External fibrillation of wood pulp

RICHARD J. KEREKES, J. DAVID MCDONALD, AND FRANK P. MELTZER

ABSTRACT: Pulp refining produces external fibrillation consisting of fibrils tethered to fiber surfaces, in addition to loose fibrils and fines. Both contribute to a larger bonding area that increases paper strength, but tethered fibrils have less likelihood of being washed out during papermaking. This study postulates the mechanism by which refining produces external fibrillation and the optimum conditions for doing so.

The postulated mechanism is surface abrasion during sliding of fibers in refiner gaps. External fibrillation occurs when forces are great enough to partially dislodge fibrils from fiber surfaces, but not large enough to break the fibrils. The refining intensities to achieve these forces were determined by a mathematical model and experiments using a laboratory disc refiner. The optimum intensities in terms of specific edge load (SEL) for chemical pulps were about 0.1 J/m for hardwoods and 1.0 J/m for softwoods

An extension of this study suggested that abrasion may also account for most of the energy consumed in the mechanical pulping process.

Application: This paper provides guidelines to maximize the external fibrillation of fibers in low consistency refining.

Pulp is refined prior to papermaking to increase paper strength. The increase is caused by the larger bonded area between fibers created by fiber flexibilization, fines, and external fibrillation. The latter is visible under a microscope and has long been thought to be a key outcome of refining. Campbell [1] was the first to postulate a mechanism for its role. In the last stages of drying, surface tension from menisci draws fibers together. The force depends on the length of the menisci at interfaces, and therefore a large number of fibrils creates a substantial attractive force between fibers, thereby enhancing bonding.

The importance of external fibrillation has been questioned by some. In a study of internal fibrillation produced by rolling compression and external fibrillation by abrasion produced by shear flow in a narrow channel, Hartman [2] found that external fibrillation did not significantly add to paper strength. However, Kang and Paulapuro [3] found that external fibrillation, produced by abrasion in a grinder, added about 20% to the tensile strength. The reasons for these differences are unclear, but the dominant view has been and remains that external fibrillation is important. Indeed, Page [4] suggested that enhanced external fibrillation might produce considerable economic benefit because, unlike adding loose fibrils and fines to increase surface area, surface fibrils are attached to the fibers and do not wash out during forming. This concept was illustrated by comparing hardwoods having tethered microfibrillated cellulose (MFC) produced by refining with hardwoods pulps mixed with MFC. The tethered hardwoods had equivalent strength properties, but significantly better drainage and formation (uniformity) properties [5].

Surface fibrillation may also play a role in some novel applications of pulp. For example, air filters require high surface area to capture particles, along with high porosity to minimize pressure loss. Surface fibrillation can provide high surface area while fibers act as a backbone of the network to provide a filter of high porosity and low-pressure loss. Based on this principle, pulp pads meeting the exacting demands of N95 filters for virus capture were produced from freeze-dried, fibrillated wood pulp [6,7].

Although surface fibrillation has been observed for many years, the mechanism by which it is created has not been studied. The objective of this study is to identify key factors governing production of external fibrillation and determine optimum conditions for doing so.

ANALYSIS

Bar crossings in refiners impose forces that strain fibers and thereby weaken their fibrillar structure. This process consumes energy, and therefore specific refining energy is commonly used to quantify the extent of fibrillation. For external fibrillation, forces must be large enough to detach a portion of a fibril from a surface but not so large as to break them off entirely. This constraint is analogous to the constraint on bar force to avoid rupture of whole fibers [8].

Surface fibrillation is an abrasion process that removes material by sliding under pressure. This "wear" is commonly modeled by the Holm-Archard equation, which relates volume of material removed to the energy expended in sliding [9]:

$$\text{Volume of Wear} = \frac{k \; X \; EnergyExpended}{Hardness} \quad (1)$$

Constant k is a wear coefficient defined as the "probability of forming a substantial wear particle" [9]. Since refining imposes abrasion by a succession of impacts on pulp, we assume that *k* is proportional to the intensity of each impact relative to a critical intensity. The resulting constant may be combined with material hardness into an abrasion coefficient linking total fibril area produced to energy expended. Based on this picture, an equation for total fibrillation has been derived in Appendix A and shown below:

$$\frac{A_F}{A_O} = \frac{\omega}{E_A D}\frac{I}{I_C}E \qquad (2)$$

where A_F is the total area of fibrils, A_O is the area of unfibrillated fiber, ω is fiber coarseness, D is fiber diameter, E is specific energy, I is intensity, E_A is fiber abrasion energy, and I_C is critical intensity.

A fraction of the total fibrils A_F remains partially attached to fibers as external fibrillation A_S. This fraction is governed by a function dependent on intensity, as described in Appendix A. The resulting fibrillation equation is:

$$\frac{A_S}{A_O} = \frac{\omega}{E_A D}E\frac{I}{I_C}e^{-\frac{I}{I_c}} = \frac{\omega}{E_A D}E\phi \qquad (3)$$

Function ϕ combines all the intensity terms:

$$\phi = \frac{I}{I_C}e^{-\frac{I}{I_c}} \qquad (4)$$

Alternatively, fibrillation can be expressed in terms of number of impacts where $N = E/I$ (Appendix A):

$$\frac{A_S}{A_O} = \frac{\omega}{E_A D}NI_C\left(\frac{I}{I_C}\right)^2 e^{-\frac{I}{I_c}} = \frac{\omega NI_C}{E_A D}\psi \qquad (5)$$

where:

$$\psi = \left(\frac{I}{I_C}\right)^2 e^{-\frac{I}{I_c}} \qquad (6)$$

This approach is advantageous when making comparisons at constant throughput rather than constant energy, for example, when changing power in an operating refiner.

