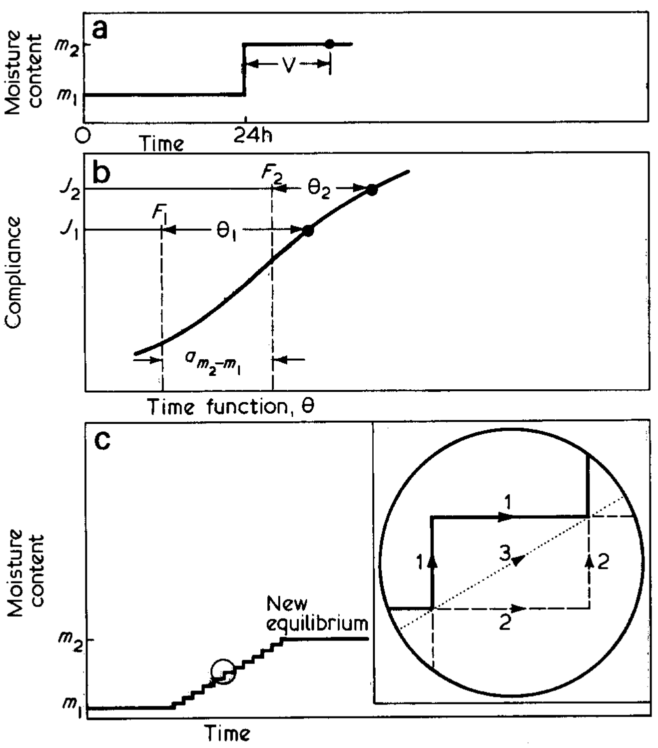

Figure 8 Details of calculation method for the increase in compliance during the step from time t_1 to time t_2 and with a moisture change from m_1 to m_2

done with a step-by-step process based on the master curves already available for this material[2] and the mean moisture content for each time step. The results are shown in *Figures 2–4* superimposed on the experimental results for 1 mm test pieces. *Figure 5* gives the predicted and experimental results of the humidity cycling experiment on 1 mm test pieces.

Whilst the concept of the prediction, as described above, appears fairly simple, the practical details of the calculation are more complicated, and an example is given below.

Consider first the case of a test piece with a constant uniform moisture content m_1, under stress σ, for 24 h, at which time the moisture content is raised instantaneously to a new constant level, as shown in *Figure 8a*. The tensile creep strain (excluding swelling) is to be determined at some time ν after the change.

For moisture content m_1, the reference frame is at F_1 on the master compliance/θ plot for the stress σ of *Figure 8b*. In 24 h, corresponding to a time-function (θ) value of θ_1, the compliance of the material has increased to J_1. For moisture content m_2 the reference frame must be moved to F_2, the movement $a_{m_2-m_1}$ being obtained from the known moisture-content dependence of the shift parameter a. Thus, immediately after the moisture content change, the test piece can be regarded as having been under load for a time corresponding to $(\theta_1 - a_{m_2} - _{m_1})$. This time is converted to real time t, and the sum $(t + \nu)$ is then converted back to $\theta - t\,(\theta_2)$. The compliance J_2 at θ_2 can then be read off, and $J_2\,\sigma$ gives the predicted creep strain in the test piece at time ν after the moisture content change.

For a step change in *relative humidity*, the mean moisture content of the test piece changes steadily with time, and this can be approximated by a series of small mean-moisture content steps (*Figure 8c*). During each time-interval the mean moisture content is changing steadily (path 3), so that the effect of the change is more accurately determined from the mean of the compliances calculated for paths 1 and 2. This is repeated for each step in turn.

