# *Fiber Orientation in Paper by Light Diffraction*

Recently, Yang, Crosby, Eusufzai, and Mark[1] reported promising results from fiber orientation measurements using the light diffraction technique. In this note, however, we present experimental evidence and theoretical arguments suggesting that the apparent orientation values measured with this technique always decrease with increasing basis weight. Thus, the light diffraction fiber orientation results obtained for samples of different basis weights or samples with strong basis weight variations cannot be directly compared.

The light diffraction technique[2,3] is based on the anisotropy of light intensity diffracted by a single fiber. The diffraction pattern is such that, away from the central maximum, the intensity is strongest in the direction perpendicular to the fiber axis. Thus a coherent beam of laser light passing through an oriented sheet of paper should form an anisotropic diffraction pattern. This was confirmed qualitatively by one of us.[3] The extensive results reported by Yang et al.[1] indicate that, at least in some cases, the laser diffraction technique also gives results that are quantitatively reasonable.

Yang et al. used nonwoven samples made from natural fibers, cellulose derivatives, and synthetic fibers. The basis weights and densities of these samples were quite low and it was reported that the output power of the laser source limited the basis weights of the samples that could be studied. This appears natural since the transmitted light intensity decreases as basis weight increases. Thus, the authors argue that a more powerful laser would enable the study of materials of higher basis weights.

We believe that basis weight unfortunately has a more fundamental effect on the diffraction pattern than just an overall decrease in transmitted light intensity and, in fact, *samples of high basis weight should appear more isotropic than samples with the same degree of fiber orientation but with lower basis weight.* In the following, we present evidence to support this claim.

First, we made some measurements with both a high-power (100 mW) and a low-power (0.5 mW) laser source. For an unsplit 60 g/m$^2$ kraft paper sample the ratio $R$ of the diffraction intensities in cross-machine and machine directions (i.e., $R$ = maximum/minimum) was measured* to be 1.05 when the high-power laser was used. With the low-power laser, however, the higher relative noise level did not permit values of $R$ below 1.1 to be determined; so we found $R \approx 1$. When the sample was split into low basis weight ($< 20$ g/m$^2$) layers, $R$ was measured to be 1.6, irrespective of the incident light intensity. In other words, even though the high-power laser did improve the signal-to-noise ratio, the unsplit sample still appeared clearly more isotropic than the split layers. Within the experimental resolution, laser power did not have any effect on the fiber orientation ratio $R$.

Second, we measured $R$ for a set of commercial LWC base paper samples using the low-power laser. Nineteen sheets with nominal basis weight of 48 g/m$^2$ were split into four layers using the freeze-splitting technique. We determined $R$ as an average from four to five measurements per layer and basis weight as an average over the approximately 50 cm$^2$ layer area. The experimental accuracy of $R$ is estimated to be $\pm 0.05$ and that of basis weight $\pm 1$ g/m$^2$.

The top and bottom layers of each sheet tended to have slightly higher basis weights than the middle layers. We therefore show the measured value of $R$ as a function of basis weight in two separate figures, in Figure 1(a) for the outside layers and in Figure 1(b) for the middle layers.

In the case of the outside layers [Fig. 1(a)], the values of $R$ decrease with increasing basis weight, whereas in the middle layers [Fig. 1(b)] the data points are scattered in a random fashion over a small range of basis weights. If the two figures are superimposed, it can be seen that the data in Figure 1(b) overlap with the data in Figure 1(a) in the basis weight range 10–14 g/m$^2$.

*Yang et al.[1] use $D_2$ to characterize the anisotropy of fiber orientation. This is related to the max/min ratio $R$ by the equation $R = (1 + \pi D_2)/(1 - \pi D_2)$.

