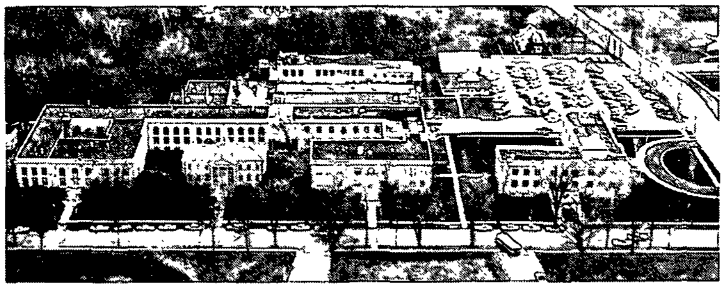

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THE EFFECT OF SUPERCALENDERING ON THE STRENGTH PROPERTIES OF PAPER

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The Effect of Supercalendering on the Strength Properties of Paper

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THE EFFECT OF SUPERCALENDERING ON THE STRENGTH PROPERTIES OF PAPER

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ABSTRACT

This investigation is concerned with how supercalendering affects certain strength and elastic properties of paper, and how these changes are affected by wet pressing and fiber orientation.

Formette handsheets were made at three levels of fiber orientation and three levels of wet pressing; they were then subjected to four levels of supercalendering using a laboratory supercalender. A reduction in both in-plane and out-of-plane elastic properties was found with increased supercalender loading. The highest rate of reduction was in the out-of-plane moduli (i.e., longitudinal and shear), and increased with increased wet pressing. The in-plane CD modulus was more severely affected than the MD modulus, with the loss in CD modulus increasing with increased fiber orientation.

The in-plane elastic anisotropy of the sheet decreased with increased densification by wet pressing, and increased with increased densification by supercalendering. This effect, together with a reduction in out-of-plane elastic moduli, strongly suggests a bond breaking process is occurring, despite the reduction in scattering coefficient with increased supercalendering.

Tensile and compressive strength losses are not as great as might be expected from the losses in elastic moduli due to supercalendering. In fact, no significant loss in failure properties was found at the highest level of wet pressing. Consequently, the correlation obtained between these strength properties and elastic moduli for wet pressing is altered by supercalendering.

INTRODUCTION

Calendering and supercalendering are important unit operations, whose main function is to improve the surface characteristics of paper, such as smoothness and gloss. Strength and other properties may also be affected during these operations. However, research to date has been mainly concerned with understanding how the surface characteristics of paper are modified by calendering and supercalendering.

Strength related properties are important with regard to the converting and end-use performance requirements of paper. For example, the gradual reduction in grammage in some fine paper grades and the need to retain stiffness places greater emphasis on minimizing stiffness and other strength losses occurring during calendering and supercalendering. Strength maintenance is also important with regard to press room runnability.

The impact of calendering and supercalendering on the strength properties of paper has been investigated by a number of researchers [1-15], with the main emphasis on the calendering of newsprint [4-6,8,10-11]. Data taken from Rance [12] given in Table I, illustrate that supercalendering can either improve or adversely affect strength properties, depending on the grade of paper involved.

Table I. Effect of supercalendering on the strength properties of some grades of paper.

Properties	NEWSPRINT Before	NEWSPRINT After	MACHINE COATED Before	MACHINE COATED After	GLASSINE Before	GLASSINE After
Grammage, g/m^2	54	--	105	--	32	--
Density, g/cm^3	0.41	0.63	0.91	1.16	0.8	1.32
Breaking length, MD (km)	2.2	2.2	4.6	1.1	1.1	2.3
Tear, MD (mN)	19	16	55	47	17	15

Peel and Hudson [2], in summarizing the impact of supercalendering on strength properties for a variety of grades, found slight losses in tensile and burst strength of 0 to 10%, a loss in tear strength of 10 to 15%, and an improvement in fold endurance of 10 to 40%. Losses in specific tensile modulus with calendering have been reported by Lyne [6] and Back and Mataki [13].

Ways to circumvent the loss of properties in calendering, particularly loss in bulk, has led to the concept of gradient calendering, e.g., temperature, Kerekes and Pye [5], and Crotogino [11]; and moisture, Lyne [6]. Taking advantage of the viscoelastic nature of paper, improvement in surface properties is accomplished by treating the surface layers of the paper without affecting its inner core. In addition to bulk preservation, strength properties are less affected when gradient calendering is employed. Clearly, it is of importance to understand the reason for these changes if we are to exercise better control over calendering and supercalendering.

