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A Damping Maximum in the Free Torsional Oscillation of Wool Fibers

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In the course of a general investigation (*Textile Res. J.*, **32,** 560 (1962)) into the torsional properties of wool fibers, the period and damping of free oscillations were measured over a range of relative humidities of 0–98% at temperatures of 30, 35, 45, and 55°C. The method used was that of Meredith,[1,2] in which the fiber to be investigated acts as the suspension of a small metal bob which is set into rotational oscillation. In the present investigation a small galvanometer mirror was mounted on the bob (about 1 g.) and the movement of a reflected beam of light was observed on a scale at a distance of one meter from the mirror. Thus the period of oscillation and the damping could be observed, the amplitude of oscillation never exceeding 14°, which corresponded to a maximum shear strain of approximately 0.0001. The correct conditions of temperature and humidity were achieved by thermostatic control to ±0.1°C. and the use of sulphuric acid solutions of appropriate strength.[3] All measurements were made on the same fiber (45μ diameter when wet, from a pen-fed Corriedale sheep) and extended over several months, as at least 24 hrs. had to elapse before equilibrium was established after each change in temperature or relative humidity. Although each individual determination of the period of oscillation and of the damping (logarithmic decrement) was accurate to about 1% or better, the scatter of the experimental results was much larger, owing partly to inaccuracies in the control of r.h. (particularly at the higher values) and partly to the uncertainty of the sorption–desorption history when acid solutions were changed and the wool fiber temporarily exposed to room conditions.

The purpose of this note is to report a maximum in the damping of the torsional oscillations of wool fibers, which seems to have escaped notice hitherto. This maximum in the damping was found at all four temperatures, and occurred between 90 and 95% r.h. The results are summarized in Figure 1, where the logarithmic decrement Δ is plotted against temperature and relative humidity is the parameter. At 0% r.h. the value of Δ is the lowest and there is little or no change with temperature. As the r.h. increases there is a general increase in the magnitude of Δ at any one temperature. At the same time, at any given r.h., there is also an increase in Δ with temperature. This trend continues up to 95% r.h., at which there is a decrease in Δ with increase in r.h. at a given temperature. At 30°C. the maximum value of Δ occurs at 95% r.h., while at 55°C. it occurs already at 90% r.h. It is also interesting to note that there is a corresponding reversal of the temperature dependence; i.e., above 95–98% r.h. an increase in temperature causes a decrease in the logarithmic decrement. The largest effect occurs at 55°C. and a plot of Δ at this temperature against water content of the wool fiber (regain) is given in Figure 2. The regains of the wool fiber for the given relative humidities were obtained by calculation from published data.[3]

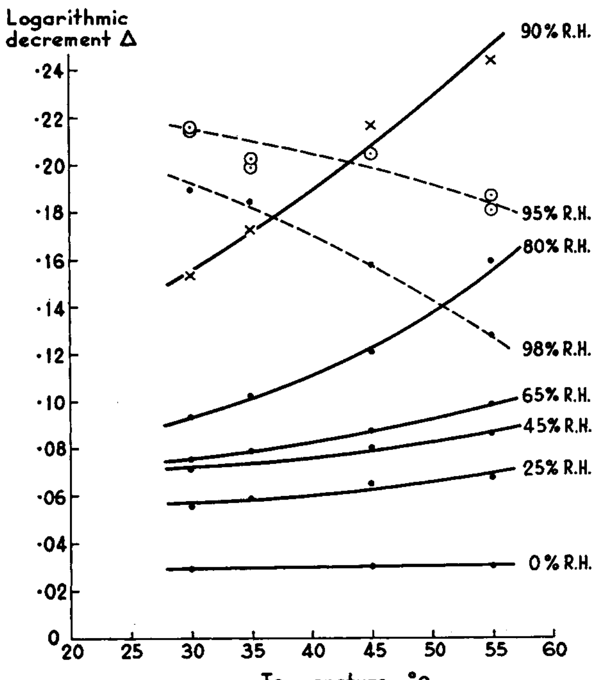

Fig. 1. Plot of the logarithmic decrement versus temperature, relative humidity the parameter: (●) 0, 25, 45, 65, 80, 98% r.h.; (×) 90% r.h.; (⊙) 95%.

The maximum in the damping or loss factor appears to be similar to that observed with longitudinal oscillations of nylon fibers by Quistwater and Dunell.[4,5] These authors reported a maximum in the loss factor of nylon 66 occurring at 70–80% r.h., and interpreted it as being caused by, on the one hand, increased freedom of motion (with increasing water content) of molecular segments in the amorphous region and, on the other, a decrease in the force required to cause the motion (due to the reduction of direct interchain hydrogen bonds by interspersed water molecules). A similar explanation for the molecular mechanism causing the observed maximum in the loss factor may well be applicable in the present case.

