A comparison of fiber orientation indices

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ABSTRACT

Five fiber orientation indices were determined for experimental paper formed from bleached Kraft pulp on the Centrifugal Dynamic Former at different jet/wire ratios and dried under the conditions of complete drying restraint. These indices were calculated, from the machine to cross-machine tear and tensile ratios for dry and wet paper and include the dry Instron index (DII), wet Instron index (WII), dry Pulmac index (DPI), wet Pulmac index (WPI) and the dry tear index (DTI).

At a jet/wire speed ratio of 1.0, for example, DII had the highest value (5.1), followed by WII (4.3), WPI (3.5), DPI (3.0) and DTI (2.2). When plotted against the jet/wire speed ratio, the relative slopes of the 5 lines followed the same order, e.g. DTI had the steepest slope (0.00217) and DTI, the lowest one (0.00052).

Among the five types of tests the reproducibility of the wet zero-span test was the best one with a coefficient of variation of 4.5%. Furthermore, this is a simple test which can be performed rapidly with the use of an inexpensive instrument. The WPI calculated from these data represent an intermediate degree of sensitivity for the measure of fiber orientation of paper.

Key words : Fiber orientation index, Instron tensile index, Pulmac tensile index, anisotropy, X-ray diffraction, microscopical index, squareness of paper, Centrifugal Dynamic Former.

INTRODUCTION

Fiber orientation in paper has been measured by X-ray diffraction (1,2,3), microscopic count (3 to 10), zero-span tensile technique (2,3,7,11,12), and most recently by laser beam (13), microwave (14), ultrasonic waves (15,17), dielectric measurement (16), elastic anisotropy (16,17), light diffusion (18), light diffraction (19), and by reflected light polarization (20). Each one of these methods has a different degree of precision, advantages, disadvantages, limitations and specific applications. Some of these methods are fairly simple and can be performed rapidly, while others are extremely time consuming tests which require highly specialized instrumentation, as well as specialized personnel.

Up to 1972 a measure of the unisotropy of industrial paper was derived from the machine to cross-machine dry tensile ratio (MD/CD), which was measured by a zerospan tensile tester according to the suggested Tappi method T481 SM-60 (21). However, this method was withdrawn in 1972 because of the effect of "dried-in strain" superimposed on the fiber orientation index during drying, an effect which "couldn't be readily separated out" (21). In spite of this, MD/CD ratios still are reported by various researchers. but these values are obtained for papers produced from different pulp furnishes, formed at different jet/wire speed ratios and dried under different conditions. Therefore, it is rather difficult to draw valid conclusions from a comparison of the data obtained in different laboratories.

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The specific objective of this study was to determine the tear, tensile and zero-span tensile strength ratios for the same wet and dry papers formed at different jet/wire speed ratios, but otherwise under identical conditions and dried under the conditions of complete drying restraint. Thus, this approach gives the various ratios a common basis and allows direct comparisons between tear, tensile and zero-span ratios of both wet and dry paper with respect to reproducibility, precision and sensitivity.

EXPERIMENTAL

The experimental paper (60 g/m^2) was formed from a bleached Kraft pulp (140 ml CSF) by the Centrifugal Dynamic Former (Fig. 1) at various jet/wire speed differences in order to produce sheets with different degrees of preferential fiber orientation. The wire speed ranged from 0.9 to 1.6 km/min, while the jet speed was varied from 0.7 to 1.2 km/min at a constant pulp consistency of 1.5 g/l. After its formation, the wet sheet (21.3 × 88.6 cm^2) was placed felt-side on a piece of fabric with a sheet of teflon on top of it The sandwich was passed (4.5 m/min) between two medium-hard rubber rolls at 300, 600 and 600kPa of pressure successively (Fig. 2). The fabric was removed, and the paper was dried at 100°C for 2 min in the dryer (Fig. 3) furnished with the Dynamic Former. The sheet of teflon was removed, and the paper was left on the dryer at 100°C for another 5 minutes.