The action of the supercalender and its impact on surface finish has been a controversial issue for a number of years. It now appears to be reduced to one of semantics, i.e., the debate between microslip and replication as proposed by Peel and Hudson [2] and Pfeiffer [9], respectively. By action we mean: what stresses does the paper web experience during passage through the supercalender nip? These stresses not only act to change the surface properties of the sheet, but can also affect strength and other bulk properties. According to Peel and Hudson [2] the principal stresses involved are a normal stress and a cyclic shear stress. Tension and bending stresses are also present. Van den Akker [1] stressed the importance of shear in the action of the supercalender. The relative contribution from shear and normal stresses will be controlled by a number of factors including the characteristics of the soft roll, particularly its Poisson's ratio.

The objective of the present study is to determine how the elastic and strength properties of paper are modified by the action of supercalendering.

EXPERIMENTAL

The main purpose of these experiments was to compare the densification of an uncoated web by wet pressing and supercalendering. Preliminary work [15] with commercial coated two side (C2S) samples convinced us that we first needed to understand the response of an uncoated base material to the action of supercalendering before considering the effects of coating.

Handsheets with three levels of fiber orientation (approximately a 1:1, 2:1, and 3:1 MD/CD elastic constant ratio measured ultrasonically) were made on the Formette Dynamique. The market pulp, which was a bleached kraft southern pine, was beaten to 600 CSF in a valley beater. After the sheets were formed (using a five shed wire 84 x 68 mesh) and couched, they were wet pressed (0 pli, 281 pli, 750 pli) to produce three levels of densification, using The Institute of Paper Chemistry's press and dryer combination. The purpose of this arrangement is to be able to produce handsheets dried as close as possible to conditions of full restraint. The dryer can surface temperature was 195°F. In order to measure any dimensional changes the sheet may undergo during wet pressing, drying, or supercalendering, the sheets were marked after couching in both the MD and CD directions.

After preconditioning (30% RH, 73°F, for 48 h) and conditioning (50% RH, 73°F, for 48 h) various nondestructive and destructive tests were performed on one handsheet from each condition. The conditioned basis weight of the handsheets was 214.8g/m^2 with a standard deviation of 3.7g/m^2.

The handsheets were supercalendered using the laboratory facilities at Wartsila-Appleton Machine Co. (now Valmet Inc.). The single nip supercalender described by Agronin [16] consisted of a 10-inch diameter iron roll and a 13.48-inch diameter AMCO 80# White cotton filled roll. The speed and temperature of the iron roll were held constant at 300 fpm and 160°F, respectively. The filled roll temperature was 153°F plus or minus 5°F. The roll surface temperatures were measured using an infrared pyrometer. This device has a bracket which holds a blackened Teflon strip in front of the thermometer lens. The Teflon strip is held in contact with the roll and the temperature of the Teflon is measured. This eliminates any other environmental effects on the temperature being read.

The Formette handsheets (approximately 36 inches x 8.5 inches) were aligned in the machine direction and hand fed into the single supercalender nip, with the wire side facing the steel roll. The sheets were supercalendered in the order of increasing load, at levels of 0 pli (< 100 pli), 1000 pli, 1500 pli, and 2000 pli. In addition, one control sheet was exposed to the environment of the supercalendering laboratory (35% RH and 72°F) but was not supercalendered. After supercalendering the samples were immediately placed in plastic bags and brought back to our laboratory for preconditioning and conditioning as noted above.

After conditioning, both nondestructive and destructive property measurements were again performed. The samples were measured for MD and CD dimensional changes after wet pressing and drying, and after supercalendering. Other nondestructive tests included soft [17] and hard platen caliper, Parker Print-Surf smoothness at a land pressure of 10 Kgf/cm^2, Gurley porosity (seconds to displace 100 mL), in-plane and out-of-plane measurement of elastic constants [18-19], and scattering coefficient. Tensile deformation behavior and STFI compressive strength measurements were also made. Tests were performed according to TAPPI standards where appropriate.

RESULTS AND DISCUSSION

Supercalendering is one important converting process where paper is subjected to combined out-of-plane stresses. The effects of densification by wet pressing and supercalendering are compared in Figures 1 through 11. The expected improvement in surface smoothness by supercalendering is shown in Figure 1. Smoothness appears to be slightly impaired by increased wet pressing.