OPTIMUM INTENSITY

At constant energy, total fibrillation increases with increasing intensity (Eq. 2) whereas external fibrillation reaches a maximum (Eq. 3). As shown in **Fig. 1**, the optimum occurs when intensity equals the critical value, $I = I_C$, and has the magnitude given by Eq. 7:

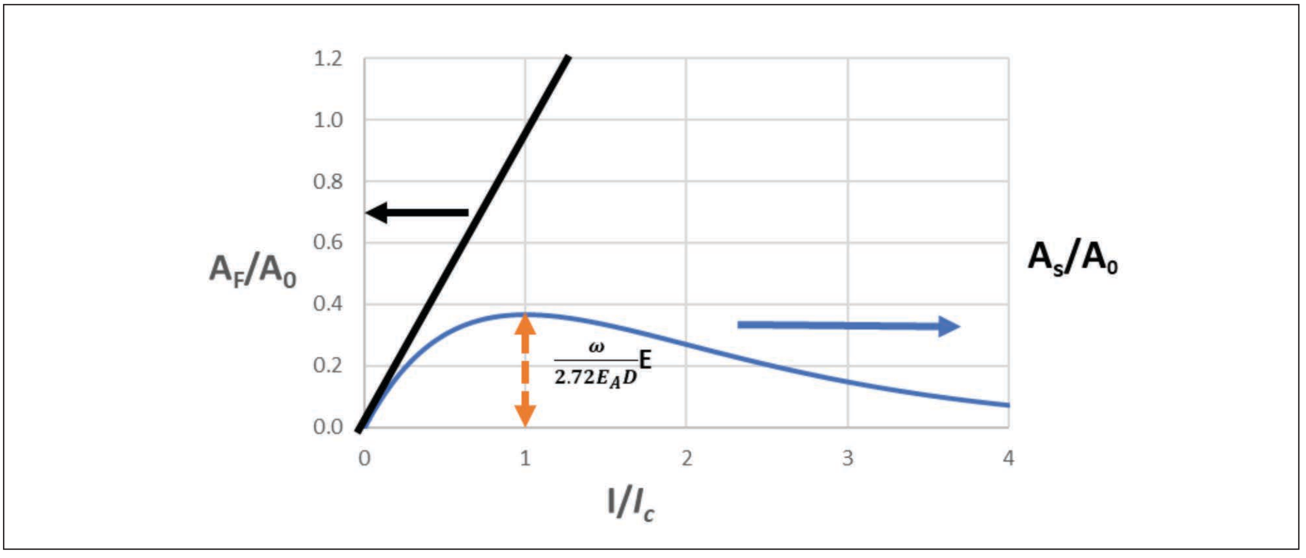
$$\frac{A_S}{A_O} = \frac{\omega}{2.72E_A D}E \qquad (7)$$

The physical explanation for the optimum is that increasing force loosens more fibrils from fiber surfaces, but above a threshold level, it also breaks them off fibers. This same phenomenon occurs for constant *N* (Eq. 5), but the maximum occurs at $I = 2I_C$, because in this case, increasing intensity also increases energy *E*.

The two key parameters from this analysis, E_A and I_C, must be determined experimentally.

EXPERIMENTAL PROGRAM

Experiments were carried out on an LR40 laboratory refiner (FRANK-PTI; Birkenau, Germany) at 4% consistency. The apparatus is a self-contained closed system having a 7-in. single disc refiner, tank, and pump. Various levels of energy are supplied to pulp by the number of cycles circulated through the refiner. Two sets of disc plates were



1. At constant energy, total fibrillation (A_F/A_0) increases with increasing intensity, whereas external fibrillation (A_S/A_0) reaches a maximum.

Pulp	Length+, mm	Diameter, µm	Coarseness, µg/m	Energy Range, kJ/kg	SEL, J/m	I, kJ/kg	Plate Code*
Birch	0.94	22.2	72.7	432	0.1, 0.2	2.7, 5.3	1.3/2.3-3.6-40
Aspen	0.85	23.1	70.7	432	0.1, 0.2	3.4, 7.0	"
NBSK	2.14	28.8	145.4	864	0.3, 0.5, 0.75, 1.0,1.2	1.6, 2.7, 4.1, 5.5, 6.6	1.7/4.0-1.45-60
Radiata	2.24	31.8	178.4	864	0.5, 1.0	2.5, 5.0	"

+ length-weighted average
* bar width/groove width-bar edge length-cutting angle; initial groove depth 5mm
SEL = specific edge load; I = intensity; NBSK = northern bleached softwood kraft pulp

I. Experimental conditions.

employed, one for hardwood and the other for softwood. Plate specifications are shown in **Table I**. After determining no-load-power, the refiner was set to a target specific edge load (SEL), which was automatically maintained through the test.

Pulp samples were taken periodically from the refiner loop and tested in an L&W Fiber Tester Plus (FT+, Lorentzen & Wettre; Stockholm, Sweden). An image of a fiber from the instrument is shown in **Fig. 2**. This instrument optically measures key fiber properties such as length, coarseness, fines, and of most interest to this study, surface fibrillation. The latter is measured for fibers greater than 0.2 mm in length. By means of image analysis, the software identifies the perimeter and area of the fiber, as well as that of the fiber plus fibrils. External fibrillation is expressed as the percentage of either fibril perimeter or area divided by the area of the fibril. Because the pixel size of this instrument is 7 µm, the measurements are of fibril bundles rather than individual fibrils.