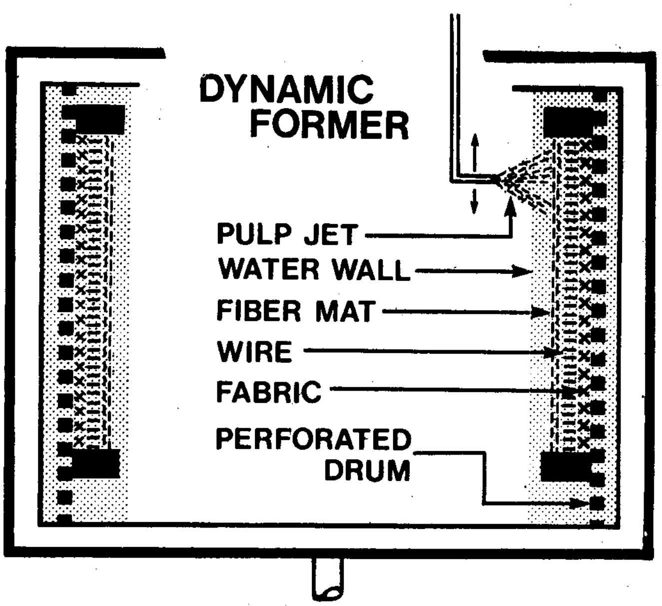

Figure 1. Schematic diagram of the Centrifugal Dynamic Former.

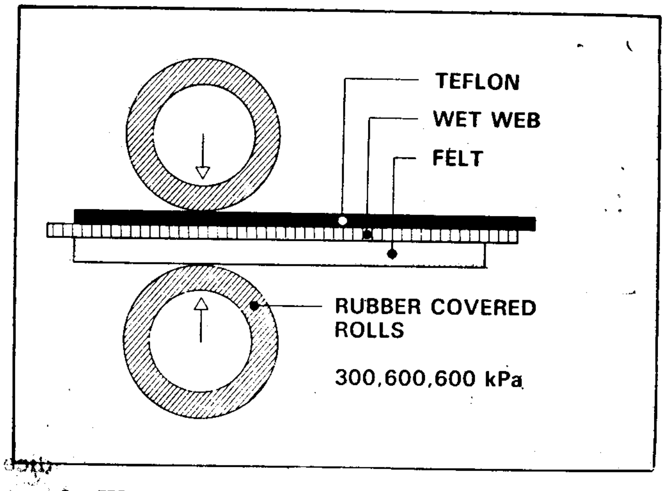

Figure 2. Wet pressing of the experimental paper.

It should be noted that in the dryer of the Dynamic Former (Fig. 3) a tension was maintained on the felt itself, which produced a complete drying restraint uniformly distributed over the entire sheet of paper. This is in contrast to a commercial paper machine, where a strong tension is maintained on the sheet in the machine direction.

After drying the experimental papers were brought to the standard moisture content in a conditioning chamber kept at 23°C and 50% relative humidity The tear and tensile strengths of each sheet were determined in both the machine (MD) and cross (CD) directions, in both wet and dry state, according to the appropriate standard methods. The instruments employed were an Elmendorf tear tester, an Instron tensile tester and a Pulmac zero-span tensile tester. For the Instron and Pulmac tensile tests the orientation indices were calculated from the MD/CD ratios, while in the case of the tear, test, the CD/MD ratio provided the dry tear orientation index.

DISCUSSIONS

The MD/CD strength ratios calculated for a number of tests in both wet and dry state produced the following fiber orientation indices :

DII = Dry Instron Index (MD/CD)
WII = Wet Instron Index (MD/CD)
DPI = Dry Pulmac Index (MC/CD)
WPI = Wet Pulmac Index (MD/CD)
DTI = Dry Tear Index (CD/MD)