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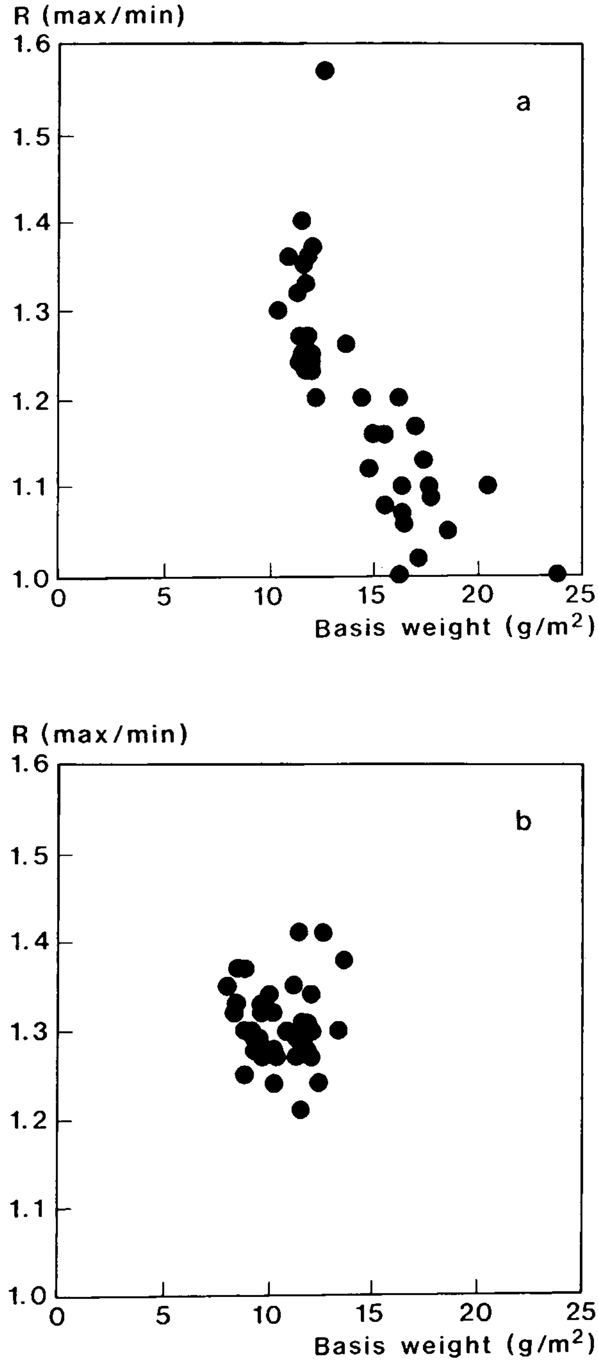


Fig. 1. Fiber orientation ratio $R$ as a function of basis weight measured with the light diffraction technique for LWC base papers: (a) top and bottom layers; (b) middle layers.

In our opinion, Figure 1 shows quite clearly how important an effect basis weight can have on the laser diffraction measurement. We admit that other than the laser diffraction measurement, we had no means of determining the variations in the true fiber orientation that occur from sheet to sheet and in the thickness direction of each sheet. Thus we cannot be sure that fiber orientation did not affect the way the sheets happened to split. Such an explanation seems, however, rather improbable.

Theoretically, the propagation of a ray of light diffracted by a fiber through a paper sample is a complicated process. The ray may be absorbed, refracted, reflected, or diffracted again, all of this depending on the geometrical arrangement and properties of structural components in the sample.

The attenuation of the intensity of the diffracted ray of light should be approximately determined by the short-range part of the fiber-to-fiber, or more generally basis weight-to-basis weight, pair correlation function. The stronger the short-range pair correlation function the stronger the attenuation. On the other hand, it is well known that in an oriented fiber network the short-range pair correlation function is stronger in the cross machine than in the machine direction.[4] Diffracted light intensity should therefore be attenuated more in the cross machine direction than in the machine direction.

The anisotropic attenuation would explain why the measured fiber orientation ratio $R$ decreases with increasing basis weight. The apparent degree of fiber orientation is also reduced by scattering from nonoriented structural components like fiber fragments, fine material, and filler and pigment particles, but it is not clear how rapidly this random scattering would increase relative to the fiber induced diffraction as basis weight increases.

