Recycled vs. virgin fiber characteristics: a comparison

Richard L. Ellis and Kelly Sedlachek

ABSTRACT: A systematic laboratory study had identified the changes in fiber properties brought about by repeated drying. The direct application of the Page equation shows that repeated drying reduces the fiber strength by about 7%. Fiber perimeter is reduced by about 7%. Fiber courseness appears to be slightly reduced. A new result is taht all levels of drying of drying lie on the same curve, for a plot of the Page parameter vs. scattering. This implies that the fiber-fiber bond strength of recycled fiber is equivalent to virgin fiber, and that the relative bonded area dominates the observed strength loss in recycled sheets.

KEYWORDS: Bibliographies, bleached pulp, fiber bonding, fiber dimensions, fiber structure, hardwoods, mechanical properties, Pinus, reclaimed fibers, recycling, tensile strength, unbleached pulps, waste papers

The role of recycled chemical fibers will grow rapidly during the 1990's. Today, the majority of packaging and printing and writing grades consists of virgin fibers. These grades amount to over 60 million tons of paper production each year. The expected increase in recovery of paper products requires a substantial increase in the amount of recycled fibers used in some paper grades. During the past 20 years, numerous studies have been conducted on the papermaking potential of recycled fiber. It has been generally observed that the use of recycled fibers in papermaking results in lower mechanical properties. This apparent deficiency of recycled fiber can be overcome by refining or by the addition of a few chemicals to the papermaking process. The papermaking operation most responsible for change in fibers is the drying process. **Figure 1** is an example of the tensile strength of linerboard produced from fibers that have undergone repeated drying operations. Figure 1 has been abstracted from the work of McKee (*1*). It is clear that repeated drying of fibers produced progressive deterioration of paper tensile strength. From this graph, there appears to be a reduced affect of drying at recycled levels greater than five. Horn (*2*) Klungness (*3*) and Bobalek (*4*) have all conducted experiments similar to McKee's (*1*) and report similar results. These researchers list the four properties shown in **Table I** as important to the behavior of recycled fibers.

Fiber strength is generally measured by zero span breaking length of paper sheets. The extent to which drying has an impact on this property is not clear. Horn (*2*) reported a 33% decrease of fiber strength for a southern unbleached pine while Bobalek reported an increase of 7% for southern pine and an increase of 19% for eucalyptus. Fiber length of virgin pulp is known to play an important role in the development of paper strength. In the recycled process, stiffening of the fibers occurs and subsequent refining of these stiffened fibers causes fiber length to decrease. Fiber-fiber bonding is influenced by two parameters. The first, sometimes referred to as fiber swelling or plasticity, dictates the conformability of fibers to each other. This conformability determines the relative bonded area. Recycled fibers are known to be less comformable than virgin fibers.

The second important fiber property is the specific bond strength. The mechanics for fiber-fiber bonding involves hydrogen bonding. When fibers dry, their hydrogen bonding potential is diminished.

No systematic approach has been suggested to quantify the extent to which recycling has an impact on these fibers properties. Only by quantifying the factors listed in **Table I** will we be able to design economic approaches to regain the observed strength loss. Further, without a systematic approach, we are unable to explore the interaction between process variables and fiber properties. A possible approach is to utilize the network theory of paper. Most representations of this theory are quite complex and generally difficult to apply; however, the particular approach devised by Page (*5*), *et al.* offers an empirical methodology for studying the impact of drying on fiber properties.

Ellis and Sedlachek are with the Institute of Paper Science and Technology, 575 14th St. NW, Atlanta, GA 30318.

Interactions between fiber properties and process variables

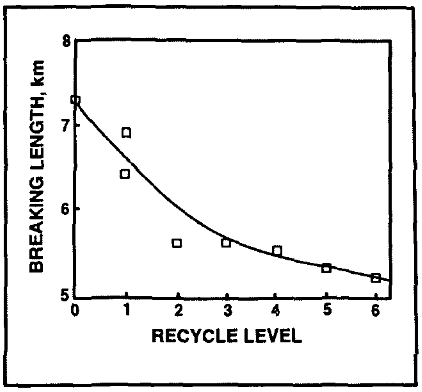
One of the most confusing terms in any discussion of the reuse of paper products is the term recycle. In its most general sense, the word means to reuse; however, in an engineering sense the word has a connotation about the unit operations in the process. Fibers which re-enter the papermaking process are subjected to a number of unit operations which modify their properties. A reader must always be careful to determine whether the word recycle is being used to denote the impact of a single unit operation on fiber properties or whether it is being used to denote the impact of a collection of unit operations on fiber properties. **Table II** divides the more important unit operations into classes. These classes are indexed by their impact on the important fiber properties discussed above. The first property listed in Table II is the fiber dimensions. This includes the length of individual fibers as well as their cross-sectional area. Fiber dimensions can receive an impact by pulpers, dispersion units, or refining. The principal impacts are to reduce the length of individual fibers by cutting and to reduce the cross-sectional area of the fiber by "sloughing off" portions of the fiber surface.