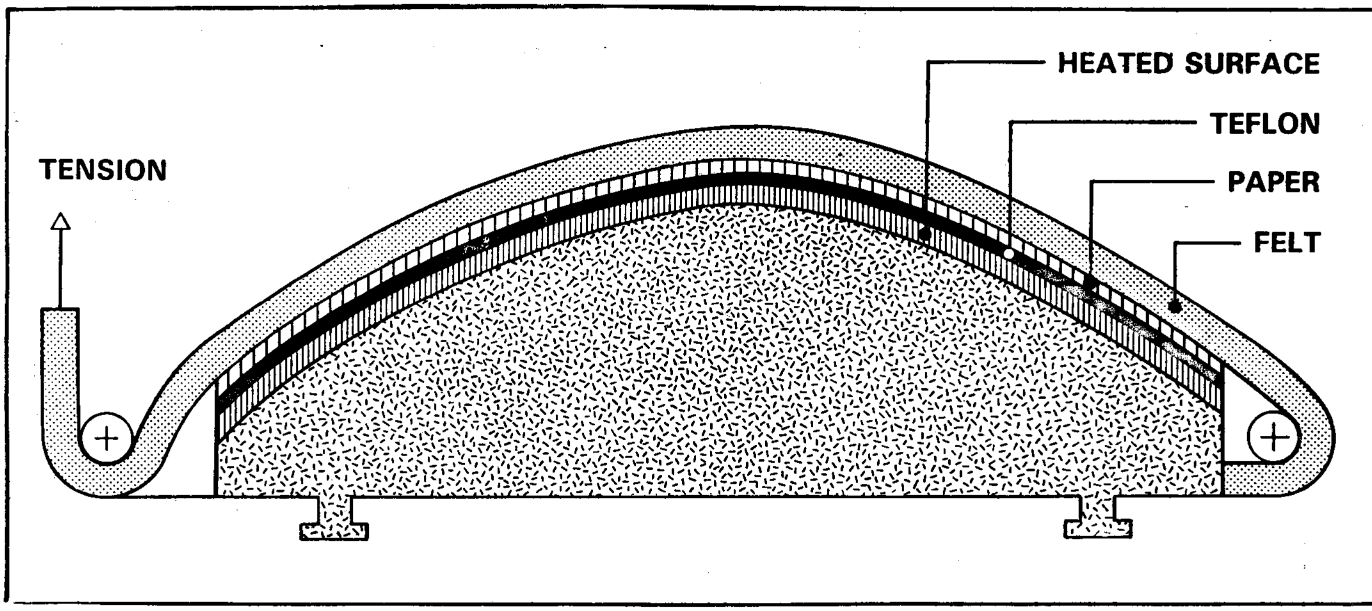

Figure 3. The dryer of the Centrifugal Dynamic Former

TABLE 1. FIBER ORIENTATION INDICES FROM TEAR AND TENSILE TESTS.

SPEED / PROPERTIES				DRY INSTRON INDEX							WET INSTRON INDEX							DRY TEAR INDEX						
				MD			CD			DII	MD			CD			WII	MD			CD			DTI
JET	WIRE	ΔV	VJ/VT	BL	SD	CV	BL	SD	CV	MD/CD	BL	SD	CV	BL	SD	CV	MD/CD	TEAR	SD	CV	TEAR	SD	CV	CD/MD
m/min				km		%	km		%		km		%	km		%		mN•m²/g		%	mN•m²/g		%	
1200	1200	0	1	20.0	1.2	5.4	3.9	.1	3.0	5.1	.25	.03	14.0	.06	.01	14.0	4.3	4.2	.9	21.6	9.1	.2	1.8	2.2
1155	1283	128	.90	19.5	.8	4.2	3.8	.3	8.2	5.2	.26	.04	14.0	.06	.01	9.8	4.4	4.4	.1	2.5	10.3	.6	6.1	2.3
1200	1400	200	.86	18.4	.9	5.2	3.4	.1	3.1	5.4	–	–	–	–	–	–	–	–	–	–	–	–	–	–
1200	1600	400	.75	18.9	1.0	6.0	3.3	.2	6.4	5.7	–	–	–	–	–	–	–	3.7	.0	.0	8.7	.2	2.6	2.4
1000	1600	600	.63	22.4	1.3	5.7	3.6	.2	6.1	6.2	–	–	–	–	–	–	–	4.2	.2	4.7	10.8	2.1	19.5	2.6
1027	1650	623	.62	23.5	1.1	4.5	3.8	.2	6.2	6.2	.25	.04	14.4	.05	.01	13.6	5.0	4.8	.2	4.2	12.6	.8	6.6	2.6
800	1600	800	.5	20.4	1.5	6.3	3.0	.2	7.0	6.7	–	–	–	–	–	–	–	4.9	.2	4.1	13.5	.8	6.0	2.7
702	1655	957	.42	21.6	1.4	6.3	3.1	.2	8.7	7.0	.28	.03	11.0	.048	.01	14.6	5.8	3.8	.3	7.8	11.0	.8	7.4	2.9
702	1670	968	.42	22.2	1.6	6.5	3.1	.4	11.8	7.2	.29	.03	11.1	.05	.01	14.8	5.8	5.4	.2	4.3	15.4	.1	.7	2.8
AVERAGE				20.8	1.2	5.6	3.4	.2	6.7	6.1	.27	.03	12.9	.05	.01	13.4	5.1	4.4	.3	6.1	11.4	.7	6.3	2.6
AVERAGE CV, %				6.2							13.2							6.2						