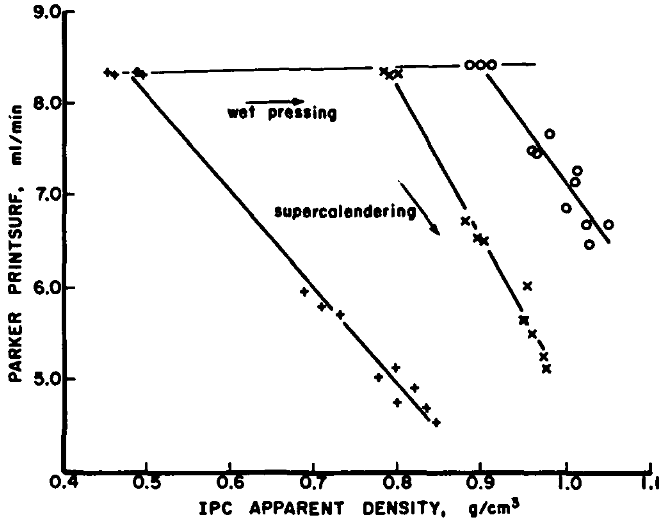

Fig. 1. Effects of wet pressing and supercalendering on Parker Print-Surf smoothness.

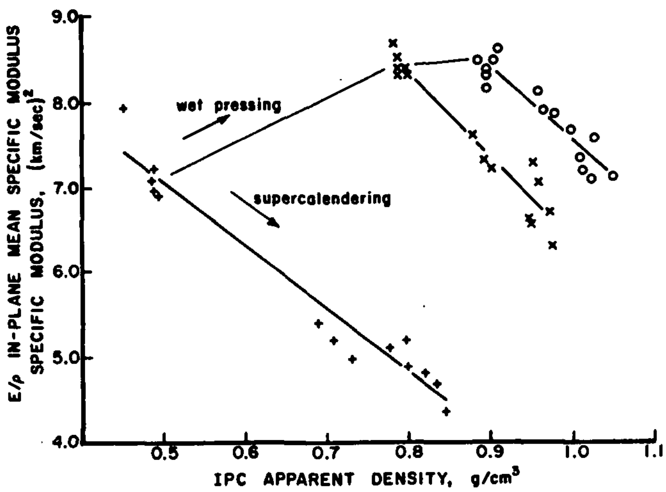

Fig. 2. Effects of wet pressing and supercalendering on in-plane mean specific modulus.

The effects of wet pressing and supercalendering on in-plane and out-of-plane elastic moduli are shown in Figures 2 through 5. We note, in general, that the moduli are improved by wet pressing, but a significant loss results from supercalendering.

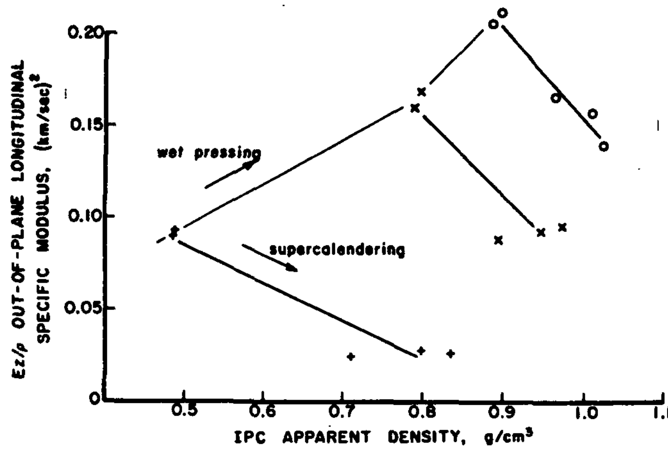

Fig. 3. Effects of wet pressing and supercalendering on out-of-plane longitudinal specific modulus.

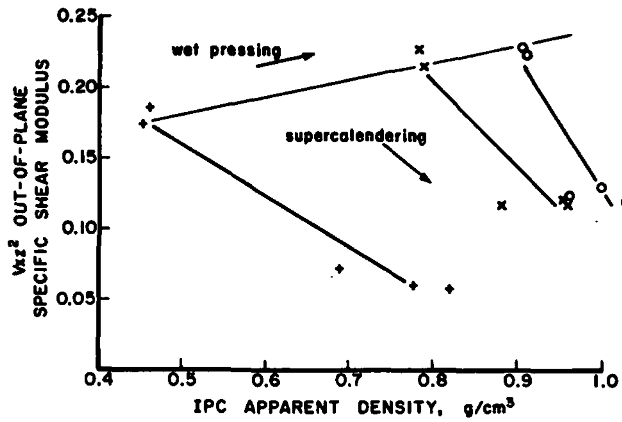

Fig. 4. Effects of wet pressing and supercalendering on out-of-plane specific shear modulus V_{xz}^2.