The second interaction between fiber and process involves modification of fiber surface properties. Since bleaching is a chemical process, it is intuitive that this unit operation will modify the surface chemistry of fibers. Also, chemical additives are intended to modify the surface chemistry of fibers. The impact of contaminants on the surface chemistry of fibers is a bit more subtle. Many contaminants such as tackifiers contain low molecular weight compounds. These compounds can "bloom" in the pulping process and deposit on the surface of fibers, thus altering their chemistry.

Perhaps the two types of changes most difficult to understand are changes in the fiber distribution function of fiber properties and the changes in fiber morphology. Many unit operations "fractionate" the fibers. Cleaner systems will remove higher density particles such as woody cells. Flotation units will remove fines, and the paper machine will fractionate fibers into fines and intact fibers. All of these unit operations are run at some equilibrium condition. Therefore, the nature of the fiber stream entering the final paper product will depend on the type and number of these unit operations.

Fiber morphology is a term that refers to the mechanical structure of individual fibers. Such issues as the presence or absence of primary wall structure, the nature of fibrillation, and the connectivity between microfiber chains within the cell walls are all dependent upon process variables. Morphology can be changed by mechanical means such as pulping and refining or by chemical means such as bleaching. In fact, one of the more significant impacts on fiber morphology is the paper drying operation. This operation causes irreversible collapse of the cell wall structure. It also causes defects to develop in the cell wall structure which in turn leads to fiber fracture in processes such as

1. Effect of fiber recycle on breaking length



I. Properties important to the strength of paper made from recycled fibers

Fiber strength
Fiber length
Fiber swelling/plasticity
Fiber bonding potential

II. Impact of unit operations on fiber properties

Modifications of fiber dimensions
Paper
Dispersion units
Refining
Modifications of surface properties
Bleaching
Chemical additive
Chemistry of contaminants
Changes in distribution of fiber properties
Screens
Cleaners
Flotation cells
Paper machine
Modification of fiber morphology
Pulping
Bleaching
Refining
Drying

III. Information required to quantify the effect of recycling on fiber properties

Irreversible effect of drying
Effect of refining, pulping, and dispersion
Chemical modification due to bleaching, additives, and contaminants
Effect of fractionation during cleaning operation

IV. Percent reduction of fiber parameters due to drying

	Zero span	*Bonded area*	*Bonding*
IPST (*1*)			
Southern pine unbleached	19	7	53
Horn (2), FPL			
Southern pine, unbleached	33		
Bobalek (*4*) *et al.*			
Southern pine	*(increase 7)*	0	61
Northern pine		13	25
Eucalyptus		4	78
Aspen	*(increase 25)*	2	22

V. The impact of repeated drying on fiber strength measured as zero span breaking length, (km)

Species	Drying level: First	Second	Sixth	Ratio sixth/first
Pine				
Bleached	12.7	12.2	11.6	0.91
Unbleached	12.6	12.8	11.7	0.93
Hardwood				
Bleached	11.5	12.4	11.8	1.03
Unbleached	12.6	10.0	10.7	0.85
			Av. ratio	0.93

VII. The impact of repeated drying on fiber length (weight average in mm)

Species	Drying level: First	Second	Sixth	Ratio sixth/first
Pine				
Unbleached	2.24	2.27	1.95	.87
Hardwood				
Bleached	1.76	1.81	1.80	1.02
Unbleached	2.22	2.19	2.23	1.01

VI. The impact of repeated drying on fiber coarseness (mg/100m) and perimeter (μm)

Species	Drying level: First	Second	Sixth	Ratio, sixth/first
Coarseness (mg/100m)				
Bleached				
Pine	25.6	26.3	26.2	1.02
Hardwood	13.8	13.2	12.9	0.93
Unbleached				
Pine	32.8	33.6	32.6	1.00
Hardwood	14.6	13.8	13.2	0.90
			Av. ratio	0.96
Perimeter (μm)				
Bleached				
Pine	76.5	79.9	79.1	1.03
Hardwood	46.6	43.6	42.1	0.90
Unbleached				
Pine	75.9	81.6	78.0	1.03
Hardwood	35.4	37.4	33.4	0.94
			Av. ratio	0.98

refining and dispersion.