$$SD=\sqrt{BL^2/(n-1)}\ ;\ n=10\ ;\ CV=SD/BL\ ;BL=\text{AVG. OF } 10$$

TABLE 2. FIBER ORIENTATION INDICES FROM THE PULMAC ZERO-SPAN TENSILE TESTS

SPEED / PROPERTIES				DRY PULMAC INDEX							WET PULMAC INDEX						
				MD			CD			DPI	MD			CD			WPI
JET	WIRE	V	VJ/VT	BL	SD	CV	BL	SD	CV	MD/CD	BL	SD	CV	BL	SD	CV	MD/CD
m/min				km		%	km		%		km		%	km		%	
1200	1200	0	1	25.5	1.5	5.8	8.5	.4	4.7	3.0	17.2	.6	3.3	5.0	.2	4.0	3.5
1155	1283	128	.90	25.2	1.2	4.9	8.2	.7	8.4	3.1	16.3	.7	4.6	4.6	.3	5.7	3.6
1200	1400	200	.86	25.3	1 0	4.0	7.9	.2	2.3	3.2	20.2	.7	3.3	5.5	.3	5.2	3.6
1200	1600	400	.75	26.0	1.2	4.7	8.0	.5	6.4	3.3	19.6	.8	4.0	4.8	.3	5.4	4.1
1000	1600	600	.63	25.6	1.2	4.9	7.2	.5	7.2	3.3	17.3	.7	3.9	4.0	3	6.4	4.3
1027	1650	623	.62	25.5	1.0	5.0	7.2	.3	4.3	3.5	17.4	.8	4.6	4.0	.2	5.0	4.3
800	1600	800	.5	25.5	1.3	5.0	7.1	.3	4.8	3.6	17.7	.8	4.3	3.8	.2	4.6	4.6
702	1655	957	.42	25.8	1.5	6.0	6.7	.2	2.7	3.9	19.1	.7	3.7	4.0	.1	3.7	4.8
702	1670	968	.42	25.9	1.0	3.9	6.9	.2	4.5	3.8	19.7	.7	3.6	4.1	.2	5.0	4.8
AVERAGE				25.6	1.2	4.9	7.5	.4	5.0	3.4	18.3	.7	3.9	4.4	.2	5.0	4.2
AVERAGE CV, %				5.0							4.5						

$SD=\sqrt{BL^2/(n-1)}$; $n= 10$; $CV= SD/BL$; BL= AVG. OF 10

The data used for the calculation of these indices are summarized in Tables I and II and the five indices and plotted in Figure 4 against one another and in Figure 5 as a function of the jet/wire speed ratio. Table III contains the slopes of the five lines derived from Figure 5.

Interrelations between the various indices

Figure 4 contains a plot of the possible interrelations between the five orientation indices. For any one of these ratios a value of 1.0 designates a randomly oriented network, which is represented by the point at the origin of the x-y axes and ratios greater than 1.0 denote increasingly higher degrees of fiber orientation in the machine direction.

Among the ten lines shown in Figure 4, line 7 is the only correlation which is based on wet sheet properties, without the effect of fiber bonding. This might be the reason why line 7 is the closest one to line 0; assuming that line 0 represents a perfect relationship between the result of two hypothetical tests. In contrast, lines 1 and 2 are the product of dry strength ratios and these are located the furthest away from the zero line. The remainder six lines represent other possible combinations between the various dry and wet sheet ratios. These lines occupy intermediate positions between the wet and dry indices. However, all 10 lines have one thing in common; they show that all of the above indices are linearly proportional to one another and are thus equally valid. Perhaps there are good physical reasons for this, which may not at the moment be clear.