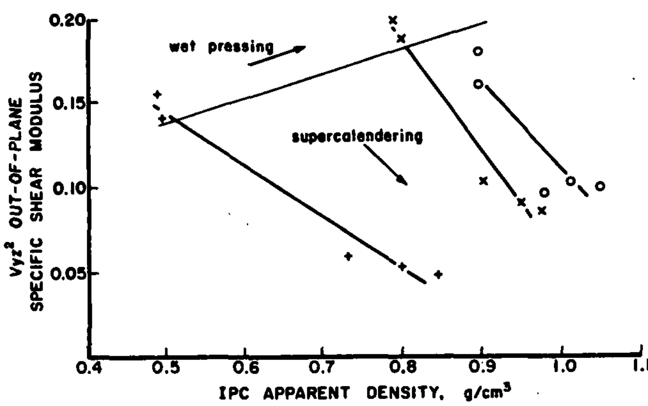

Fig. 5. Effects of wet pressing and supercalendering on out-of-plane specific shear modulus V_{yz}^2.

According to the regression line data shown in Table II, the rate of loss in elastic properties with increased supercalendering appears to be dependent on the level of wet pressing. Its dependence is particularly strong for the out-of-plane moduli, and surprisingly the rate of loss increases with increased wet pressing.

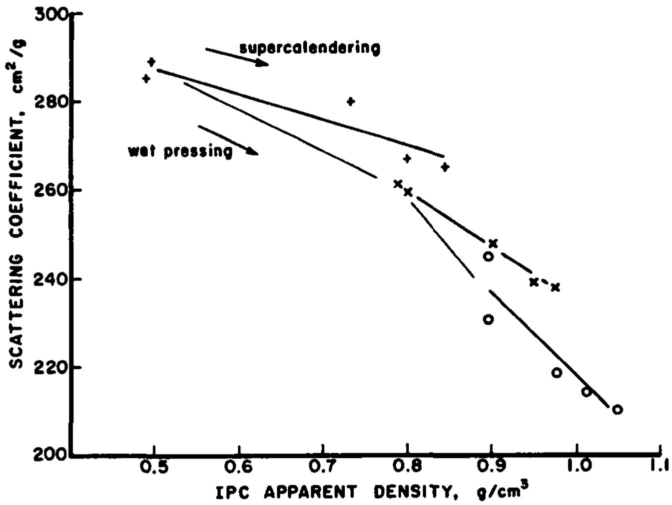

Fig. 6. Effects of wet pressing and supercalendering on scattering coefficient.

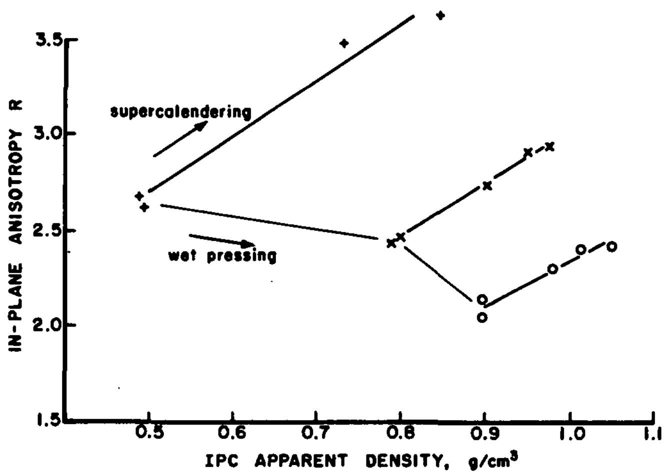

Fig. 7. Effects of wet pressing and supercalendering on in-plane anisotropy.

