Opacity, smoothness, and toughness of mechanical printing papers: the effect of softwood kraft pulp properties

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ABSTRACT

The toughness of paper appears to be a linear function of fiber length. Long fibers from old-growth trees provide a considerable toughness, despite their greater coarseness. This allows about 20% less reinforcement pulp in the printing paper furnish, which in turn has positive effects on the opacity of the paper and the cost of the furnish. The toughness of paper appears to be a linear function of the proportion of reinforcement pulp, thus no effect of percolation transition is found. Differences between the reinforcement pulps appear to vanish with heavy calendering, and thus the "best" pulps should be used in products where the process stages that are critical for runnability take place before calendering.

Application:

Utilization of the toughness potential of long and coarse slabwood fibers requires a considerable degree of beating.

THE PROPERTIES OF PULP FIBERS have a drastic effect on paper properties. Chemical pulp fiber properties are largely controlled by the inherent properties of wood fibers, and such effects on paper properties have been studied extensively *(1-7)*. However, the value of different kinds of papermaking pulps can be evaluated only from the point of view of the specific demands of a particular paper grade. Further, experiments with pulp handsheets may yield biased results, since many paper properties result from the interaction of different kinds of pulps in the furnish, as well as being affected by papermaking treatments like web forming, coating, and calendering.

In this paper, we first define three critical properties for mechanical printing-paper grades: opacity, smoothness, and runnability. We then discuss the effects of reinforcement pulp properties on these, concentrating on the runnability of a web of relatively high solids content, assuming that the most critical stages with modern paper machinery are coating or slitting on the one hand and pressroom runnability on the other hand. We support our arguments with experiments in which the kraft pulps are blended with pressure groundwood and the sheets are subjected to calendering. Finally, conclusions on the functionality of different kinds of chemical softwood pulps in reinforcing different grades of mechanical printing paper are offered.

THE OPACITY OF PAPER

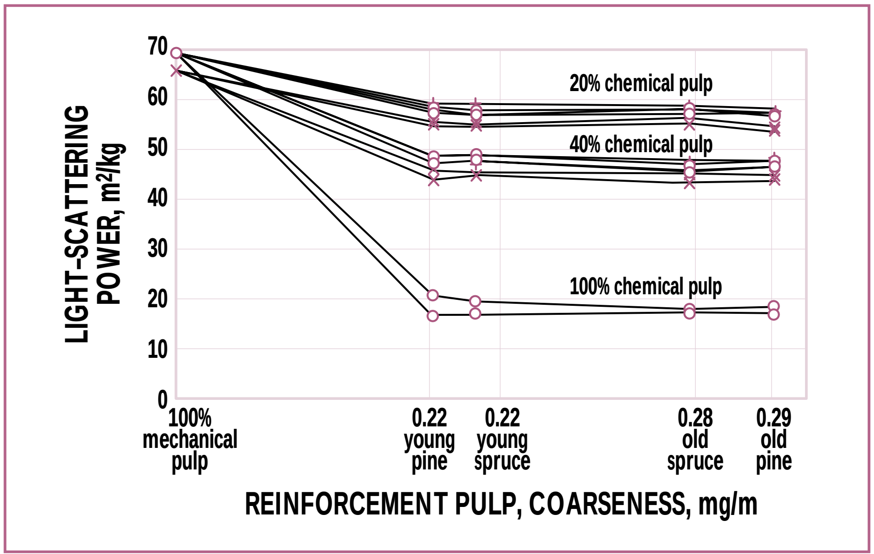
Since the opacity of paper can be expressed as an almost linear function of the product of its light-scattering coefficient and grammage, this coefficient, despite its deficiencies *(8-10)*, can be interpreted as the material property determining opacity. In this paper, we are less interested in components of paper brightness other than the light-scattering power, since light-absorption properties can be manipulated by changing pulp bleaching treatments, which are beyond the scope of this study.

