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An Effect of Moisture Content on Successive Changes in the Load-Elongation Curve for Paper

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Synopsis

Changes in the stress-strain curve for paper undergoing cyclic loading have been studied as a function of moisture content. It has been found that the extensional stiffness of the paper progressively decreases at both low and high moisture levels but progressively increases at intermediate moisture levels. The moisture content at which the transition from decreasing to increasing stiffness occurs (when passing from low to intermediate moisture content) has been determined and for the particular paper used in these experiments has been shown to correspond to a relative humidity of approximately 60%. It is postulated that at low and high moisture levels, conditions are not favorable for interfiber bond re-formation, whereas conditions are favorable for such reformation at intermediate moisture levels.

It has long been known[1,2] that when a paper specimen is subjected to repeated cyclic loading in tension at a relative humidity of 65%, the extensional stiffness (elastic modulus $\times$ thickness) as calculated from the slope of the initial "elastic" portion of the load-elongation curve increases systematically. However, similar treatment carried out at a 50% R.H. resulted in a systematic decrease in extensional stiffness. Further work was therefore carried out in an attempt to elucidate the effect of moisture content on the changes of stiffness.

Experimental

The paper used for these experiments was a medium weight, uncoated rawstock, and all specimens were strained in the machine (grain) direction. Load-elongation curves from the Instron tester (Instron Engineering Corp., Canton, Mass., U. S. A.) were obtained with the following settings: full-scale load, 50 lb.; chart speed, 12 in./min.; crosshead speed, 0.2 in./min.; gage length, 7 in. At each moisture level, four replications were made, each replication being taken through ten cycles.

The test specimens and the instrument jaws were completely enclosed in a polyethylene bag into which were placed beakers of sulfuric acid of concentration appropriate to the required relative humidity. The system

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was allowed to equilibrate for at least an overnight period, and replicate determinations could be made without the bag being opened. All specimens were conditioned initially at approximately 95% R.H.

Cyclic loading was carried out between zero and 70% rupture load over a range of relative humidities from less than 10% to ca. 95%. Specimens were strained to the predetermined point at a constant rate of 2.85%/min., then destrained to zero load at the same rate. There was a pause of approximately 5 sec. between the end of one cycle and the commencement of the next.

Results and Discussion

A typical set of cycling curves in which the extensional stiffness decreases with each successive cycle is shown in Figure 1. (Occasionally the very first or "take-off" portion of the curve was not linear, but this was ignored as it could clearly be shown as an effect of misalignment of the specimen in the jaws of the instrument.) The magnitude of the stiffness after each individual cycle for each humidity level is shown in Figure 2.

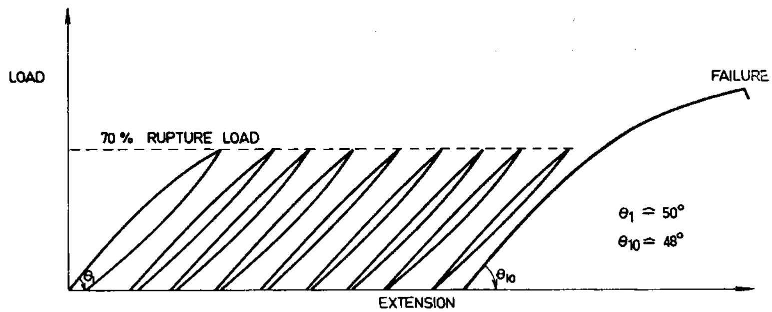

Fig. 1. Load cycling curves for paper at 20% R.H.

It can be seen from this figure that, below 60% R.H., the stiffness decreases successively over the first few cycles. The curve for 60% R.H. is almost horizontal, showing only a slight decrease in stiffness over the ten cycles. However, at 80% R.H., a definite increase in stiffness is noted. At a moisture content corresponding to a relative humidity of approximately 95%, a progressive decrease in stiffness is again noted.

It might be expected that, as interfiber bonds are progressively broken, as happens in the case of cyclic loading, the fibrous structure would become progressively weaker, as shown by a decrease in extensional stiffness. This behavior might be expected at all moisture levels. This is indeed the observed behavior at low moisture levels. However, at intermediate moisture levels, the extensional stiffness is observed to increase progressively with cyclic loading. This suggests that bond re-formation is taking place, together with an enhancement of load-bearing characteristics brought about by the degree of orientation imparted to the more mobile assemblage

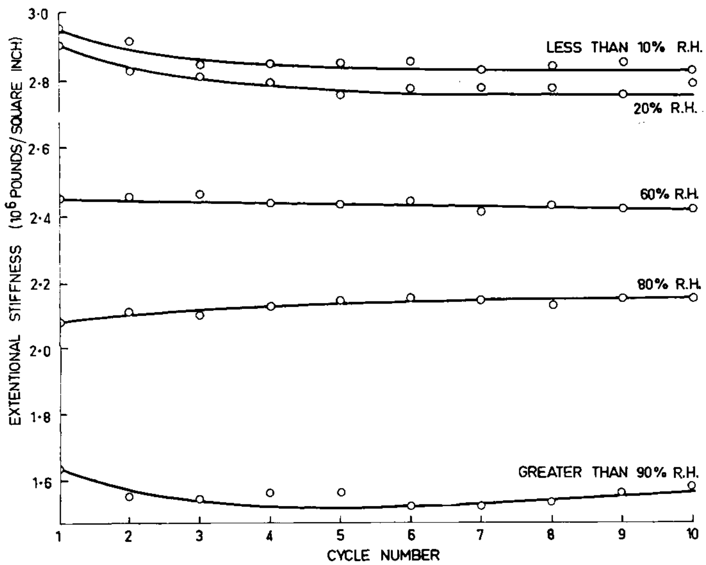

Fig. 2. Changes in extensional stiffness with cycling as a function of relative humidity.