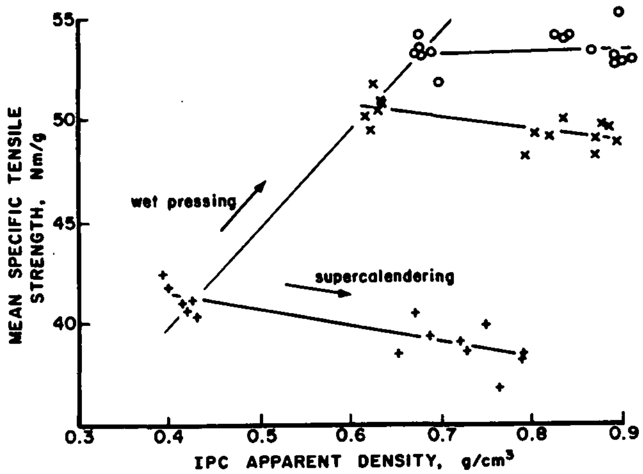

Fig. 8. Effects of wet pressing and supercalendering on mean specific tensile strength.

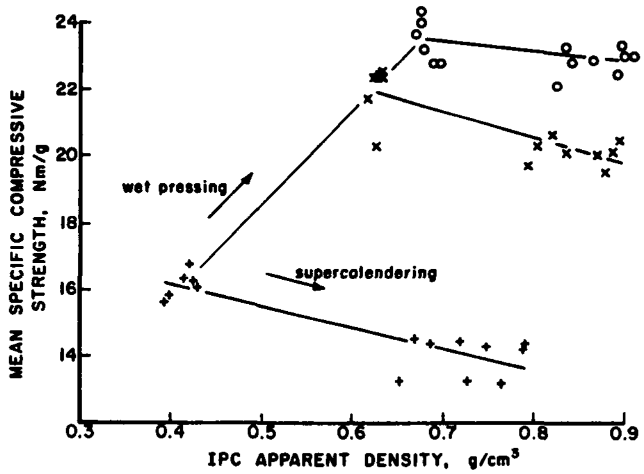

Fig. 9. Effects of wet pressing and supercalendering on mean specific compressive strength.

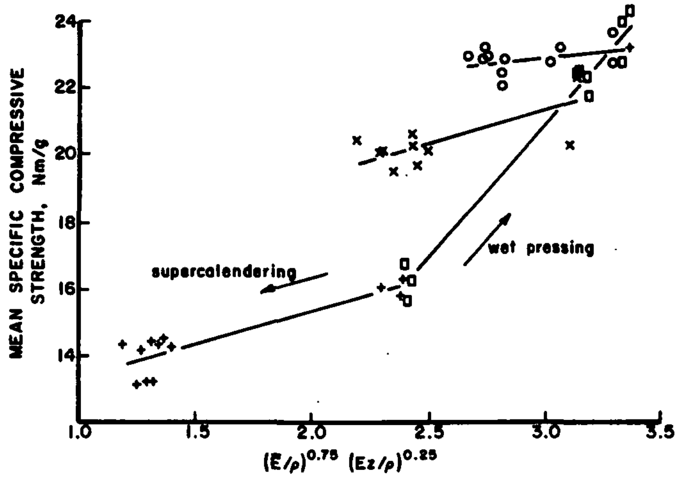

Fig. 10. Effects of wet pressing and supercalendering on mean specific compressive strength and $E/\rho^{0.75} \times E_z/\rho^{0.25}$ relationship.

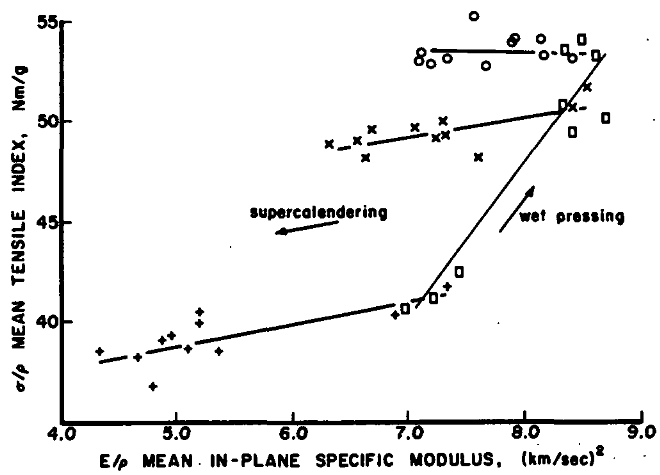

Fig. 11. Effects of wet pressing and supercalendering on mean tensile index and mean in-plane specific modulus relationship.