Light scatters from optical surfaces, thus the light-scattering power of paper depends on the number of optical surfaces in the paper. This in turn means that the fiber morphology contributes to the light-scattering power. The surface area of any fiber being proportional to the product of fiber perimeter and fiber length, and the mass of any fiber being the product of fiber length and coarseness, the surface area per mass unit is proportional to the ratio of perimeter and coarseness. With constant cell-wall density *(11-13)*, this can further be interpreted as cell-wall thickness. Since only the unbonded fiber surface scatters light effectively, the light-scattering power of paper should be proportional to

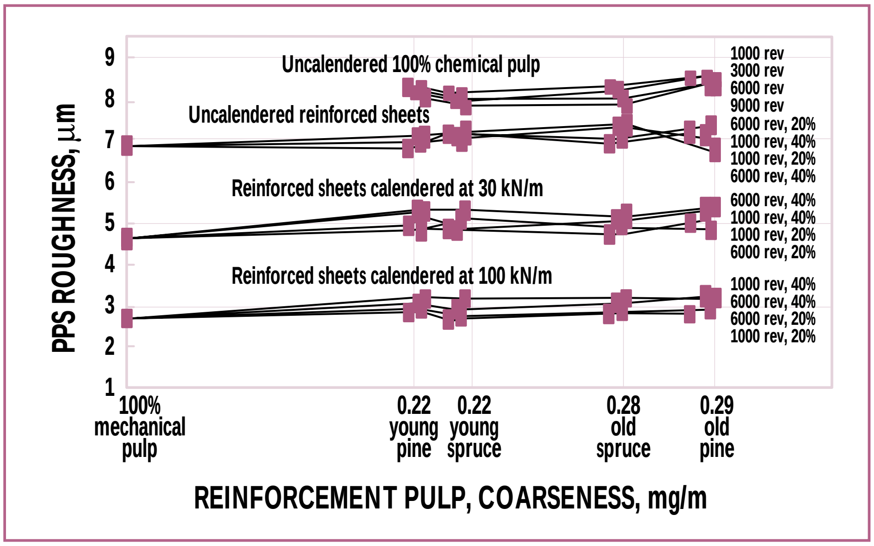
$$r/C\ (1-\mathrm{RBA}) \quad (1)$$

where r is fiber perimeter, C is coarseness, and RBA is the relative bonded area. Only the outer fiber surface was considered in deriving Eq. 1. Light also scatters in fiber lumens, so a different degree of lumen collapse should cause variation from the proposed fiber property dependency. However, the inverse effect of fiber coarseness on the light-scattering power of paper handsheets has indeed been experimentally demonstrated *(1, 4, 6, 14)*.

Another issue is whether the light-scattering power of softwood kraft reinforcement pulp essentially contributes to the light-scattering power of paper containing a major proportion of a highly refined mechanical pulp. As such, Eq. 1 should be applicable to any kinds of particles, and the light-scattering power of the paper might be pro-



1. Light-scattering power of paper with four reinforcement pulps of different coarseness. Each reinforcement pulp has been given two beating treatments, but the effect of beating on light scattering is small.



2. Parker print–surf roughness of paper with four reinforcement pulps of different coarseness. 95% confidence limits for the mean values are illustrated by black bars, and PFI beating revolutions and chemical pulp proportions are given.

duced by integrating it across the distribution of particle properties. However, in softwood kraft pulp consisting of large fibers (on the scale of the mechanical pulp particles), the specific surface and thus light-scattering contribution should presumably be low. Further, when the cavities between the large fibers are filled by the fine particles of the mechanical pulp, the free optical surface of the reinforcement fibers may change drastically. Thus optical properties measured from kraft handsheets may yield biased results, and differences observed in such experiments may well level off in mixtures with mechanical pulps.

However, **Fig. 1** shows that, although the fiber coarseness varies considerably between four softwood kraft pulps, the light-scattering power of kraft handsheets is not very different. This may be due to different lumen collapse or different external fibrillation. Including 60% or 80% pressure groundwood (44 mL CSF) in the furnish makes even the rest of these differences vanish—the mechanical pulp heavily dominates the light-scattering power. Also the effect of beating the kraft pulp is small.