The prediction of creep during concurrent sorption or desorption, by assuming a continuously-changing mean moisture content in a single layer, may be compared with the method used by Smith[8], and by Machin and Rogers[15], who assumed constant solvent contents in each of two layers separated by a moving boundary: the surface layer at the new equilibrium content and the core layer at the original equilibrium content. As explained above, their use of the equilibrium and compatibility equations on the two layers is equivalent to the use of a *continuously changing* stress on a single layer at a *constant solvent content*: as compared with the *continuously-changing moisture content* of the single layer at *constant stress* used here.

In addition to comparison with experimental results, it was also considered important to compare this 'mean moisture' calculation method with a more theoretically-correct 'explicit' calculation method. Whilst the above simplified 'mean-moisture' method can be used to predict approximate dimensional changes under stress during moisture content changes, it takes no account of moisture gradients nor of internal stresses. A more correct method of predicting dimensional changes during moisture changes either with or without an external applied load, was to imagine the test piece divided into a number of parallel layers (20 layers were chosen for this calculation). The mean moisture content of each layer was then calculated by the Crank–Nicholson finite difference method for each step forward in time, using the equation $D = 0.147 \exp(0.2696\,C) \times 10^{-3}$ mm^2 h^{-1}, where D is the diffusion coefficient and C i the moisture content in percent[4]. Each moisture change was then converted to an equilibrium (i.e. unrestrained) dimensional change by the use of a simple expansion coefficient, $\alpha = 0.00278/1\%$ moisture (*Figure 9*).

As all layers must move together, it is evident that at each time step an adjustment must be made to the strain of each strip, with a consequent change of stress. This adjustment to the layer stress or 'stress increment' must start a new creep curve which, at subsequent time steps, can be added, by the Boltzmann Superposition Principle, to all of the creep curves resulting from previous stress increments at previous time steps. At any time step then, such as that from 15.3–20.3 h shown in *Figure 9*, there is for each layer a strain resulting from the addition of the previous creep curves to be added to the simple moisture-change strain. These added strains, shown as the dotted line in *Figure 9*, clearly do not meet the compatibility requirements of equal movements in each layer unless the strains are adjusted with a suitable new 'stress increment'. The equations of compatibility were then applied, giving a set of simultaneous equations. These were solved by Gaussian elimination with pivoting, to give the incremental change of stress on each layer.

Some difficulty arose in using the Boltzmann Superposition Principle with a material whose creep response is not linear with respect to stress. Each individual creep curve resulted in a strain which was calculated from $\epsilon_i = \sigma_i J_i$ where σ_i is the stress increment and J_i is the compliance which is obtained from a master curve. However, because of the viscoelastic nonlinearity, there is not just a single master curve but a whole set, based on the basic master curve for infinitesimal strains and a correction factor F that is a function of a stress σ_j and of θ, the distorted log time. Whilst θ increases as the test progresses, for ease of calculation the stress σ_j was taken as remaining constant and equal to the