Table II. Slopes of regression lines for supercalendering at three levels of wet pressing.

	Low WP	Med WP	High WP
E/ρ	-7.55	-10.1	-8.78
G/ρ	-2.05	-2.99	-2.25
E_z/ρ	-0.205	-0.428	-0.491
G_{xz}/ρ	-0.362	-0.610	-0.949
G_{yz}/ρ	-0.315	-0.527	-0.523

There is little published data on the effects of calendering or supercalendering on elastic properties. In his investigation of the effects of moisture on the calendering of newsprint furnishes, Lyne [6] found a loss in mean extensional stiffness and strength properties of newsprint with increased calender loading. Back and Matuki [13] also found a loss in specific modulus with the calendering of a highly filled rotogravure paper. Furthermore, they also reported a loss in Scott bond which suggests that there may also have been a loss in out-of-plane stiffness.

The elastic properties of paper are dependent on network, interfiber bonding, and fiber properties. It is clear, therefore, that supercalendering, leaving aside for the moment network considerations (e.g., changes in fiber orientation and formation), has modified either interfiber bonding or fiber properties or both.

Let us first consider interfiber bonding. The variation of scattering coefficient (which is commonly used as a measure of unbonded surface area in paper) with densification by wet and supercalendering is shown in Figure 6. It is seen that both these processes reduce the scattering coeffficient as the sheet is densified, implying that there is an increase in bonded area. Wet pressing appears to be more effective in developing bonded area than supercalendering. However, it is possible that the reduction in scattering coefficient with supercalendering does not represent a real increase in bonded area, i.e., optical contact does not imply that the surfaces are sufficiently close to each other to establish bonding. Furthermore, since interfiber bonding according to Page and Seth [20] affects sheet modulus by its contribution to load transfer at fiber ends, this may also be a factor which is adversely affected by supercalendering. Lyne [6] also found a small reduction in scattering coefficient with calendering, and when the surface layers of the sheet were plasticized by the application of heat or surface moisture, strength losses were not as great and the scattering coefficient was further reduced. Lyne [6] suggests that the reduction in scattering coefficient may be due to a loss of intrafiber surface area as a result of web heating during supercalendering.

An interesting consequence of the effect of wet pressing and supercalendering on elastic properties is the change in the in-plane elastic anisotropy ratio shown in Figure 7. We note, that whereas wet pressing decreases the anisotropy ratio, supercalendering increases it. In unpublished work we have found that processes which are expected to improve interfiber bonding, e.g., refining, wet pressing, and certain chemical additives, reduce the anisotropy ratio, and possible bond breaking processes such as calendering tend to increase it. In processes such as calendering and supercalendering, we cannot ignore the fact that this effect may also be due, in part, to changes in fiber structure. The effect of increased bonding on elastic anisotropy, however, is in agreement with the theoretical predictions of Perkins [21].

In determining the effects of calendering and supercalendering on the recycling behavior of paper, Gottsching and Sturmer [7] found significant fiber damage as a result of increased calendering, but, none was found as a result of supercalendering. The indicators of fiber damage were changes in the long fiber fraction and a reduction in water retention value. It is possible that part of the damage may have occurred during the redispersion of the fibers.

Another aspect of fiber damage we might consider is the possibility that supercalendering may induce axial compression in the fibers. This effect could certainly contribute to a reduction in in-plane moduli, while the direction of change in out-of-plane moduli is less certain. The loss in the out-of-plane shear moduli, Figures 3, 4, and 5, suggests that bond breaking is also occurring. Leporte [3] found that web shrinkage occurred during supercalendering and increased with increasing basis weight. This suggests that supercalendering might produce a Clupak effect, evidence of which might include increased stretch and tensile energy absorption, Rance [12], Ihrman and Ohrn [22]. However, we find very little change in MD and CD stretch values as a result of increased supercalendering. Lyne [6] found that mean stretch values were significantly reduced as a result of calendering. We note that the optimum Clupak process takes place at a much higher web moisture content than used in these experiments [12]. The Clupak process has been suggested as a means of improving newsprint runnability, see Hamrick [23].

The effects of fiber orientation and wet pressing on the reduction of in-plane machine and cross machine direction elastic moduli due to supercalendering are summarized in Table III. The reduction is defined as the ratio of the specific modulus at the highest nip loading (2000 pli) to the specific modulus prior to supercalendering.