Any prediction about the paper quality which can emerge from a given recycle stream must take into account the interactions between fibers and process variables. **Table III** suggests a prescription for developing a knowledge base which has sufficient depth for the prediction of paper properties. Since all chemical fibers undergo some irreversible effect during drying, this effect needs to be quantified. The impact of mechanical action on once-dried or multiple-dried fibers requires quantification. These effects primarily occur in refining, pulping, and dispersion. The effect of chemical changes must be included. This requires a knowledge of the effect of the bleaching process, additives, and contaminants. Finally, a sufficiently detailed process model must be developed to account for fractionation of the fiber distribution by the various unit operations.

Page equation

Page (*5*) teaches that Eq. 1 is a satisfactory representation of well bonded sheets. The typical packaging paper and printing/writing paper are considered to be well bonded sheets. This equation has been used as the basis for the MAPPS computer simulation program. This program predicts the properties of paper based on fiber and process variables. The current validated database for this program is based on virgin fiber properties.

$$1/T = 9/8Z + (12gc/PLbRBA) \qquad (1)$$

where

T = tensile breaking length, km

Z = zero span breaking length, km

C = fiber coarseness, mg/100m

P = fiber perimeter, μm

L = fiber length, weight average

b = fiber-fiber bond strength, dynes/cm^2

RBA = relative bonded area, %

g = gravitational constant

The work presented by Clark (*5*) and Jones (*6*) has shown that the best representation of fiber length is the weight average fiber length which is compatible with the measurement of coarseness. RBA can be calculated from the scattering coefficient of the sheets.

$$RBA = (S_0 - S) / S_0 \qquad (2)$$

where

S_0 = the scattering coefficient for an unbonded sheet

S = the scattering coefficient for a paper sheet

Substituting Eq. 2 into Eq. 1 and rearranging leads to a relationship between tensile properties of the sheet and scattering coefficient:

$$[1/T - 9/8Z]^{-1} = b/\gamma - (b/\gamma S_0)S \qquad (3)$$

where

γ = $12gc/PL$

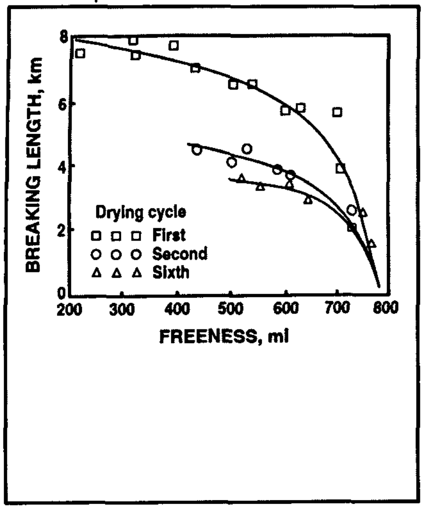
By using the concepts embodied in Eqs. 1 through 3 and data provided by McKee (*1*), Horn (*2*), and Bobalek (*4*), one can get a "snap-shot" view of the impact of drying on fiber properties. **Table IV** summarizes the results. The results for zero span are not clear. McKee (*1*) and Horn (*2*) show decreases while Bobalek (*4*) shows an increase. In principle, fiber strength should decrease with drying. The results shown in Table IV suggest that the loss in specific fiber-fiber bond strength is more important than the loss in relative bonded area.

As part of the newly initiated project of recycled fibers at the Institute of Paper Science and Technology, we have decided to develop an information base for the important fiber species found in North American paper products. The data are being generated to utilize the Page equation for analysis.

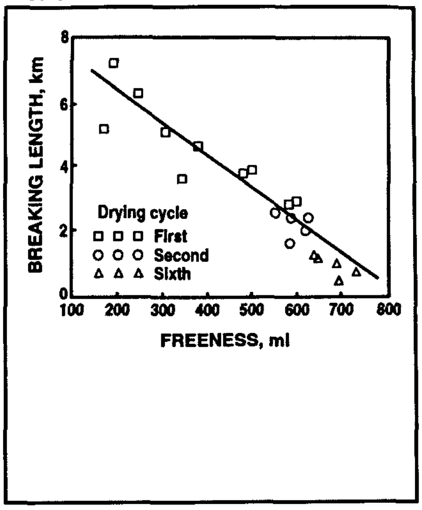
Approach

Virgin kraft pulps are refined in a laboratory Valley beater, and sheets weighing 42 lb/1000 ft^2 are formed on a Formette Dynamique paper machine. These sheets are pressed at a pressure of 50 psi and dried under restrained conditions using a pilot scale dryer. The final sheet moisture is controlled to between 4% and 6%. These sheets are soaked in deionized water for 24 h. Repulping is achieved by a gentle "hand" mixing followed by 20 min of slurring by a laboratory mixer. Handsheets are made by Tappi Method T 205 om-88, fiber length is measured by projection method T 232 cm-85, and coarseness is measured by