The fact that Yang et al.[1] observed fiber orientation in samples with basis weights as high as 60–70 g/m$^2$ is probably due to the optical properties of their nonwoven fiber materials. For a given basis weight, light intensity is attenuated less in nonwovens than in paper. This also applies to the diffracted light rays. In addition, it seems that in low-density nonwovens the average distance between fibers, in the $xy$-plane, is longer than in a typical paper sheet and therefore the short-range pair correlation function would be weaker. These two factors suggest that the oriented diffraction pattern should be less attenuated in a nonwoven sample than in a paper sample of the same basis weight.

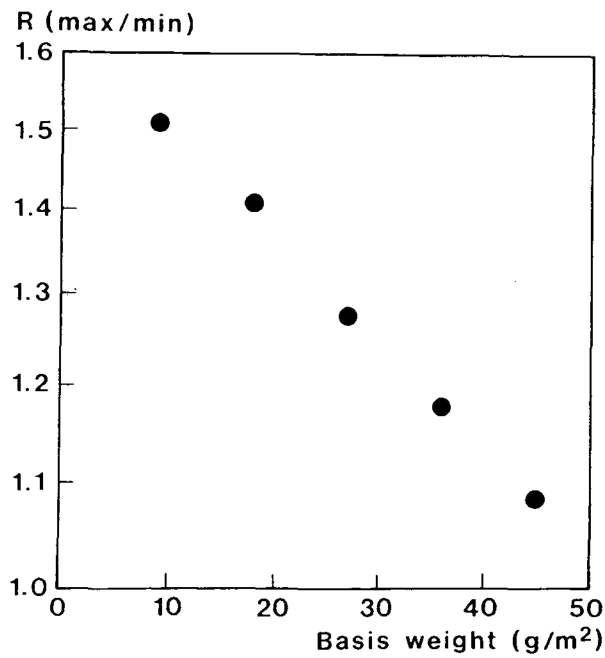


Fig. 2. Fiber orientation ratio $R$ as a function of total basis weight for a sample of one to five sheets of a 9 g/m$^2$ nonwoven glued on top of one another with machine directions set parallel in all the sheets.

In spite of the fact that oriented diffraction patterns are observed for nonwoven samples with relatively high basis weights, basis weight still has the same fundamental effect on the apparent degree of fiber orientation as in the case of paper samples. In order to show this, we made measurements with a 9 $g/m^2$ nonwoven lens paper. Figure 2 shows how the ratio $R$ decreased when one to five sheets were glued together using an ordinary adhesive stick. The orientation ratio $R$ of each individual sheet was checked to be $R = 1.5$, and the sheets were glued together with machine directions parallel in all sheets.

In Figure 2 the vertical axis is logarithmic so that $R$ in fact decreases exponentially with increasing basis weight. In general, one could measure the total intensity of the transmitted diffraction pattern and thus obtain a measure of the average attenuation. It might then be possible to correct the values of $R$ to account for the basis weight effect (compare, e.g., with the analysis of Bernard et al.[5]). It is not, however, *a priori* clear that this should work since the correction could well depend not only on furnish properties but also on the degree of fiber orientation itself.

In conclusion, light diffraction measurement is quite sensitive to basis weight. Results obtained for samples of different basis weights or samples with large basis weight variations cannot be directly compared.

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## References

1. C.-F. Yang, C. M. Crosby, A. R. K. Eusufzai, and R. E. Mark, *J. Appl. Polym. Sci.*, **34**, 1145 (1987).

2. L. Rudström and U. Sjölin, *Sv. Papperstidn.*, **73**, 117 (1970).

3. J. W. Sadowski, *Pap. Puu*, **61**(9), 588 (1979).

4. L. Haglund, B. Norman, and D. Wahren, *Sv. Papperstidn.*, **77**(10), 362 (1977).

5. P. Bernard, P. Villeneuve, R. Boulay, B. Drouin, and R. Gagnon, CPPA 73th Annual Mtg., 1987.

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