A note on the effect of fiber strength on the tensile strength of paper

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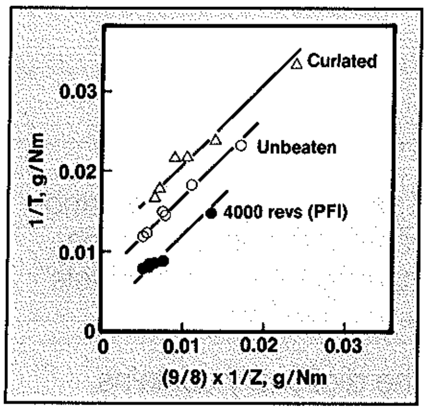
Fibers fail during the tensile failure of paper. Van den Akker *et al.* (*1*) showed that for a softwood kraft pulp the number of fibers that failed increased as the degree of bonding in the sheet increased. For well-bonded sheets, as many as 70–80% of fibers crossing the rupture line failed. Helle's work (*2*) confirmed and complemented these findings for both sulfite and kraft pulps. That fiber strength becomes more important as bonding increases is implicit in the Page equation of tensile strength (*3*):

$$1/T = 9/(8Z) + (12A\rho/b\,P\,L\,RBA) \qquad (1)$$

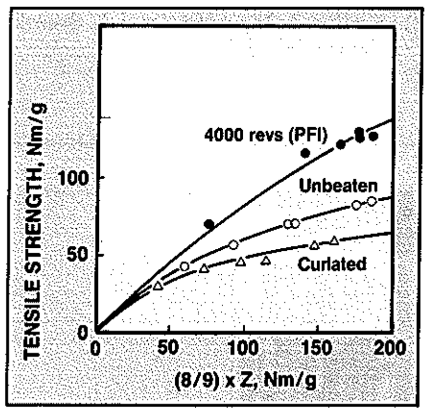
where

- T = the finite-span tensile strength of paper, Nm/g
- Z = the zero-span tensile strength, a measure of fiber strength, Nm/g
- A = the average cross-sectional area of the fibers' solid fraction, m^2
- P = the average external perimeter of the fiber, m
- L = the average fiber length, m
- ρ = the density of cellulose, g/m^3
- RBA = the relative bonded area in the sheet
- b = the shear strength of the fiber-fiber bond, N/m^2.

1. Reciprocal of tensile strength vs. reciprocal of 8/9*ths* of the zero-span strength for handsheets of unbleached softwood kraft pulp



2. Finite-span tensile strength vs. zero-span tensile strength



Unfortunately, the equation is difficult to test completely, because it is not easy to measure all the variables. In particular, there is no obvious means of measuring the bond strength b. However, tests have previously been made by modifying parameters one at a time and observing the functional relationship between the tensile strength of paper and the parameter. The linearity of $1/T$ vs. $1/L$ has been tested (*3*) using the data of Clark (*4*), Arlov (*5*), and Watson and Dadswell (*6*). The linearity of $1/T$ vs. $1/RBA$ has been tested (*3*) using the data of Ingmanson and Thode (*7*), and this relationship has been confirmed independently by Jones (*8*).

Here, a further check of the equation is made by varying the fiber strength in a way that maintains the other parameters constant.

Experimental procedure

Sheets prepared from a variety of pulps were exposed to the vapor of 10 *N* hydrochloric acid in a desiccator for various times, ranging from a few minutes to a few hours as previously described (*9*). After exposure, the sheets were aerated in a room at constant humidity for 24 h. Zero-span and finite-span tensile strengths were measured.

The treatment had no effect on sheet density or scattering coefficient, the two principal indices of paper structure. Because the cellulose fibrils tend to be hydrolyzed preferentially at regions of dislocations and microcompressions, the treatment might be expected to change sheet failure properties while leaving other mechanical properties unchanged. Indeed, the elastic modulus of the sheet was unchanged by the treatment. The bond strength should also be unchanged, since the adhesive strength of a low-molecular-weight polymer is not materially affected by the modest change in molecular weight that would be expected from the treatment. Thus, the treatment is expected to change only Z in Eq. 1, all other factors being constant.

Discussion

The data may be portrayed as plots of the reciprocal of the tensile strength T against the reciprocal of $[(8/9)\ Z]$. According to the theory, the data should fall on straight lines of unit slope, but with different intercepts depending on the bonding degree. **Figure 1** shows the data plotted in this way. The data indeed fall on lines of unit slope.

An alternative portrayal is given in **Fig. 2**. The lines are theoretical, according to Eq. 1, and the data fit well.

This test of the equation is severe, since there is no room for the introduction of arbitrary parameters. It must be concluded that the equation completely represents, within experimental error, the loss in tensile strength that is caused by a weakening of the fibers.

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