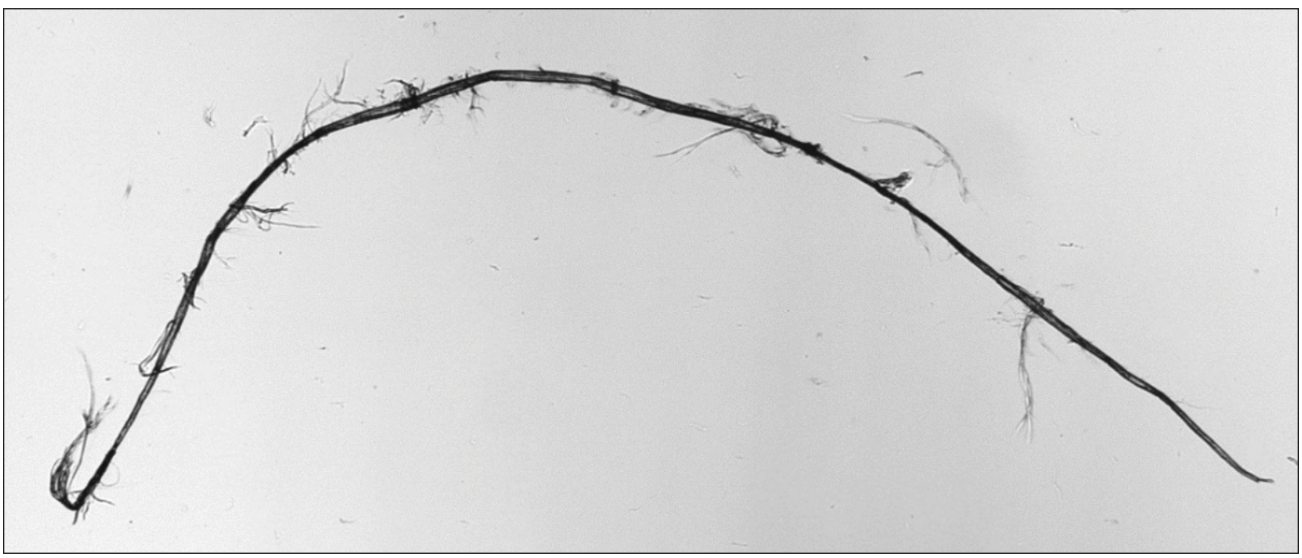
Two hardwood and two softwood kraft pulps were tested under conditions shown in Table I.

RESULTS AND DISCUSSION

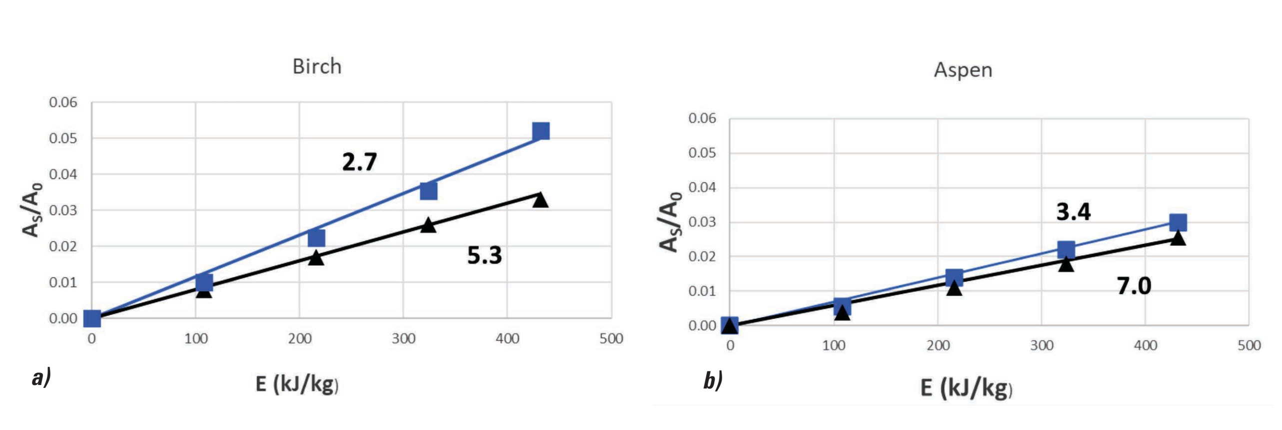
Because Eq. 3 and Eq. 5 are expressed in terms of fibril area, we used the area measurement for the degree of fibrillation. However, from our measurements, fibril perimeter is proportional to fibril area. The L&W Fiber Tester Plus (FT+) reports the degree of fibrillation (area) for fiber lengths in increments of 10 µm. The shorter fibers exhibit a higher degree of fibrillation, which is similar to the finding for HC refining of mechanical pulp [10], probably because these fibers were exposed to a greater number of higher intensity impacts. In this study, we used fibril area weighted to fiber length to determine the average area of the sample.

Fibrillation dependence on energy

Figures 3 and 4 show the external fibrillation, A_S/A_O, for the four pulps plotted against E for different levels of intensity, I. In all cases, A_S/A_O increased linearly with energy. Increasing intensity produced decreasing surface area for hardwoods and increasing area for the softwoods.



2. Image of a pulp fiber showing external fibrillation.



3. The fibril area of (a) birch pulp and (b) aspen pulp increased with energy. Increasing the intensity, shown in units of kJ/kg, reduced the slope of the fibril area/energy relationship. Lines are fits to Eq. 4, giving the coefficients in Table II.

Dependence on number of impacts

Figures 5 and 6 show A_S/A_O plotted against number of impacts, N, for differing levels of intensity, I. Here, too, area increased linearly with N. However, in contrast to the case for E, at a given N, area increased with I in all cases.