Table III. The effect of fiber orientation and wet pressing on the reduction of in-plane MD and CD elastic moduli.

Fiber Orient. $(=E_x/E_y)$		1:1	2:1	3:1
Low dens.	E_x/ρ	0.638	0.721	0.733
	E_y/ρ	0.634	0.578	0.528
Med. dens.	E_x/ρ	0.805	0.820	0.842
	E_y/ρ	0.817	0.745	0.692
High dens.	E_x/ρ	0.814	0.887	0.908
	E_y/ρ	0.921	0.776	0.817

The decrease in the elastic moduli is greatest for the low density sheets and diminishes with increasing densification by wet pressing. Furthermore, as fiber orientation increases, we see a greater loss in the cross machine direction than the machine direction. This is consistent with the increase in plane elastic anisotropy shown in Figure 7, which we have already discussed.

An improvement in both tensile and compressive strength with increased wet pressing is shown in Figures 8 and 9. The change in strength due to supercalendering is not as great as found with the elastic properties. In fact, at the highest level of wet pressing, there is no significant loss in tensile strength as a result of supercalendering. (This result is not inconsistent with the possibility of interfiber bond damage occurring during supercalendering, since if paper is strained beyond its yield point and interfiber bonds are partially broken, its ultimate strength is not usually affected.) Moffatt, Beath, and Mihelich [4] investigated the effects of mass distribution, fiber type and orientation on the strength properties of calendered newsprint. They found that as the severity of calendering increased, the locus of failure moved from a zone where the local grammage was below the sheet average to a zone where it was significantly above. It was argued that higher grammage areas would be subjected to more damage during calendering. Initially, they found no loss in tensile strength, but as the severity of calendering increased, there was a rapid drop in tensile strength. A similar result was also found by Berger [14] who investigated the effects of temperature and pressure on the calendering of linerboard. Further work would be required to determine if the formation effect, reported by Moffatt et al. [4] is a significant factor in the present study. It is possible that the high basis weight and good formation of the Formette handsheets used in this study would preclude that effect. Furthermore, as we have already noted, Gottsching and Sturmer [7] did not find any evidence of fiber damage as a result of supercalendering.

It is surprising that compressive strength, Figure 9, is not more adversely affected by supercalendering in view of its strong dependence on both in-plane and out-of-plane elastic constants, as demonstrated by Habeger and Whitsitt [24]. The correlation of mean specific compressive strength with the product of in-plane and out-of-plane elastic moduli (one form of their correlation) is shown in Figure 10. We note that the correlation obtained for wet pressing is altered by supercalendering. Another important factor, (which we usually assume to be constant), in the Habeger and Whitsitt model is the "roughness-weakness" factor RW given below. Compressive stength is inversely proportional to RW.

$$RW = \frac{(\text{initial curvature amplitude})\ (\text{elastic stiffness})}{(\text{lamina thickness})(\text{shear strength})}$$

We speculate, in view of the fact that tensile strength is not as adversely affected as the elastic properties, that changes in out-of-plane shear strength would also be small. This would decrease the "roughness-weakness" factor and thus partly offset the reduction in elastic constants due to supercalendering. Therefore, a change in the correlation is not unexpected.

It is also interesting to note, as shown in Figure 11, that the correlation between mean tensile index and mean in-plane specific modulus is also altered by supercalendering. We have also checked the correlation between the in-plane specific modulus measured using Instron and ultrasonic techniques, and find that it is unaffected by supercalendering. Therefore, caution must be exercised in drawing conclusions about the failure properties of paper and board from elastic constant measurements when processes such as calendering and supercalendering are involved.

CONCLUSIONS

Our investigation has been concerned with how supercalendering affects certain strength and elastic properties of paper, and how these changes are affected by wet pressing and fiber orientation. A reduction in both in-plane and out-of-plane elastic properties was found with increased supercalender loading. The largest reduction was in the out-of-plane moduli (i.e., longitudinal and shear), and increased with increased wet pressing. The in-plane CD modulus was more severely affected than the MD modulus, with the loss in CD modulus increasing with increased fiber orientation.

The in-plane elastic anisotropy of the sheet decreased with increased densification by wet pressing, and increased with increased densification by supercalendering. This effect, together with a reduction in out-of-plane elastic moduli, strongly suggests a bond breaking process is occurring, despite the reduction in scattering coefficient with increased supercalendering.

