IDEAL FIBERS FOR PULP AND PAPER PRODUCTS

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Abstract.--The various paper and paperboard products are made for different purposes and therefore have different product specifications and standards. Printing applications require smooth, low porosity paper with sufficient strength to carry the mineral fillers and coatings needed to obtain opacity and gloss. Paperboard products need stiffness and compressive strength to perform well under stacking loads. As the paper requirements change, so do the preferred characteristics of the pulp fibers and the ability of the papermaker to adjust for unfavorable fiber form. Pulping processes also differ in ability to handle diverse tree species. In particular, the mechanical pulping processes are highly species dependent, favoring low-density softwoods with fine fibers and thin cell walls.

Performance requirements for typical paperboard and coated paper products are reviewed and the softwood fiber characteristics that maximize performance are identified. In addition, the influence of fiber morphology on the production and performance of mechanical pulps is considered.

Keywords: Fiber morphology, mechanical pulp, coated paper, paperboard, linerboard, spruce *(Picea),* western hemlock *(Tsuga heterophylla),* Douglas-fir *(Pseudotsuga menziesii),* southern pine *(Pinus).*

INTRODUCTION

Of the many parameters useful as a measure of product performance, board bending stiffness is probably of greatest interest to the construction industry, and paper breaking length or tensile strength is of most interest to the papermaker. In Figure 1, average bending modulus for boards cut from various softwoods (*Wood Handbook,1974)* is graphed against breaking length (MacLeod, 1980) for kraft pulps derived from the same species. Species that routinely give fibers capable of forming strong papers generally have poor stiffness as solid lumber products. Of the four softwoods selected, the spruces, often considered ideal papermaking fibers, have the weakest bending modulus as solid lumber products.

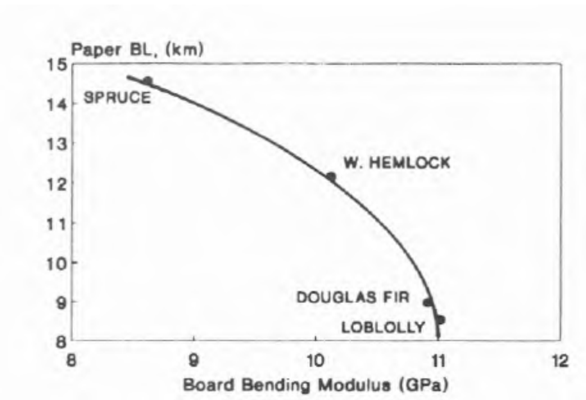

Figure 1. Paper breaking length graphed against board bending modulus for typical pulpwoods.

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In an effort to highlight the needs and desires of the paper industry for wood fiber form, this paper will review the product requirements of various paper and paperboard grades and attempt to identify the key fiber characteristics that contribute to the manufacture of a superior product. To simplify the problem, the hardwood pulp contribution to paper and paperboard performance will not be considered in this paper, and the discussion will be limited to softwoods. The performance of the following representatives of four genera: spruce (white, black and Norway), western hemlock, Douglas-fir, and southern pine (loblolly and shortleaf) will be evaluated in various paper products. Table 1 summarizes average wood density and typical fiber characteristics for representatives of these four softwood genera.

Table 1. Fiber characteristics of common U.S. pulpwoods (Isenberg, 1980; Horn, 1972; Koch, 1972).

Species	Specific Gravity g/cc	Fiber Length mm	Fiber Diameter p.m	Fiber Wall µm	Latewood Content %
Loblolly Pine	0.47	3.5-4.5	35-45	4-11	20-45
Douglas-fir	0.43	3.5-4.5	35-45	3-8	25
W. Hemlock	0.38	2.5-4.2	30-40	2-5	10-30
W. Spruce	0.37	2.5-4.2	25-35	2-3	3

MECHANICAL PULPING

In mechanical pulping, fiber characteristics are a dominant variable and exercise considerable control over the paper quality. Typical quality data for mechanical pulps from the four genera are presented in Table 2. The white wood and thin cell walls of spruce give the strongest and brightest mechanical pulp of the four, making it the preferred genus for high-yield pulping. Douglas-fir, giving low strength and low brightness, is rarely used in mechanical pulping.

Table 2. Typical pulp properties and energy consumptions of different species compared with spruce groundwood (Kurdin, 1980; Hatton and Cook, 1990).

	Genus: Spruce	W. Hemlock	Loblolly	Douglas-fir
Energy kWh/BDT	1900	1960	2500	2750
Freeness ml	120	80	100	100
Breaking Length **km**	4.8	3.7	3.3	3.4
Tear Index mNm2/g	9.7	8.3	7.3	6.3
Brightness	59	56	58	53

Traditionally, wood density has been the parameter most associated with differences in high-yield pulp quality between species. However, wood density does not control mechanical pulp quality but rather, some aspect of fiber structure that correlates well with wood density.