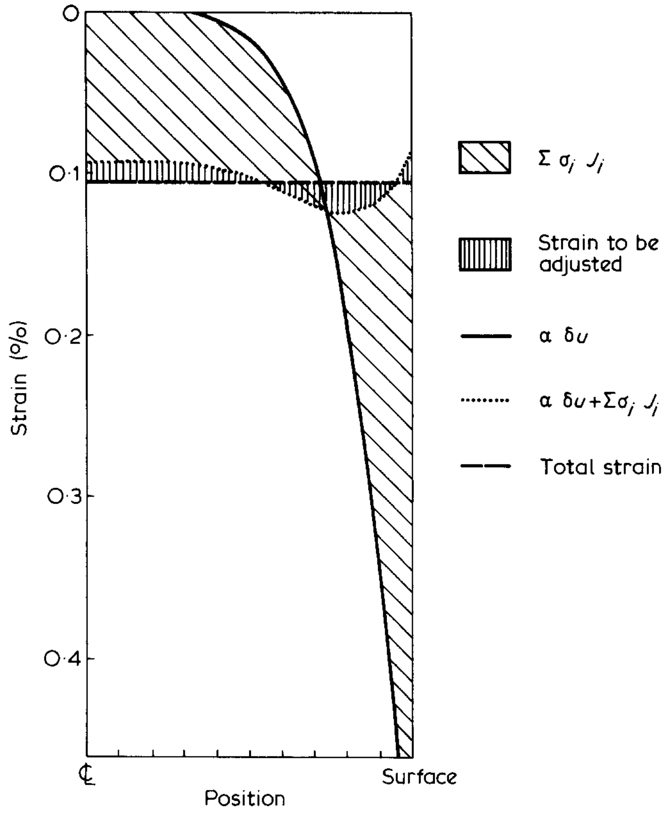

Figure 9 Strain components after 20.3 h during zero-load desorption of nylon-6,6 from 60% to 30% r.h. (α, moisture-expansion coefficient; δu, moisture-content change, σ_j, stress increments, J_j, corresponding compliances)

summation of all previous stress increments on the layer,

$$\sigma_j = \sum_{i=1}^{j} \sigma_i$$

In other words, σ_j is the total value of stress on the layer at the time the new creep curve was started. Without this simplification, Boltzmann's Superposition Principle would be very difficult to use in such a case.

At each moisture change, due to the change in shift factor, each creep curve was adjusted by the 'mean moisture' method described above and in the diagram of *Figure 8*. The resulting strains, after 20.3 h of desorption with zero applied load, are shown as the dashed line of *Figure 9*, which is of course a horizontal straight line indicating compatibility of layers.

This 'explicit' calculation method was also used to predict zero-load dimensional changes during sorption, desorption and humidity cycling. The results showed that during the early stages of sorption the percentage equilibrium length increase should lag significantly behind the moisture increase, as is shown in *Figure 10*, whereas during desorption the length decrease is very slightly in advance of the moisture decrease, as is shown in *Figure 11*. The experimental results of *Figures 10* and *11* show these predictions to be correct. (It should be noted here that the new equilibrium air humidity was reached after a $t^{1/2}$/thickness value of only 0.25, giving a true 'step' change as compared with the 'ramp' change observed with the thinner pieces of *Figure 7*).

The results of *Figures 10* and *11* may be compared with the experimental and predicted results for nylon-6 of Inoue and Hoshino[5], with which they agree qualitatively.

Comparison of predicted results

The prediction of creep during sorption, desorption or humidity cycling by the two methods was almost identical, so nearly so that no separate results have been plotted for the 'explicit' method, those for the 'mean-moisture' method being shown in *Figures 2–5*. However, whereas the mean-moisture method used about 1 s of computer time for the 40–44 time steps used for the sorption or desorption predictions and about 2 s for the 110 steps used for the humidity-cycling test prediction, the explicit method used about 4 min and 26 min respectively. Such a large use of computer time is hardly surprising in view of the ten new creep curves that were started at each step in time. After the 110 time-steps used for the humidity-cycling calculation, 1 100 separate creep curves were running simultaneously and had to be combined in order to calculate the next stress increments.

With the zero-load dimensional changes, however, the results of the two methods are not the same. This is because the simpler mean-moisture method assumes that a zero applied load means zero stress, and therefore the mass-change and the length-change curves would be of identical shape. The explicit method, on the other hand, correctly predicts the differences in shape between the length-change and the mass-change curves both for sorption and desorption.

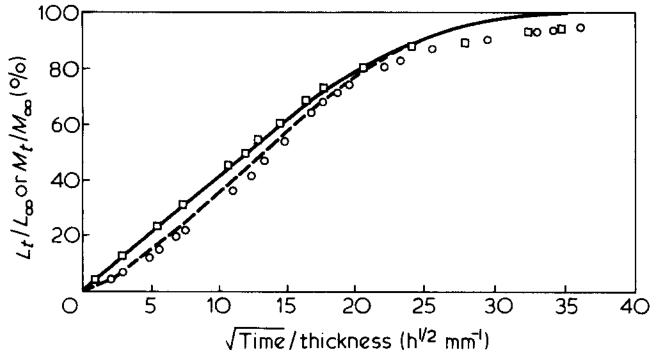

Figure 10 Predicted and measured mass (M_t/M_∞) and length (L_t/L_∞) changes of a 1 mm test piece during zero-load sorption against the square root of time divided by thickness ($t^{1/2}/L$). (Measured: mass (□), length (○); predicted: mass (———), length (– – – –)