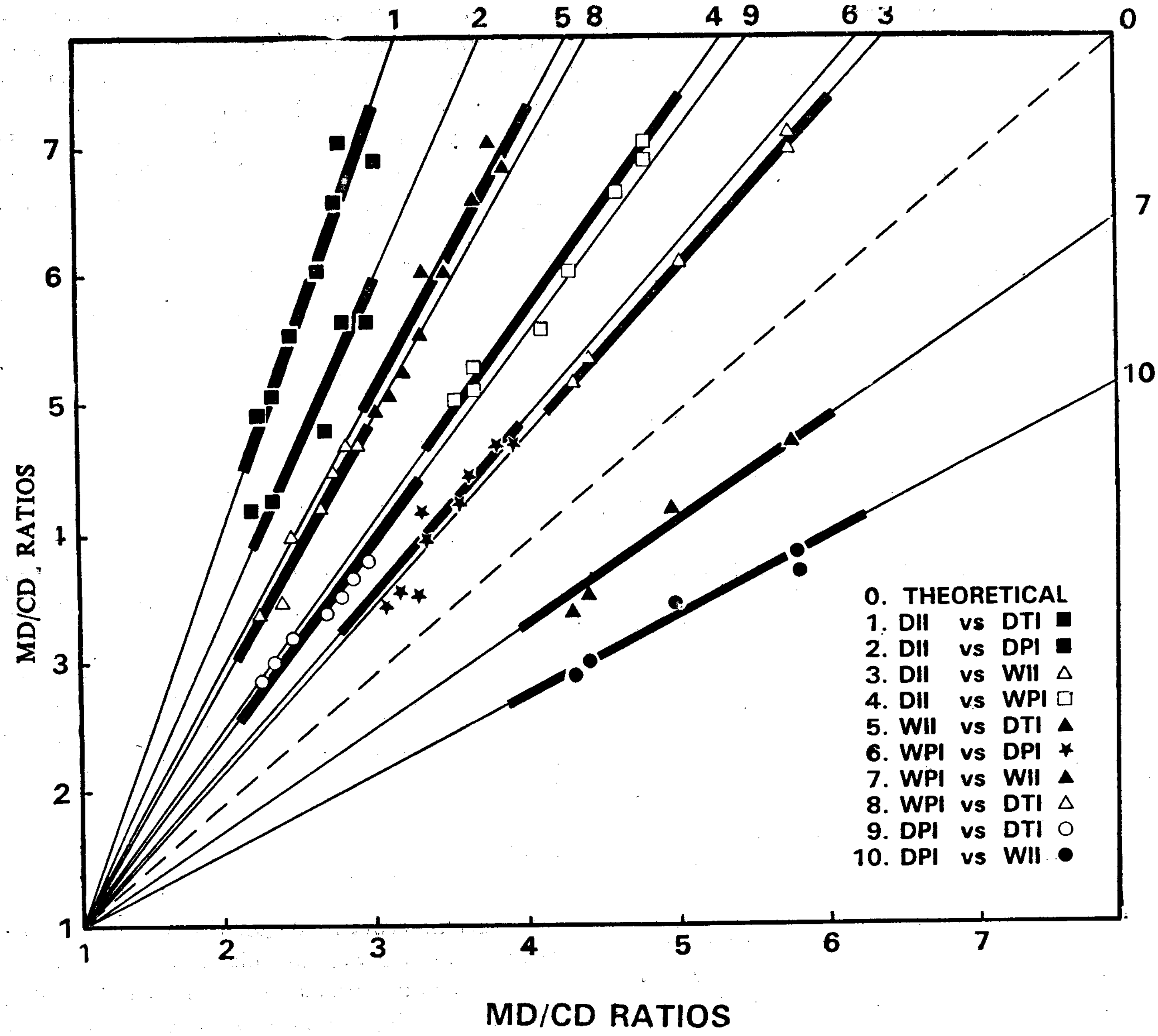

Figure 4. Interrelations between the five orientation indices. The broken ine (0) represents a hypothetical correlation between two perfect tests.

The effect of jet/wire speed on sheet properties

The fiber orientation parameters of Tables 1 and 2 are plotted in Figure 5 as a function of both the jet/wire speed ratio and difference. For example, a 1.2 km jet speed coupled with a 1.2 km wire speed yields a jet/wire ratio of 1.0, and a wire-jet speed difference of zero (Table 1) Simi'arly, the combination of the maximal wire speed (1.67 km) and the minimal jet speed (0 7 km) produces a jet/wire ratio of 0.42, and a wire jet speed difference of 0 97 km (Table 1; Fig 5.

Figure 5 shows that all orientation parameters have values greater than 1.0. In fact, the lowest orientation index (2.2) was produced for DTI at a jet/wire speed ratio of 1.0. Thus, it appears to be impossible to produce a randomly oriented fibrous network on the dynamic former even at the minimal jet speed of 702 m/min.