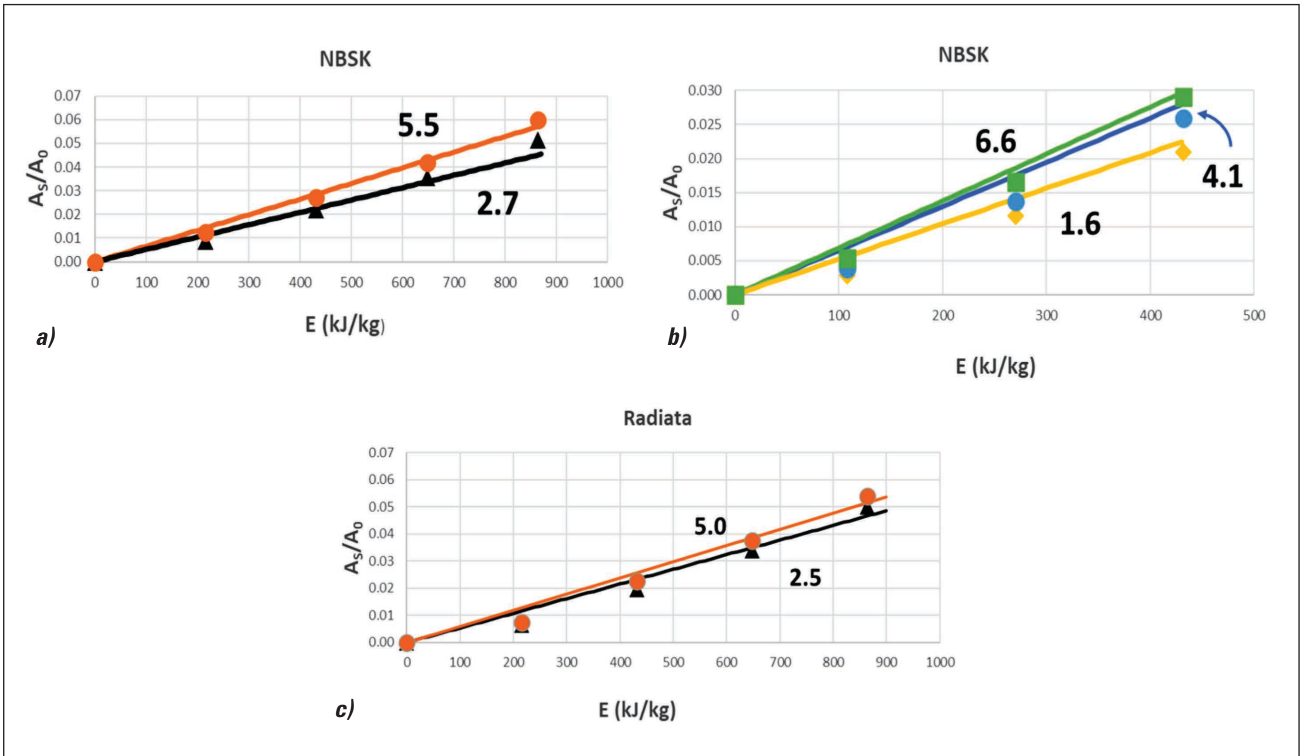
The experimental data was fitted to Eq. 5 by a nonlinear, least-squares fitting technique. Values of E_A and I_C obtained from the fits are shown in **Table II**.

As shown in Table II, values of E_A and I_C for softwoods are about two to three times larger than those of hardwoods. This suggests that softwoods require more energy to fibrillate than hardwoods. This accords with a somewhat similar finding in production of MFC by disc refining in which softwood pulp required about 2 times the energy of hardwood for similar quality MFC [11].

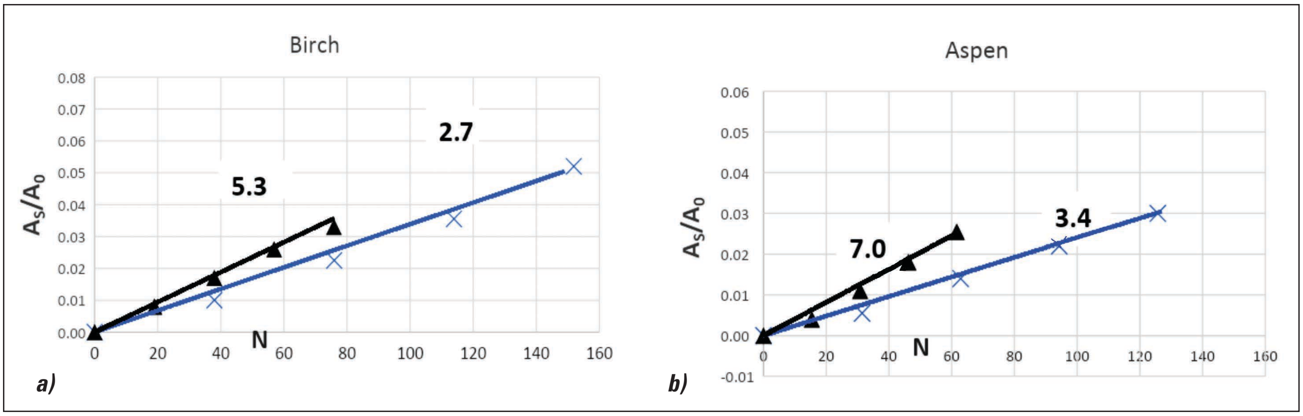
Dependence of ϕ and ψ on intensity

The effect of intensity on A_S is specified by the function φ for fixed E (Eq. 4) and by the function ψ for fixed N (Eq. 6). The data and functions are plotted in **Figs. 7 and 8**.