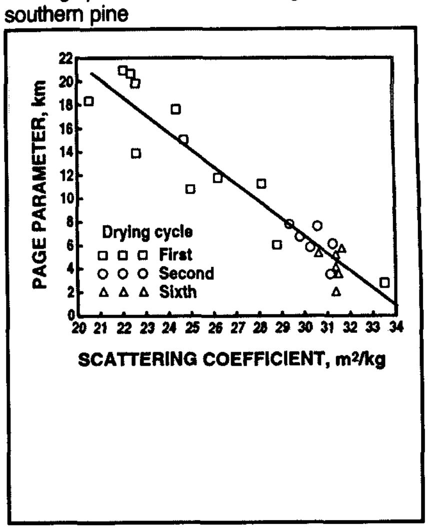
2. Breaking length vs. freeness for bleached southern pine



3. Breaking length vs. freeness for bleached southern hardwood



4. Page parameter vs. scattering for bleached southern pine



TAPPI Method T 234 cm-84.

After drying, these sheets are allowed to condition for at least 24 h and are then reslurried for the next drying treatment. Handsheets are made on a British sheet machine using standard TAPPI techniques and dried with restraint using a steam heated dryer. These handsheets are tested under TAPPI standard conditions.

Results and discussion

This part of the recycled project is in its early phases; however, some results are available. Four pulps are being studied. These are bleached and unbleached southern kraft pine and hardwood.

Fiber strength

Table V summarizes the zero span results. The bleached hardwood results show an increase in zero span. This result is similar to that reported by Bobalek (*4*) The other observations behave as reported by Horn (*2*) and McKee (*1*), i.e., general decrease in zero span in successive drying steps. The average behavior of these pulps is a decrease in zero span tensile of about 7% after six drying events.

Coarseness/perimeter

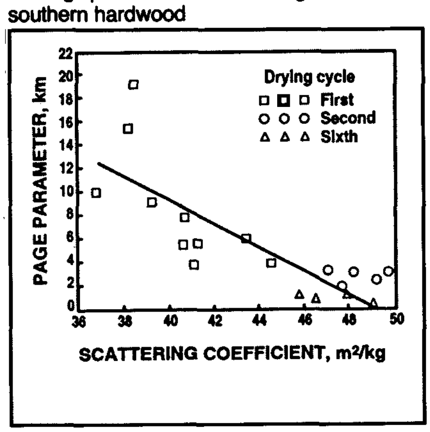
Table VI shows the behavior of fiber coarseness and perimeter. Both of these parameters show a slight decrease at the end of six drying cycles. This is the expected behavior based on fiber wall collapse arguments.

Table VII is a summary of fiber length data. This property has not received an impact by successive drying. However, this is expected since no additional refining has been done on the fibers. A point of a future study is to determine the impact of refining on fiber length.

Freeness change of recycled fibers

The most curious observation to date is best shown in **Figs. 2 and 3.** They show the relationship between tensile strength of the paper sheets and freeness. Figure 2 shows the relationship for pine and behaves as expected. Separate curves are generated for each recycle level. Corresponding points on the "zero" recycle curve move to high freeness on the other curves. The major impact of recycle occurs at the first recycle level. Figure 3 shows the breaking length freeness relationship for hardwood. In this case, the data form a single curve. The higher recycle levels lie at the higher freeness levels. Both the pine and hardwood pulp show a similar behavior of "forgetting" their previous history of refining (refers to drainage/breaking length behavior). The hardwood is extreme in this behavior and appears to have lost all memory of its refining history. **Figures 4 and 5** show "Page Plots" for bleached pine and hardwood. The data from each recycle level fall on a common curve in both the pine and hardwoods cases. This result implies that recycled fiber has the same fiber-fiber bond strength as virgin fiber. If this observation holds in future work, then the implication is that loss of bond strength observed in recycled sheets is the sole result of poor development of bonded area.

5. Page parameter vs. scattering for bleached southern hardwood



Literature cited.

1. McKee, R. C., Paper Trade J. (5): 34(1971).
2. Horn, R., Paper Trade J. 159(7/8): 78(1975).
3. Klungness, J. H., Tappi 58(10): 128(1975).
4. Bobalek, J. F. and Chaturvedei, M., Tappi J. (6): 123(1989).
5. Page, D. H., Tappi 52(4): 674(1969).
6. Clark, J. d'A., Tappi 45(8): 628(1962).
7. Jones, A. R., Tappi 55(10): 1522(1972).

Received for review Jan. 22, 1992.

Accepted April 13, 1992.

Presented at the TAPPI 1992 Papermakers Conference.