Each one of the five orientation indices seems to rise in a linear manner as a result of an increasing $\triangle V$. The increase in DII, for example is 2.17 for the entire

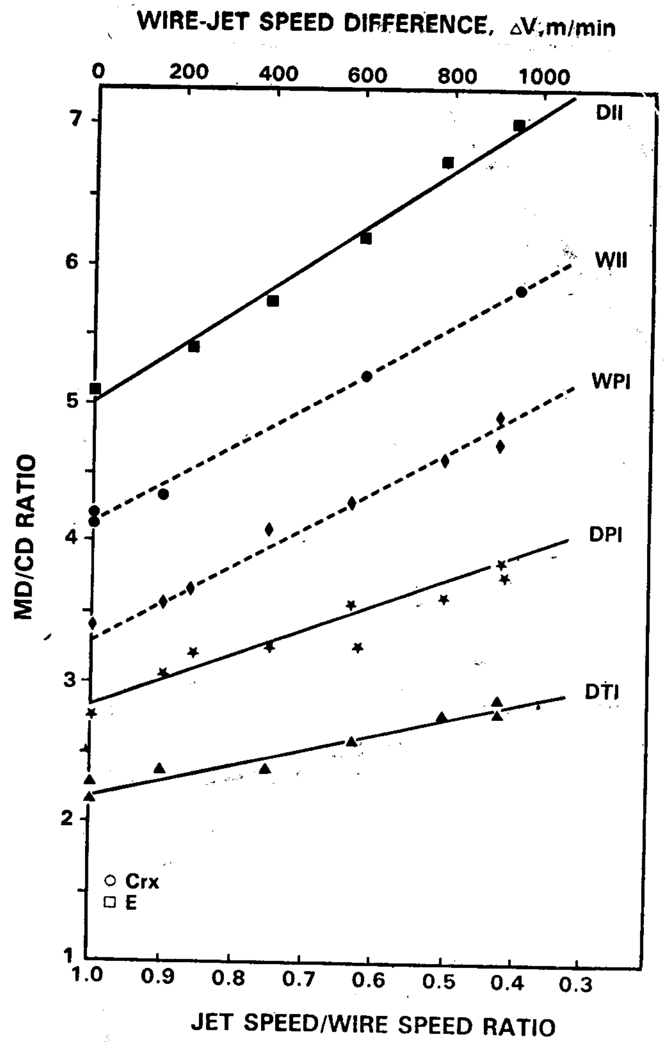

Figure 5. Five orientation indices are shown as a function of the difference between wire and jet speed for experimental paper (60 g/m²) produced from Kraft pulp (140ml CSF) with the dynamic former.

These are : DII=Dry Instron Index; DPI=Dry Pulmac Index; DTI=Dry; Tear Index; WII=Wet Instron Index; WPI=WPI Pulmac Index. The X-ray (Crx) and microscopical (E) indices were plotted from the literature (2,3) for comparison.

1 000 m/min ΔV range, or 0.217 for each 100 m/min increase in ΔV, yielding a slope of 0.00217. The corresponding slopes are summarized in Table III for quantitative comparison.

Figure 5 also shows that the dry Instron index (DII) gives the highest MD/CD ratios at all levels of jet/wire speed ratios and at the same time provides the highest slope (Table III) among the 5 lines. This would imply that DII is the most sensitive fiber orientation index among the 5 indices plotted in Figure 5. In comparison, WII, WPI, DPI and DTI produced increasingly smaller slopes in that order, DTI giving the least sensitive measure of fiber orientation in paper. For the sake of comparison the X-ray orientation index (Crx) and the microscopic orientation parameter (E) are also included in Figure 5 from our previous study (3).

Table III—Slopes of the lines formed by the 5 orientations indices in Figure 5.

Orientation Index	SM/ST Ratio at zero ΔV	Gradient per 100 m/minΔV	SLOPE Gradient/ m/min
DII	5.1	0.217	0.00217
WII	4.3	0.155	0.00155
WPI	3.5	0.124	0.00124
DPI	3.0	0.0830	0.00083
DTI	2.2	0.0520	0.00052
Crx	1.6	—	—
E	1.4	—	—
Handsheet	1.0	—	—

It should, however, be pointed out that the relations shown in Figure 5 were obtained for experimental paper made on the dynamic former of bleached Kraft pulp (140 ml CSF), where the sheets were dried under conditions of complete drying restraint. It is expected that the above relations would change as a function of pulp type, degree of refining, and drying conditions.