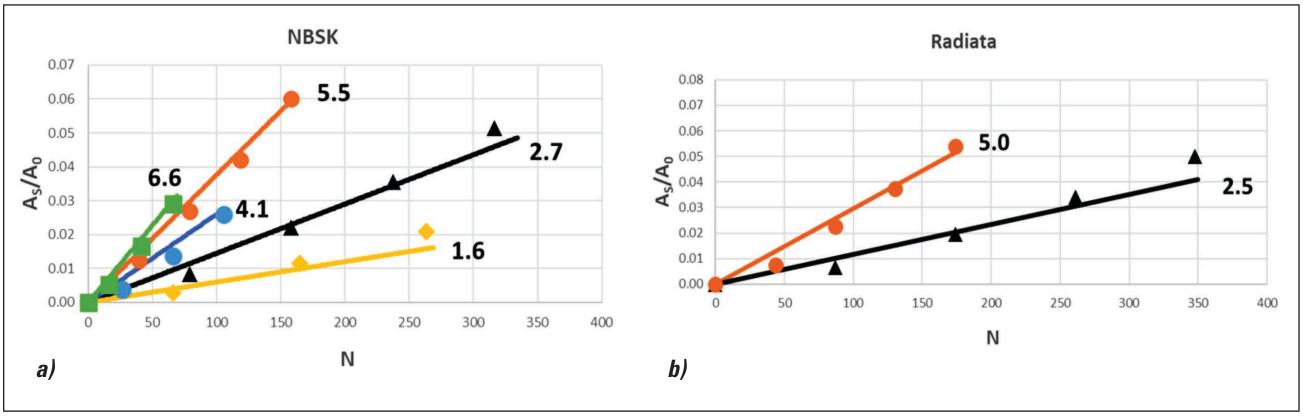
The fits in Fig. 7 for constant energy show that for all hardwoods tested, A_S/A_O decreased with increasing intensity. In



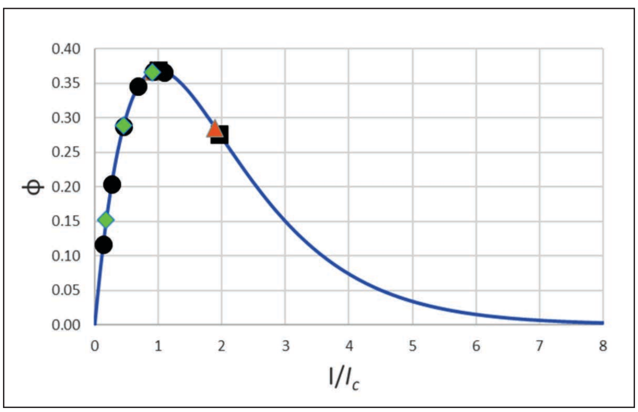
4. The fibril area of (a,b) northern bleached softwood kraft (NBSK) and (c) radiata pulps increased with energy. Increasing the intensity, shown in units of kJ/kg, increased the slope of the fibril area/energy relationship.



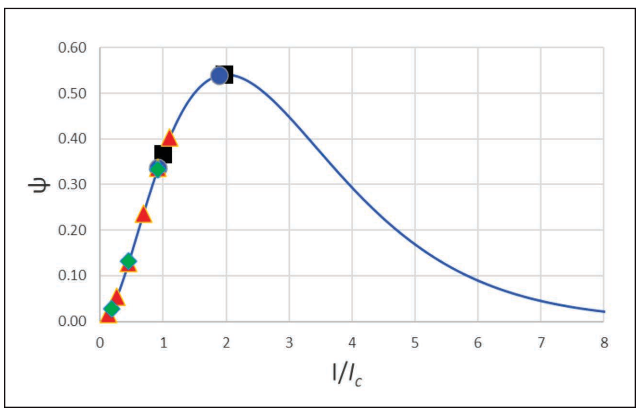
5. Fibril area of birch and aspen pulps increased with number of impacts (N) and intensity (I) shown on the graph in units of kJ/kg. Lines are fits to Eq. 5, giving the coefficients in Table II.



6. Fibril area of NBSK and radiata pulps increased with number of impacts (N) and intensity (I) shown on the graph in units of kJ/kg. Lines are fits to Eq. 5, giving the coefficients in Table II.



7. Plot of ϕ (Eq. 6) versus intensity (I) divided by the critical intensity (I_c): ■ birch, ▲ aspen, ● NBSK, and ♦ radiata.



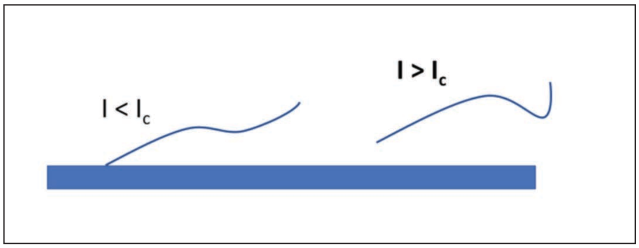
8. Plot of ϕ (Eq. 7) vs. intensity (I) divided by the critical intensity (I_c): ■ birch, ▲ aspen, ● NBSK, and ♦ radiata.

contrast, for softwoods, all data lie in the range $I/I_C < 1$, meaning that A_S/A_O increases with increasing intensity. Unfortunately, in no case did one pulp pass through the maximum, which is a limitation of these tests.

Critical intensity

We postulate that critical intensity I_C reflects the strength of fibrils and therefore the possibility of being detached from fibers, as illustrated in **Fig. 9**.

The average values of I_C in Table II are 3.2 kJ/kg for hardwood and 5.8 kJ/kg for softwood. As stated earlier, a similar finding of lower energy for hardwood in MFC production by refining was observed [11], suggesting hardwood is a weaker pulp. This was confirmed by Jajcinovic et al. [12], who found breaking load of spruce/pine to be 6 times that of eucalyptus. When converted to breaking stress, from estimated cross sec-



9. Fibrils are partially detached from fibers at intensities below the critical intensity and are fully detached at intensities above the critical intensity.

tion areas, the softwood is about three times stronger, and when squared to obtain I_C, the difference is 9 times. This is larger than our measured difference, but there are many reasons for this, not least being the extraordinary difficulty of measuring surface fibrillation on moving fibers less than 1 mm in length. Nevertheless, our findings suggest that the hardwood pulp is easier to fibrillate.