The Shallhorn, Karnis equation for the tensile strength of a bond limited paper domain such as newsprint, is given below (Shallhorn and Karnis, 1979).

$$T = \frac{N \pi r \Gamma l}{2}$$

where N is the number of fibers in the break, r is the fiber wall radius, F is the bond strength per unit fiber surface, l is the average fiber length.

All paper grades are made to a basis weight specification. Adjusting for basis weight by dividing by g/m^2 gives tensile index (or breaking length) and introduces the term N/g. Whereas basis weight is dictated by paper grade, N/g is controlled by fiber morphology. Average fiber weight can be calculated from fiber volume and density $[\pi r^2 - \pi(r-w)^2] l \rho$ where w is average fiber wall thickness and ρ is cell wall density.

Fiber length (1) cancels, cell wall density (Besley, 1969; Smith, 1965; Wangaard, 1969) *(p)* and bond strength per unit fiber surface area (F) are relatively constant for a given mechanical pulping process and within the softwoods of interest. The term m^{-2} introduced with basis weight is constant within a nailer grade or a standardized test Procedure. This leaves the term Tu. which is 1 /2 average fiber circumference, and $\pi r^2 - \pi(r-w)^2$, which is average fiber wall cross-sectional area (CSA).

$$TI = k \frac{\pi r}{CSA}$$

Using data from various literature sources, this ratio is graphed against TMP breaking length in Figure 2. The straight line obtained indicates that the ratio is a key factor in strength development of mechanical pulps. This result still needs to be evaluated using a coherent set of data.

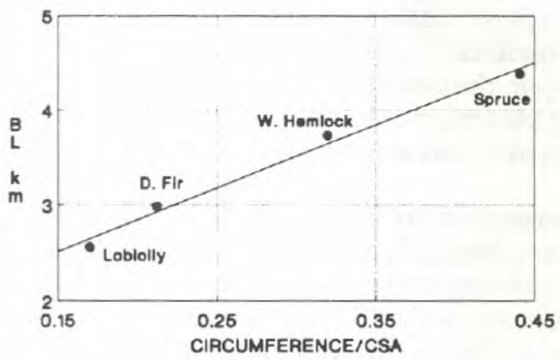

Figure 2. TMP breaking length at 2000 kWh/BDT specific energy graphed against the ratio of average fiber circumference divided by average fiber wall cross-sectional area.

COATED PRINTING PAPERS

The key performance requirements of coated printing papers are high smoothness, low porosity and high paper surface strength.

Smoothness and Porosity

To obtain high gloss and even print density on the coated paper, the final surface must be very smooth (Bristow and Ekman, 1981). The clay coating layer on a sheet of paper is on the order of 5µm thick (Kartovaara, 1989), comparable to the double-wall thickness of the average spruce fiber and half the double-wall thickness of a loblolly pine fiber. Although the coating process fills in the surface roughness of the sheet with the slurry coating clay, shrinkage on drying reproduces the original surface topography in reduced scale. Additional smoothness is gained by calendering the coated paper. The calendering process improves smoothness and unprinted sheet gloss but can also create other problems. Calendering can cause ink to absorb at different rates (Kartovaara, 1989) and can reduce sheet strength and opacity.

To obtain both high smoothness and low porosity in the base paper, papermakers prefer fibers with thin cell walls that collapse on drying to form ribbon-like fibers that conform to the surface of the other fibers in the sheet. This increases paper density, decreases porosity and assures that the maximum surface defect is on the order of 1 double-wall thickness, about 5 μm for spruce. Fibers with thick cell walls resist collapse. A cylindrical fiber is unable to conform to the other fibers in the paper, opening up the paper structure and increasing porosity. If a southern pine latewood fiber on the paper surface fails to collapse on pressing and drying, it can protrude above the average surface of the paper by one whole fiber diameter, 25 to 50 μm (Koch, 1972) and 5 to 10 times the average coating thickness.

Surface Strength

The heatset web offset printing process is a torture test for coated papers. Starting with the low porosity base paper, the coating reduces the porosity even further. In the offset printing process, water is used to protect the non-image part of the printing blanket so the paper picks up moisture in the press. After printing, the paper is dried rapidly in an oven to set the inks. The water in the paper turns to steam, which is restricted from expanding and escaping by the low porosity of the paper and the coating. The result is an internal force working to blow the sheet apart.

In lightweight coated papers containing mechanical pulps, the steam contributes to fiber rise, reforming the lumens in previously collapsed fibers. In lightweight coated papers with 100% chemical pulp in the base paper, the weak link is generally the interface between the paper and the coating that leads to coating blisters, much like paint blisters. Improved surface strength reduces the severity of both fiber rise and heatset printing blisters (Perry, 1972).