Comparison of the five strength tests

Among the five tests, the Instron wet tensile test is by far the most time consuming test to perform and at the same time it requires a great deal of special attention. Even with the greatest care, the reproducibility of this test is considered poor as indicated by the 13.2% coefficient of variation (Table 1). In comparison all of the dry tests, including tear, Instron and Pulmac tensile tests, are equally simple tests, which can be performed rapidly.

With respect to rapidity, the Pulmac wet tensile test is a somewhat more time consuming test to perform, because of the added step of rewetting the paper. However, the extra time of manipulation is well invested, considering the excellent reproducibility of this test. Tables I and II show that among the five tests, the Pulmec wet test produces the lowest average coefficient of variation (4.5%) and the lowest standard deviation for both MD (3/4km) and CD (1/4km). This is most likely due to the absence of fiber bonding in the wet sheet during its tensile straining.

With respect to its sensitivity the straight line of WPI processes an intermediate slope (0 00124 m/min) on Figure 5 and it occupies a central position on the graph. This implies that WPI has an intermediate sensitivity for the prediction of the degree of preferential fiber orientation in paper. Even in Figure 4, line 7 shows a linear relationship between WPI and WII. This line is the closest one to the zero-line, the latter assumed to represent a perfect relationship between two hypothetical tests.

In the light of the above results and considerations, the zero-span Pulmac wet test seems to be a good choice for the measure of preferential fiber orientation in paper. This is a simple test, which can be performed rapidly. It is also a fortunate coincidence that most paper testing laboratories already possess a zero-span tensile tester, which is used routinely to determine the tensile breaking length of dry paper. With an added step of rewetting the test sample, the MD/CD ratios could also be quickly determined for the measure of fiber orientation in paper, without the effect of inter-fiber bonding.

REFERENCES :

1. Prud'homme, R.E., Hien, N.V.; Noah, J. and Marchessault R.H.; *J. Appl. Polymer Sci.*, 19 : 2609 (1975).
2. Koran, Z.. Buissieres, D. and Prud'homme. R.E., *Taypi*, 65 (8) : 88-91 (1982).
3. Koran, Z., Silvy, J. and Prud'homme, R.E., *Tappi* 69 (5) : 126-128 (1986).
4. Danielson, R. and Steenberg, *Svensk Papper-stidning*, 50: 301-305 (1947).
5. Forgacs, O.L. and Strelis, I., *Pulp and Paper Mag. Can.*, 64 (1): T3-7 (1963).
6. Prusas, Z.C., *Tappi*, 46 (5): 325-330 (1963).
7. Kallmes, O.J. *Tappi*, 52 (3): 482-485 (1969).
8. Sauref, G., *Techniques et recherches papetieres*, Bulletin no. 6 : 30-40 (1965).
9. Yang, C.F. Eusufzal, A.R.K., Sankar, R., Mark, R.E. and Perkins Jr. R.W., *Sevensk Paperstidning*, 13: 426-432 (1978).
10. Silvy, J., *Institut National Polytechnique*, Ph.D, thesis, Grenoble, France, p. 167 (1980).
11. Ruck, H. and Krassing, H., *Pulp Paper Mag. Can*, (1): 183-189 (1959).
12. Votava, R J., *Tappi*, 65 (4): 67-70 (1982).
13. Boulay, R , Drouin, B., Gagnon, R. and Bernard, P., *Journ. of Pulp and Paper Sci.*, 12 (1): J26-29 (1986).
14. Osaki, S , *Tappi*, 70 (2) : 105-113 (1987).
15. Vahey, D.W., *Tappi*, 70 (3): 79-82 (1987).
16. Fleischman, E.H., Baun, G.A. and Habeger, C C., *Tappi Joarnal*, 65 (10): 115-118 (1982).
17. Niskanen, K.J. and Sadowski, J.W., Paper presented at the 1987 International Paper Physics Conference, Mont Rolland Canada.
18. Kohl, A. and Hartig, W., *Das Papier*, 39 (10A) : V171-177 (1985).
19. Sadowski, J.W., *Paperi ja Puu*, 61 (9): 588-589 (1979).
20. Similk, P., *Patent 3 807 868 (1974)*.
21. Tappi method T 481 SM 60 (1960).