We may estimate a theoretical value of I_C from cellulose properties reported in the literature, as shown in Appendix B. Unfortunately, individual values for the softwood and hardwood could not be found. Accordingly, an average value of the elastic modulus and rupture strength of all pulps tested were employed to obtain a theoretical value of I_C = 13.6 kJ/kg. This is within an order of magnitude of the average value of I_C measured in this study, 4.5 kJ/kg.

An indirect comparison to critical intensity can be made from findings in pulp refining. Although optimal SELs for tensile strength of hardwood and softwood differ by an order of magnitude, both correspond to an intensity of about I = 8 kJ/kg [13]. Optimal tensile strength is caused by good fibrillation with little fiber shortening, conditions analogous to those for critical intensity described previously. The value 8 kJ/kg is near the average in **Table II**.

In summary, the average values obtained for I_C in this study appear realistic. Based on this knowledge, the optimum SEL for external fibrillation would be about 0.10 J/m for hardwoods and about 1.1 J/m for softwoods.

Fiber abrasion energy

The average value of the fiber abrasion energy E_A in Table II is 2.3 x 10^4 J/m². No values of this energy could be found in the literature for comparison, nor could methods be found to estimate it theoretically. However, an approximate comparison can be made from mechanical pulping.

In mechanical pulping, wood is broken down (comminuted) into fibers that are "developed" into paper-grade pulp. About 30% of the wood ends up as fines/fibrils. Kano et al. [14] and Neill and Beath [15] found that the comminution stage consumed no more than 20%–30% of energy. The mechanism causing this is likely fracture mechanics. However, given that the forces causing fracture are imposed by moving bars, comminution is likely accompanied by abrasion. For the fiber development stage, Karnis [16] found that fiber flexibilization was produced by peeling off surface material from fibers. The mechanism causing this removal clearly seems to be abrasion.

These findings suggest that abrasion plays a major role in energy consumption in mechanical pulping. We may test this by determining E_A, assuming the typical energy ot the process (1500 kWh/metric ton) is consumed in producing 30% fibers/fibrils. As shown in Appendix C, this gives E_A = 2 x 10^4 J/m², a value of the same order as those in Table II.

This value of E_A is vastly larger than previous energies used to estimate "theoretical energy" of mechanical pulping. As discussed by Kerekes [17], earliest estimates were based on surface energy of 0.65 J/m², without considering how new surface was produced. This accounted for only 0.012%–0.07% of the actual energy used [18]. Later estimates were based on fracture mechanics to produce new surface. These experiments in quasi-static wood cleavage gave 100 J/m² [19-21]. Using this approach, 10%–15% of the energy in mechanical pulping could be accounted for. What accounts for the rest? We postulate that abrasion accounts for most of the energy. Abrasion, or wear, is caused by friction, which is an inherently inefficient process generating much heat. Copious heat is a well-known outcome of mechanical pulping.

SUMMARY AND CONCLUSIONS

This study has derived mathematical models to predict external fibrillation of pulp produced in refining. Predictions from the models were compared to data obtained from an online surface fibrillation measurement on a laboratory disc refiner.

Experimental findings confirmed predictions that surface fibrillation increased linearly over the energy range

Pulp	E_A, J/m²	I_c, kJ/kg	R^2
Birch	1.14 x 10^4	2.7	0.99
Aspen	1.6 x 10^4	3.7	0.99
NBSK	2.8 x 10^4	6.0	0.98
Radiata	3.5 x 10^4	5.5	0.95

E_A = fiber abrasion energy; I_C = critical intensity; R^2 = coefficient of determination; NBSK = northern bleached softwood kraft.

II. Values of parameters obtained from curve-fitting.

0–250 kWh/metric ton. In addition, the findings were consistent with theoretical predictions of optimum intensities for maximum fibrillation. The optimum intensities expressed as SELs were found to be about 0.10 J/m for hardwoods and 1.1 J/m for softwoods. However, additional experimental data are required to fully confirm these findings. A particular need is refining conditions in which single pulps are refined over an intensity range passing through the maximum.

In addition to providing insight on external fibrillation of chemical pulp, this study has cast new light on the fiber development stage of mechanical pulping. Considering this stage to essentially be removal of material from fiber walls, the estimated energy for mechanical pulping is close to that found in practice. In contrast, previous theoretical estimates of energy for mechanical pulping have been too small by at least an order of magnitude. **TJ**