The similarity in the behavior of the loss factor, for nylon 66 in extension and for wool in torsion, is not obvious, however, when the complex moduli are compared. The real part of the complex modulus for nylon 66 shows a dependence on the r.h. which is only small, its value falling away to about half its initial magnitude on passing from 10 to 90% r.h.

In using the relation

$$\tan \delta = \Delta/\pi = E''/E' \tag{1}$$

where δ is the loss angle and E' the real, E'' the imaginary, part of the complex modulus, it is seen that a slight variation in E' over the humidity

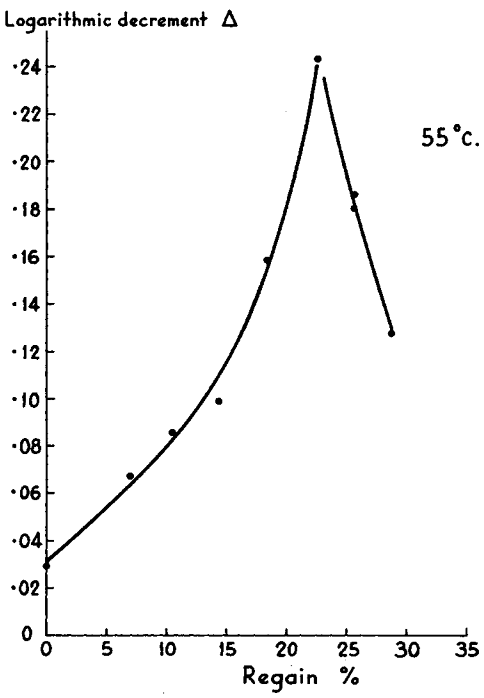

Fig. 2. Plot of the logarithmic decrement against regain obtained by calculation from relative humidity at one temperature.

range will not affect very greatly the maximum in E'' corresponding to that in tan δ. Quistwater and Dunell's figures indicate that the maximum in tan δ is shifted from between 70 and 80% r.h. to 60% r.h. for E''. For wool, on the other hand, probably due to its larger absorptivity of water, the real part of the complex modulus shows a much more pronounced dependence on relative humidity.

A plot of the period of free oscillation of the pendulum (which depends inversely on the square root of the real part of the complex modulus) against temperature for various values of r.h. is shown in Figure 3. It is seen that the period of oscillation increases uniformly as the temperature increases for *all* values of r.h., and that the higher the r.h. the longer the period. No maximum is observed either with r.h. or with temperature. If this large dependence of the real part of the modulus on r.h. is used in conjunction with the maximum in tan δ according to eq. (1), then it will be seen that the effect on E'' may be severe. In fact, in a calculation of the dependence of the imaginary part of the modulus E'' on r.h. (Fig. 4) the maximum flattens and shifts to such a low value of r.h. that a mechanism of the type proposed for nylon appears unlikely, although it is not excluded.

There seems to be a number of difficulties associated with the calculation of the elastic moduli from the experimental data. The calculation is based

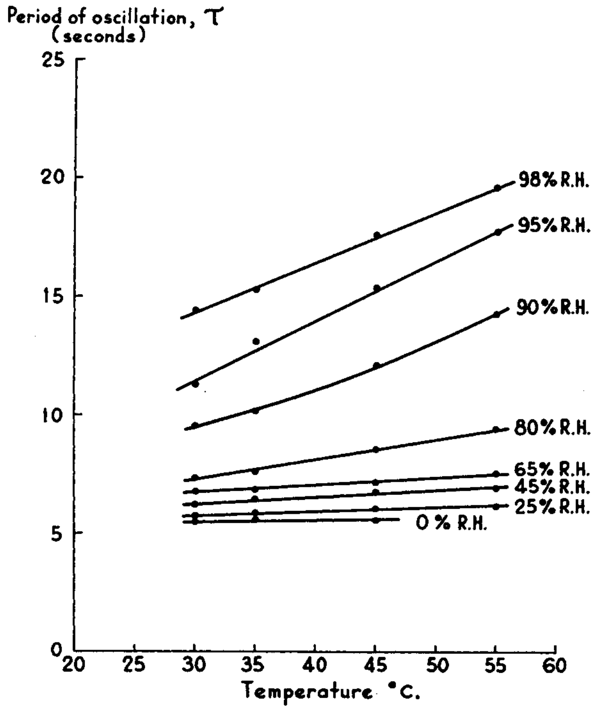

Fig. 3. Plot of the period of oscillation of pendulum against temperature, relative humidity the parameter.

on the normally accepted linear differential equation describing the motion of the pendulum,

$$I(d^2\theta/dt^2) + \eta(d\theta/dt) + G\theta = 0 \quad (2)$$

and

$$\Delta = \pi\eta/I\omega \quad (3)$$

where I is the moment of inertia of the bob, η the friction factor due to the internal friction $\eta\omega$ (ω being the angular frequency), and G the stiffness of the fiber which is related to the real part of the complex modulus through its dimensions.