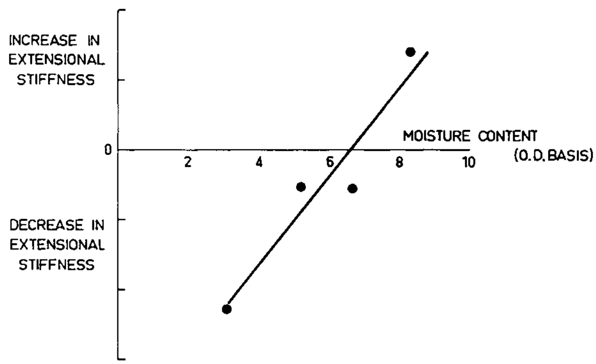

Fig. 3. Effect of moisture content on the development of extensional stiffness of paper undergoing cyclic loading. Regression line shows moisture level at which this development changes direction.

by prerupture tensile loading. Broughton and Wang[3] have observed strength development in paper at humidity levels in this range.

In the case of very high humidities, interfiber bonds tend to be replaced by water bridges which produce a weak mechanical structure, giving rise to the progressive decrease in stiffness as shown in Figure 2.

The difference in stiffness between the seventh and first cycles as a function of moisture content is shown in Figure 3.

Although the points are scattered, the general trend seems clear, i.e. the progressive change in extensional stiffness with cycling varies with moisture content and the point at which the change goes from positive to negative occurs between 6 and 7% moisture content (oven-dry basis). Reference to the desorption isotherm for the paper used in these experiments (Fig. 4) shows that this point corresponds to a relative humidity of a little more than 60%. Further tests, carried out on the Instron tester and the D.F.P. rheometer[4] gave similar results, showing that the observed behavior could not be attributed to instrumental variables.

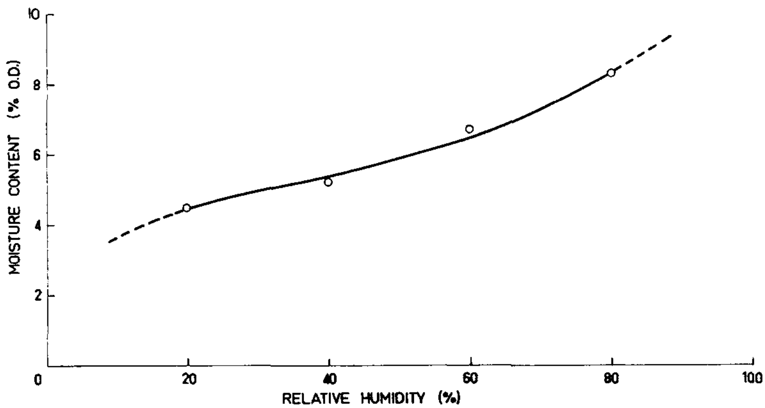

Fig. 4. Desorption isotherm for the paper under test.

Conclusions

The concept of work hardening when applied to paper must apparently be qualified further in terms of moisture conditions. There appears to be a critical moisture level below which the extensional stiffness (as determined from the initial portion of the load–elongation curve) decreases with cyclic loading and above which it increases with cyclic loading. This phenomenon is thought to be associated with the capacity for the re-formation of interfiber bonds.

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Résumé

On a étudié les modifications de la courbe de tension-élongation du papier subissent une traction cyclique en fonction de la teneur en humidité. Il est apparu que la tenacité du papier à l'élongation décroît progressivement à la fois aux basses et hautes teneurs en humidité pour augmenter à des teneurs intermédiaires. La teneur en humidité pour laquelle a lieu la transition entre les valeurs décroissantes et croissantes de la tenacité (lorsque on passe des teneurs basses aux teneurs intermédiaires en humidité) a été déterminée et s'est avérée correspondre à une humidité relative d'environ 60% dans le cas du papier utilisé pour ces expériences. On postule qu'aux basses et hautes teneurs en humidité, le réformation de liens entre fibres n'est pas favorisée dans ces conditions tandis qu'une telle réformation est favorisée aux teneurs intermédiaires en humidité.

Zusammenfassung

Die Änderung der Spannungs-Dehnungskurve wurden für Papier unter zyklischer Belastung als Funktion des Feuchtigkeitsgehalts untersucht. Es wurde gefunden, dass die Extensionsstiefigkeit des Papiers sowohl bei niedrigem als auch bei hohem Feuchtigkeitsgehalt ständig abnimmt, jedoch bei mittlerem Feuchtigkeitsgehalt ständig zunimmt. Der Feuchtigkeitsgehalt, bei welchen der Übergang von abnehmender zu zunehmender Steifigkeit eintritt (beim Aufsteigen von niedrigem zu mittlerem Feuchtigkeitsgehalt), wurde bestimmt und entsprach bei dem speziellen, für diese Versuche verwendeten Papier einer relativen Feuchtigkeit von etwa 60%. Es wird angenommen, dass bei niedrigem und hohen Feuchtigkeitsgehalt die Bedingungen für eine Ausbildung von Zwischenfaserbindungen nicht günstig sind, während sie bei mittlerem Feuchtigkeitsgehalt für eine solche Bindung günstig sind.

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