LITERATURE CITED

1. Campbell, W.B., *Paper Trade J.* 95(8): 29(1932).
2. Hartman, R.R., "Mechanical treatment of pulp fibers for paper property development," in *Papermaking Raw Materials, Trans. VIIIth Fund. Res. Symp.* (V. Punton, Ed.), September 1985, Oxford, UK, Mechanical Engineering Publications Ltd., London, 1985, Vol.1, pp. 413-442.
3. Kang, T.A.P.H. and Paulapuro, H., *Pulp Pap. Can.* 107(7-8): 51(2006).
4. Page, D.H., "The beating of chemical pulps – the action and the effects," in *Fundamentals of Papermaking, Trans. IXth Fund. Res. Symp.* (C.F. Baker and V. Punton, Eds.), 1989, Cambridge, FRC, Manchester, 2018, pp. 1–38.
5. Su, J., Mosse, W.K., Sharman, S., et al., *Cellulose* 20(4): 1925(2013). https://doi.org/10.1007/s10570-013-9955-x.
6. Mao, J., Grgic, B., Finlay, W., et al., *Nord. Pulp Pap. Res. J.* 23(4): 420(2008). https://doi.org/10.3183/npprj-2008-23-04-p420-425.
7. Macfarlane, A.L., Kadla, J.F., and Kerekes, R.J., *Ind. Eng. Chem. Res.* 51(32): 10702(2012). https://doi.org/10.1021/ie301340q.
8. Kerekes, R.J. and Meltzer, F.P., *Nord. Pulp Pap. Res. J.* 33(2): 220(2018). https://doi.org/10.1515/npprj-2018-3028.
9. Rabinowicz, E., *Friction and Wear of Materials*, 2nd edn., John Wiley & Sons, Hoboken, NJ, USA, 1995.
10. Persson, J., Ferritsius, O., Ferritsius, R., et al., "Opportunities and challenges in describing the heterogeneity of fibers," presented at the *32nd Int. Mech. Pulping Conf.*, University of British Columbia, Vancouver, BC, Canada, 2022.
11. Kargupta, W., Seifert, R., Martinez, M., et al., *Ind. Crops Prod.* 171: 113868(2021). https://doi.org/10.1016/j.indcrop.2021.113868.
12. Jajcinovic, M., Fischer, W.J., Mautner, A., et al., *Cellulose* 25(4): 2681(2018). https://doi.org/10.1007/s10570-018-1720-8.
13. Kerekes, R.J., and McDonald, J.D., *TAPPI J.* 21(9): 497(2022). https://doi.org/10.32964/TJ21.9.497.
14. Kano, T., Iwamida, T., and Sumi, Y., *Pulp Pap. Can.* 83(6): T157(1982).
15. Neill, M.T. and Beath, L.R., *Pulp Pap. Mag. Can.* 64(2): T299(1963).
16. Karnis, A., *J. Pulp Pap. Sci.* 20(10): J280(1994).
17. Kerekes, R.J., *J. Pulp Pap. Sci.* 36(1): 10(2010).
18. Campbell, W.B., *Pulp Pap. Can.* 35(4): 218(1934).
19. Lamb, G.E.R., *Tappi* 43(11): 989(1960).
20. Atack, D., May, W.D., Morris, E.I., et al., *Tappi* 44(8): 555(1961).
21. Lamb, G.E.R., *Pulp Pap. Mag. Can.* 63(3): T188(1962).
22. Kerekes, R.J. and Senger, J.J., *J. Pulp Pap. Sci.* 32(1): 1(2006).
23. Kerekes, R.J., Heymer, J.O., and McDonald, J.D., *Nord. Pulp Pap. Res. J.* 36(3): 696(2021). https://doi.org/10.1515/npprj-2021-0012.
24. Saito, T., Kuramae, R., Wohlert, J., et al., *Biomacromolecules* 14(1): 248(2013). https://doi.org/10.1021/bm301674e.
25. Zhai, L., Kim, H.C., Kim, J.W., et al., *Cellulose* 25(7): 4261(2018). https://doi.org/10.1007/s10570-018-1836-x.
26. Paulapuro, H., Ed., *Papermaking Science and Technology, Volume 5, Mechanical Pulping*, Fapet Oy, Helsinki, 1999, p. 399, Fig. 4.
27. Garner, R.G. and Kerekes, R.J., "Aerodynamic characterization of dry wood pulp," *Trans. CPPA Tech Sect.* 4(3): R82(1978).

APPENDIX A

Derivation of fibrillation equations

External fibrillation is modeled as an abrasion process using the Holm-Archard equation for wear. This equation relates volume of material removed to the energy expended in sliding [9]:

$$\text{Volume of Wear} = \frac{k\ X\ EnergyExpended}{Hardness} \tag{A-1}$$

Constant k is a "wear coefficient" defined as the "probability of forming a substantial wear particle." We assume that k is proportional to intensity I, defined as energy per mass of pulp impacted at a bar crossing. This can be expressed in non-dimensional form normalized to a critical intensity, I_C, giving $k \propto \frac{I}{I_C}$. Constant k can be combined with material density and hardness into constant k_M in an equation that gives the mass of fibrils partially and completely detached from fiber surfaces, m_F, as a function of the energy expended per area of sliding, E_S:

$$m_F = k_M \frac{I}{I_C} E_S \tag{A-2}$$

In this study, we are interested in fibril area rather than fibril mass. These variables are linked through specific surface area, SSA; fibril diameter, d; and fibril density, $\rho_F = 1500$ kg /m³ by:

$$SSA = \frac{1}{d\ \rho_F} \tag{A-3}$$

For the purposes of this study, we combine k_M and SSA into a fiber abrasion energy, E_A:

$$\frac{1}{E_A} = \frac{k_M\ SSA}{\pi} \tag{A-4}$$

Energy in refining is typically measured as energy per mass pulp, E, rather than energy per area. These are related by $E = \frac{\pi D}{\omega} E_A$ where D is fiber diameter and ω is fiber coarseness.

Combining the above gives the total fibril area, A_F, as a fraction of the unfibrillated surface area, A_O:

$$\frac{A_F}{A_O} = \frac{\omega}{E_A D} \frac{I}{I_C} E \qquad \text{(A-5)}$$

The fraction of A_F that remains partially attached to fibers (i.e., surface fibrillation, A_S) is governed by a function ϕ dependent on intensity. The form of the dependence can be determined from the effect of incremental change in intensity on incremental change in area of attached fibrils, A_S:

$$dA_S = -A_S \, d\left(\frac{I}{I_C}\right) \qquad \text{(A-6)}$$

Integrating Eq. A-6 and applying the boundary condition that all the fibrils remain attached to fibers at very low intensity ($A_S = A_F$ when $I = 0$) gives:

$$\frac{A_S}{A_F} = e^{-\frac{I}{I_C}} \qquad \text{(A-7)}$$

Intensity I is the energy per mass expended on pulp during a bar crossing. It may be calculated from the commonly-used intensity, specific edge load (*SEL*), which has been shown to be the energy expended per bar crossing per bar length [22]. Intensity I is determined by dividing *SEL* by the estimated amount of pulp captured in a gap per bar length, $\rho C_S l S$, to give:

$$I = \frac{SEL}{\rho C_S l S} \qquad \text{(A-8)}$$

where $\rho = 1000$ kg/m³ (approximate density of the low consistency suspension); C_S = pulp consistency (fraction); l = fiber length (m); and S = sliding distance (m). The derivation of Eq. A-8 is fully described in [23]. In brief, l reflects the probability of capture from a groove, and S is the distance on bar width over which force is applied. For tensile strength increase., Kerekes and McDonald [13] found that fiber length was the most appropriate approximation of S, and therefore $S = l$ was employed in this study.