There is evidence[6] that the strains used are sufficiently low for the constants in eq. (2) to be unaffected by the amplitude of oscillation. However, the equation is strictly true only for one frequency, as both η and G may be functions of ω. Thus, when the influence of either r.h. or temperature on the elastic constants is examined and a method employed (as in the present case), when a change in the constants to be examined is evidenced by a change in frequency, the distinction disappears, whether the observed change was due to frequency or due to the change in external conditions. It would be much more satisfactory, for example, to change the inertia I in eq. (2) in such a way that the change in η or G due to the external conditions would still cause the pendulum to oscillate at the same frequency.

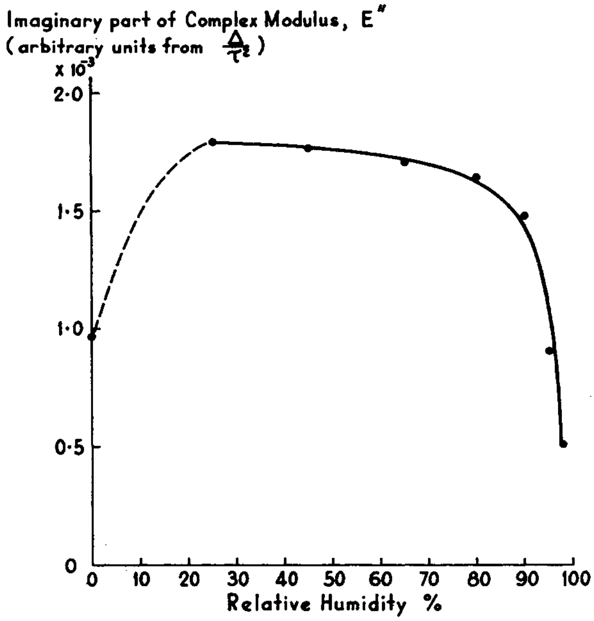

Fig. 4. Plot of the deviation of the imaginary part of the complex modulus obtained by calculation against relative humidity.

The second difficulty arises when the real part of the complex modulus, E', is calculated from G. There is, at present, no accepted method of allowing for dimensional changes of swelling polymers in calculating the elastic moduli. On the one hand it may be argued that the basic number of molecular units supporting the load remain the same, even after swelling,[7] while on the other hand (particularly in the case of torsion) there is the additional effect of the altered shear-strain as the geometry of the fiber changes.

It is the primary purpose of this work, therefore, to report the observed maximum in the damping of torsional oscillations of wool fibers with changes in r.h. and temperature, reasons being given for exercising caution in interpreting observed phenomena in terms of molecular mechanisms.

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Synopsis

A maximum in the damping of free torsional oscillations of wool fibers has been observed with changes in relative humidity at constant temperature. At relative humidities below that at which the maximum occurs, there is an increase in the logarithmic decrement as the temperature increases. At relative humidities larger than that of the maximum, however, an increase in temperature causes a decrease in the decrement. The implications of these observations on the complex elastic modulus are discussed.

Résumé

Un maximum dans l'amortissement des oscillations libres de torsion des fibres de laine a été observé en fonction des changements d'humidité relative à température constante. A des degrés d'humidité relative inférieurs à celui où a lieu le maximum, il y a une augmentation dans l'abaissement logarithmique lorsque la température augmente. A des humidités relatives superieures à celle du maximum, une augmentation de temperature provoque une diminution dans le décrément. Les interprétations de ces observations sur le module d'élasticité complexe sont discutées.

Zusammenfassung

In Abhängigkeit von der relativen Feuchtigkeit wurde bei konstanter Temperatur ein Dämpfungsmaximum für freie Torsionsschwingungen von Wollfasern beobachtet. Bei einer relativen Feuchtigkeit unterhalb des Wertes für das Maximum, findet eine Zunahme des logarithmischen Dekrements mit steigender Temperatur statt. Bei höherer relativer Feuchtigkeit, als dem Maximum entspricht, verursacht jedoch eine Temperaturzunahme eine Abnahme des Dekrements. Die Bedeutung dieser Beobachtungen für den komplexen Elastizitätsmodul wird diskutiert.

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