Good paper surface strength is favored by a high bonded surface between fibers. Bonded surface can be increased by mechanically tearing fibrils from the surface of the fibers. Fibers with a large surface area to mass also help. In studies of fibers readily pulled from the surface of papers containing mechanical pulp, heavy walled latewood fibers invariably dominate (Mohlin, 1989). As with smoothness and porosity, species with thin fiber walls, such as the spruces and the true firs, are preferred.

Manufacturers of lightweight coated printing papers prefer the lower density softwoods, primarily the spruces and true firs. Over 70% of the coated papers manufactured in the United States are produced in the northeast and north-central states where white and black spruce and balsam fir are available (Table 3).

Table 3. Pulp and paper production by region (Statistics, 1990).

	% of U. S. PRODUCTION		
	South	N.E./N.C.	West
Total Paper	53%	31%	14%
Newsprint	58	11	31
Coated	22	71	4
Uncoated Free	40	45	12
Bleached Board	89	0	11
Kraft Board	82	0	17
Market Pulp	67	16	16

BLEACHED PAPERBOARD

Bleached paperboard is used in folded cartons and liquid packaging applications. Paperboard used in consumer packaging is a store display item and, for these applications, the board is coated to improve the printing characteristics. The requirements for printed folding carton applications are similar to those for lightweight coated papers, but the heavier basis weights and thicker clay coatings provide added flexibility for handling difficult fibers.

Stiffness

The other major requirement of packaging board is stiffness (Grangård, 1970). High board stiffness improves stacking strength and product protection. For liquid packaging applications it reduces carton bulge (Bridger and Munday, 1969) and makes the carton easier to hold.

Bending stiffness in a solid bleached paperboard can be estimated from Young's modulus of elasticity (E), and paperboard thickness or caliper (c) (Schrier and Verseput, 1967).

$$S = kEc3$$

Typical results for handsheet bulk and elastic modulus for the four sample genera are given in Table 4. Estimated handsheet stiffness is calculated from these data using this equation for stiffness.

Table 4. Fiber properties for structural papers.

Genus	Bulk cm3/g	Elastic Modulus kma	STFIb Compression Strength Nm/g	Estimated Stiffness arbitrary units
Spruce	1.42	830-920	40-43	210-217
W. hem	1.34	900[c]	37-41	180-350
D. Fir	1.67	659-866	31-33	230-371
S. Pine	1.66	888	36	326-348

[a] DeGrace and Page, 1976. [b] Seth et al., 1986 [c] Horn, 1972

Modulus favors fiber forms giving dense papers, such as the spruces. Caliper invariably favors the coarse fiber species, loblolly pine and Douglas-fir. Since stiffness is linearly dependent on modulus but increases according to the cube of caliper, handsheet stiffness is best for loblolly pine and Douglas-fir. Referring again to Table 3, 90% of the bleached board manufactured in the U.S. is produced in the south using the available southern pines and hardwoods.

The advantage of the coarse southern pine fiber has helped the U.S. paperboard industry for many years, but recent advances with paper machines using several forming sections endangers the southern pine dominance of the paperboard market. Multi-ply paperboard using high modulus fiber furnishes on the outer plies, and a bulking furnish for the inner ply, can improve bending stiffness by 50% over that available with a single furnish paperboard (Fineman, 1985; Engman, 1989). Since spruce and fir refine easily to give high modulus papers for the outer plies, and mechanical pulps and waste paper are good choices for bulking inner plies, the success of the three-ply paper machine offers Canada and the Nordic countries the means to challenge the southern kraft paperboard industry (O'Brien, 1991).

CORRUGATED BOARD

Corrugated board is not really a paper or paperboard but rather an engineered product constructed from paperboard. It is influenced by both the manufacturing process and the nature of the original paperboard products, the linerboard forming the outside of the corrugated sheet, and the medium glued in place between the two liners. Through the years there have been extensive efforts to understand the role of the liners and medium on the performance of the combined board product. The two critical performance tests for linerboard are considered to be compressive modulus and compressive strength (Koning, 1975).

Compressive modulus is generally identical to the modulus of elasticity measured in tensile (Fellers et al., 1980; Wink, et al., 1982) reported in Table 4. Technically, a high elastic modulus requires fibers of low fibril angle (Page et al., 1977) and papers of high density (Page et al., 1979). Modulus is also influenced by the drying restraint applied when producing the paper or handsheet (Setterholm and Chilson, 1965) and can be improved by any means capable of increasing paperboard density, such as improved wet pressing, increased beating (Page et al., 1979) and lower pulp yield (Koning and Haskell, 1979).