Intensity I takes into account the mass upon which energy is expended. In short, it is specific energy per impact (J/kg). When multiplied by the number of impacts on fibers, N, the product gives the specific refining energy E:

$$E = N I \qquad \text{(A- 9)}$$

where N is [13]:

$$N = \frac{l^2 \, CEL}{Q} \qquad \text{(A-10)}$$

Here, *CEL* is cutting edge length (bar edge length x rotational speed); Q is the flow rate through the refiner; and l is fiber length.

Parameters N and I are independent of one another, whereas the traditional parameters E and *SEL* both depend on power. In addition, N reflects homogeneity of refining, an important factor in refining. These concepts are comprehensively discussed in recent work by Kerekes and McDonald [23].

APPENDIX B

Estimate of critical intensity

We define the critical intensity as the energy expended per mass to break a fibril in tension. Assuming linear strain, ε, to the rupture stress, σ_R, for a fibril of length l and diameter d, the energy to rupture a fibril is:

$$e_T = 0.5 \frac{\pi}{4} d^2 \sigma_R l \varepsilon \qquad \text{(B-1)}$$

Dividing energy e_T by the mass of the fibril, $\frac{\pi}{4} d^2 l \rho_F$ where ρ_F is the density of the fibril, and substituting $\varepsilon = \sigma_R / E_T$, where E_T is the tensile modulus, gives a theoretical rupture intensity I_C:

$$I_C = \frac{\sigma_R^2}{2 \rho_F E_T} \qquad \text{(B-2)}$$

From the literature, tensile strength has a range σ_R = 1.3 – 3 GPa [24] and modulus E_T = 88 – 110 GPa [25]. Using ρ_F = 1500 kg/m³ and average values σ_R = 2 GPa and E_T = 100 GPa gives an average critical intensity of I_C = 13 kJ/kg.

APPENDIX C

Estimate of fiber abrasion energy from mechanical pulping

The area of fines/fibrils removed from fiber surfaces is given by Eq. A-5, which rearranged, gives fiber abrasion energy, E_A:

$$E_A = \frac{A_O}{A_F} \frac{\omega}{D} \frac{I}{I_C} E \qquad \text{C-1}$$

Assuming that 30% of original fiber mass is reduced to A_F and that all the energy of 1500 kWh/metric ton is consumed in abrasion, and then using the values for other variables shown in **Table C-I**, we obtain:

$E_A = 2.25 \times 10^4$ J/m²

A_F	Total fibril area	1,200 m² *	
A_O	Unfibrillated area of the fiber	1,000 m² +	
D	Fiber diameter	30×10^{-6} m	
ω	Fiber coarseness	1.5×10^{-7} kg/m	
E	Energy	5.4×10^{6} J/kg	1,500 kWh/ metric ton
*Assuming 0.3 kg of fines/fibrils with *SSA* of 4000 m²/kg (average of 2 – 6 x 10³ m²/kg (from [26]). + Assuming 1.0 kg of unrefined fiber with *SSA* of 1000 m²/kg [27].			

C-I. Assumed values for calculation of E_A for mechanical pulp.

ABOUT THIS PAPER

Cite this article as:
Kerekes, R.J., McDonald, J.D., and Meltzer, F.P., *TAPPI J.* 22(6): 363(2023). https://doi.org/10.32964/TJ22.6.363

DOI: https://doi.org/10.32964/TJ22.6.363

ISSN: 0734-1415

Publisher: TAPPI Press

About this journal

ABOUT THE AUTHORS

Production of fibrils from pulp fibers is currently of high interest. One use of fibrils is as an additive to enhance paper strength. Loose fibrils may wash out during forming, but fibrils partially attached to fibers are likely to be retained during papermaking. Partially detached fibrils on fiber surfaces are called external fibrillation. They are produced by pulp refining, but the optimal conditions for doing so are unknown. The objective of this research was to answer this question.

In our previous recent work on refining, we developed a fiber-based approach to characterize refining and applied it for tensile strength of paper. This paper completes this series by focusing on one cause of strength increase — external fibrillation.

The most difficult aspect of this research was identifying the roles of refining energy and refining intensity in causing external fibrillation. This cleared up when we determined that that relevant mechanism of new surface creation was abrasion (wear) rather than fracture mechanics.

A particularly interest finding in this study was that the energy for new surface creation by abrasion (wear) is about 100 times the energy required for fracture mechanics. This finding also casts light on another unsolved problem in this industry: theoretical estimates of energy for mechanical pulping. Previous estimates based on fracture mechanics can only account for 10%–15% of the energy used. It is known that fiber development in mechanical pulping consumes most of the energy, and that this occurs by removal of surface material from fibers.

Kerekes

McDonald

Meltzer

Considering this removal to be the result of abrasion rather than fracture mechanics can account for the hitherto unaccounted for energy.

For mills, the optimal refining energy and intensity for external fibrillation are presented in this paper. Currently, there are no plans for further work on this topic because, sadly, a key member of this team, Dave McDonald, passed away unexpectedly on 21 March 2023.

Kerekes is professor emeritus in the Department of Chemical and Biological Engineering at the University of British Columbia in Vancouver, BC, Canada. McDonald was president of JDMcD Consulting in Vaudreuil-Dorion, QC, Canada. Meltzer is director of Technical Sales & Marketing at Mercer Pulp Sales GmbH in Berlin, Germany. Email Kerekes at richard.kerekes@ubc.ca.