Tensile and compressive strength losses are not as great as might be expected from the losses in elastic moduli due to supercalendering. In fact no significant loss in failure properties was found at the highest level of wet pressing. Consequently, the correlations obtained between these strength properties and elastic moduli for wet pressing is altered by supercalendering.

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REFERENCES

1. VAN DEN AKKER, J. A. The Possible Role of Shear in Calendering, The Paper Industry and Paper World, April, 1946:57-59.
2. PEEL, J. D. and HUDSON, F. L. Application of Elasticity Theory to a Supercalender Nip. Paper Technology 7(5):460-470 (October, 1966).
3. LEPORTE, L. E. Observations Regarding Web Behavior in a Supercalender Nip. Tappi 52(8):1495-1497 (1969).
4. MOFFATT, J. M., BEATH, L. R. and MIHELICH, W. G. Major Factors Governing Newsprint Strength. The fundamental properties of paper related to its end uses. Trans. of Symposium held at Cambridge (1973).
5. KEREKES, R. J. and PYE, I. T. Newsprint Calendering and Experimental Comparison of Temperature and Loading Effects. Pulp Paper Canada 75(11):65-72 (1974).
6. LYNE, M. B. The Effect of Moisture and Moisture Gradients on the Calendering of Paper. Fiber-Water Interactions in Papermaking, Trans. 6th Fundamental Research Symposium, held at Oxford, 1977, Fund. Res. Comm., Tech. Div. Brit. Paper Board Ind. Fed., London, 1978 Vol. 2, 641-669.
7. GOTTSCHING, L. and STURMER, L. The Effect of Calendering and Supercalendering on the Properties of Secondary Fibers. Fiber-Water Interactions in Papermaking, Trans. 6th Fundamental Research Symposium, held at Oxford, 1977, Fund. Res. Comm., Tech. Div. Brit. Paper Board Ind. Fed., London, 1978 Vol. 2, 877-897.
8. MITCHELL, J. G. Calendering Alternatives for Reducing the Bulk of TMP Newsprint. Pulp Paper Canada 81(4):T102-107 (1980).
9. PFEIFFER, J. D. Supercalendering - 1980 Update. TAPPI Proceedings, Paper Finishing and Converting Conference (1980):19-31.
10. CROTOGINO, R. H. Machine Calendering - Recent Advances in Theory and Practice Trans. Tech Sect. CPPA (December 1981): TR75-87.
11. CROTOGINO, R. H. Temperature Gradient Calendering. Tappi J. 65(10):97-99 (1982).
12. RANCE, H. F., Handbook of Paper Science, Vol. 1, Elsevier Scientific Publishing Company (1982):279-291.
13. BACK, E. L. and MATAKI, Y. Potentials of Hot Calendering for Printing Papers. Svensk Papperstid. 12:R83-R93 (1984).
14. BERGER, B. The Effects of Heat and Pressure on the Machine Calendering of Linerboard. A-190 Masters Independent Study Project, The Institute of Paper Chemistry (1985).
15. CHARLES, L. A. The Effect of Supercalendering on the Strength Properties of Paper. A-190 Masters Independent Study Project, The Institute of Paper Chemistry (1985).
16. AGRONIN, R. D. TAPPI Paper Finishing and Converting Conference Proceedings, Wausau, WI., October 2-5, 1978:69-80.
17. WINK, W. A. and BAUM, G. A. Tappi 66(9):131 (1983).

18. BAUM, G. A. IPC Technical Paper Series No. 119, Dec., 1981.

19. HABEGER, C. C. and WINK, W. A. J. Applied Polymer Science 32:4503-4540 (1986).

20. PAGE, D. H. and SETH, R. S. The Elastic Modulus of Paper. II. The importance of fiber modulus, bonding and fiber length. Tappi 63(3):113-116 (1980).

21. PERKINS, R. W. NSF Workshop on Solid Mechanics Related to Paper, August 1986, Blue Mountain Lake, N.Y.

22. IHRMAN, C. B. and OHRN, O. E. Extensible Paper by the Double-roll Compacting Process. Cambridge Symposium, Consolidation of the Paper Web, Vol. 1: 410-434 (1966).

23. HAMRICK, H. L. Extensible Newsprint by the Compaction Process. Paper 184(1):12-16, 24 (1975).

24. HABEGER, C. C. and WHITSITT, W. J. A Mathematical Model of Compressive Strength in Paperboard. Fiber Science & Technology 19:215-239 (1983).