Compressive strength is largely a matter of paperboard density (Fellers et al., 1980), but is also influenced by pulp yield (Koning and Haskell, 1979), double-wall thickness and fibril angle (Seth et al., 1986). Under standard pulping and papermaking conditions, species that form higher density papers give higher compressive strength. In Figure 3, compressive strength is plotted against double-wall thickness for the four softwood varieties in the review; spruce gives the best compressive strength, followed by western hemlock, loblolly pine and Douglas-fir (Seth et al., 1986).

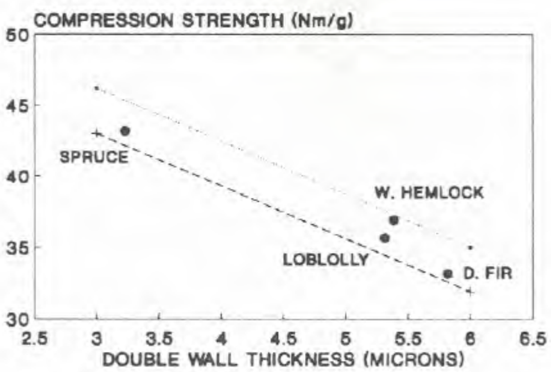

Figure 3. Paperboard compression strength graphed against fiber double wall thickness. Top line is for a 5°, bottom line for a 25° fibril angle (Seth et al., 1986).

In practice, over 80% of the kraft board manufactured in the United States is produced in the south. Compressive strength is largely controlled by sheet density under typical paper machine conditions as seen in Figure 4 (Wink et al., 1982). Southern producers can adjust for the performance characteristics of the southern fibers by improving wet pressing and refining to lower freeness, but it is not possible for the northern producers to adjust for the comparatively high wood costs. For a commodity product such as linerboard, the cost issues are of greater concern than the marginal performance improvement available with thin-walled northern fibers.

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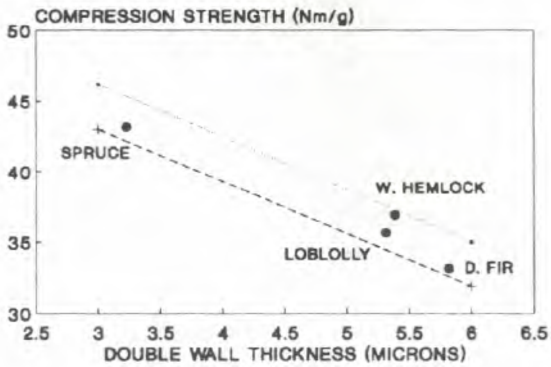

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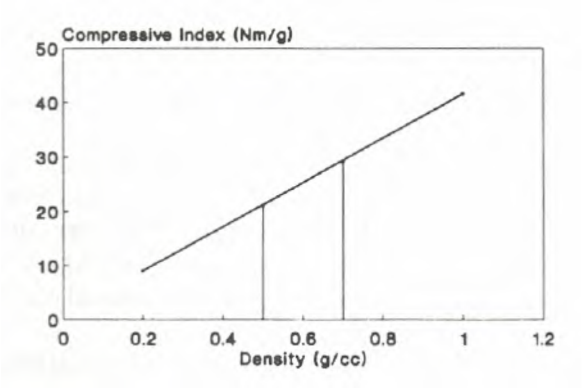

Figure 4. Paper compressive index plotted against paper density. Normal machine densities fall between 0.5 and 0.7 g/cc (Wink et al., 1982).

CONCLUSIONS

Over the past half century, the southern U.S. has come to account for over half of the pulp and paper products produced in the United States. The south provides significant advantages in wood costs but, in most paper grades, the southern pine fiber has poor performance characteristics and requires greater care in papermaking. In mechanical pulps, high energy requirements and poor performance characteristics of the southern pines are a serious problem for the industry, and U.S. expansion in mechanical pulping capacity has been limited since the late 70's. A few southern producers manufacture coated papers, but they must work harder to match the quality of coated paper products from the northeast and north-central states, Canada and northern Europe.

The southern pine industry has benefitted from the improved paper stiffness using the bulky southern pine fibers in production of solid bleached paperboard, but advances in multi-ply papermaking technology have improved the paperboard quality from thin-walled fibers, and northern producers are now able to compete with the southern industry. In corrugated containers, the lower cost of southern fibers dominates the market, but quality would improve with a thinner-walled fiber supply (Fahey and Laundrie, 1968).

Like linerboard, southern pines are a commodity. The paper industry adjusts for their performance limitations to take advantage of the low price and availability. In a quality-conscious world, forest scientists need to search for the means to improve southern pine performance. Low-density southern pine variants with thin fiber walls should give improved performance in most paper products. Since the performance requirements of the paper industry oppose the needs of the solid lumber products industry, the forestry industry needs to develop the capability to select, breed, and deploy trees for a specific end use—if they hope to please both customers.

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