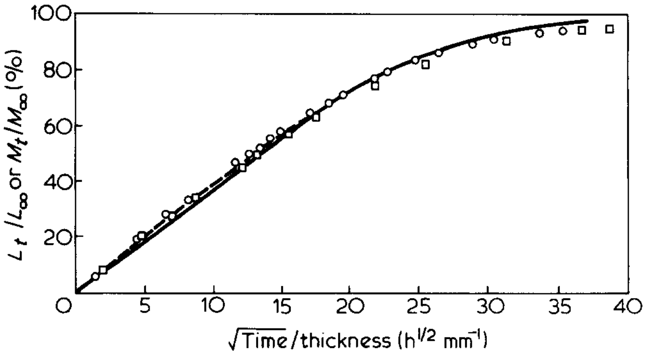

Figure 11 Predicted and measured mass (M_t/M_∞) and length (L_t/L_∞) changes of a 1 mm test piece during zero-load desorption, plotted against the square root of time divided by the thickness ($t^{1/2}/L$). (Measured: mass (□), length (○); predicted: mass (———), length (– – – –)

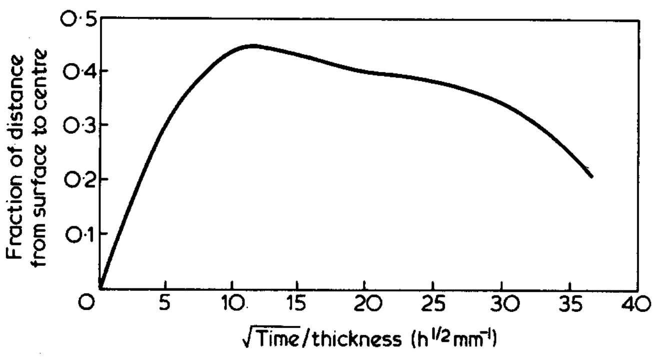

Figure 12 Calculated location of the zero-stress plane during sorption under zero load as a function of the square root of time divided by the thickness ($t^{1/2}/L$)

The third method, which involves the assumption of a moving boundary between the 'moist' and 'dry' regions (e.g. Machin and Rogers[15]) was considered inapplicable here, as it has been shown that diffusion of moisture in nylon is simple Fickian[4,5], so that there is no real boundary except in the very early stages of sorption or desorption.

Figure 12 shows the movement of the boundary between tensile and compressive stresses as a function of the square root of time during sorption from 30–60% r.h. under zero applied stress. This was calculated by the explicit method, assuming Fickian Diffusion. It can be seen that whilst in the earlier stages of sorption the graph is nearly straight, and so the moving boundary concept is valid, the slope of the curve soon starts to decrease and the boundary reaches a maximum and then actually recedes.

CONCLUSIONS

There appears to be three ways of predicting creep with concurrent sorption or desorption, two of which have been developed in this study. Of these two, the 'mean-moisture' method gives almost identical results to the 'explicit' method but at a small fraction of the cost in terms of computer time. The main advantage of the explicit method is that it also calculates the stresses at points within the test piece at any time. Both methods have been shown to give results that agree reasonably well with the experimental values.

The experimental results led to the conclusion that nylon does not show the anomalous creep behaviour of wood during moisture changes; in other words, if compliance curves are available for various constant relative humidities, then the total creep compliance of a part in service is likely to always remain below the compliance curve for the highest relative humidity that the part will experience.

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