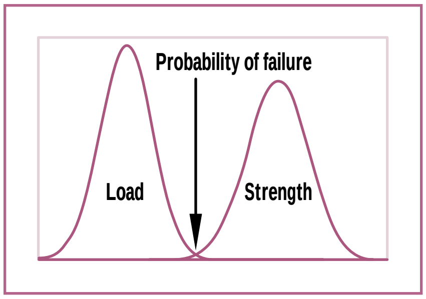
We find from Fig. 1 that heavy hard-nip calendering somewhat decreases the light-scattering power of the paper, but this effect is not dramatic. It is obvious that particles are pressed closer to each other in calendering, but new optical surfaces are created by bond failure and possibly particle splitting *(15–18).* The more conformable the particles are, the more easily they form new optical contacts; thus the moisture content of paper affects the decrement of light-scattering power during calendering fundamentally, in addition to temperature and pressure *(19, 20).*

THE SMOOTHNESS OF THE PRINTING SURFACE

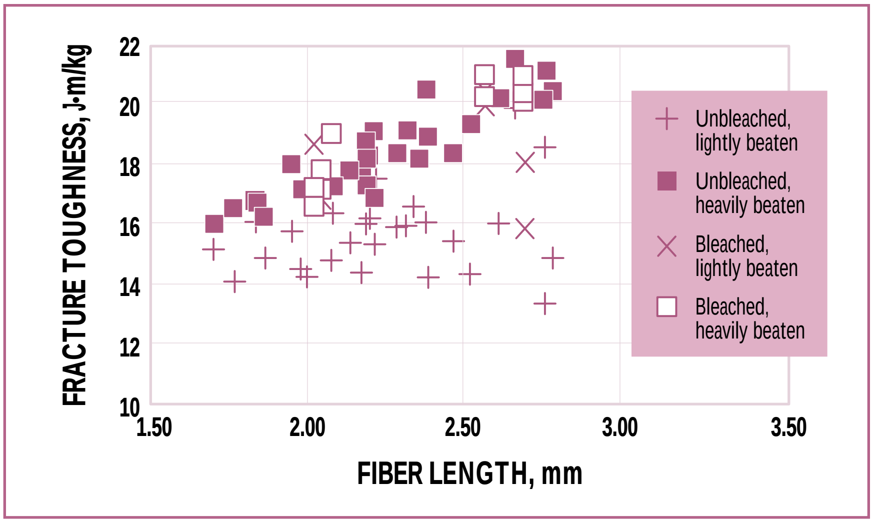
Depending on the printing process, a very smooth paper surface may be required. Typically, stiff fibers with thick cell walls tend to form a rough surface *(3–5, 18).* Recent simulations show that the roughness of a handsheet should depend exponentially on the flexural rigidity of the fibers *(21).* Even a rough surface can be smoothened by heavy calendering, but such treatment degrades other important properties *(4, 18).*

However, the roughness volume between coarse fibers can be decreased by including fine particles in the furnish *(4, 18).* With the small particles filling the cavities between coarse fibers, differences in smoothness between different kinds of fiber networks could be expected to level out. This effect should be most pronounced if the proportion of small particles within the furnish at least reaches the "limiting state" proposed by Brecht and Klemm *(22).*

Figure 2 shows that in this case, the differences between the smooth-



3. Illustration showing the variation of load and strength. Local failure is expected when local load exceeds local strength.



***4. Fracture toughness of 75 laboratory softwood kraft papers* (33)**

ness of pure kraft handsheets are not very great. The coarsest pulp yields somewhat rougher sheets; this result was reconfirmed by another method of measurement (Bendtsen roughness, results not reported here). At a specified coarseness, spruce fibers appear to be somewhat more conformable than pine and thus form smoother and denser sheets. This finding is consistent with previous observations *(6, 23).*

We also find from Fig. 2 that most of the roughness decreases when a major proportion of mechanical pulp is added. Differences induced by different reinforcement pulps then disappear with calendering. Papers containing a greater proportion of softwood kraft are somewhat rougher still.

When moistened, calendered paper tends to regain its original surface shape at least to some degree *(24–27, 18).* This shape recovery is most pronounced with mechanical fibers *(25–28).* Since moisture is introduced into the surface of the paper in coating and printing processes, these stages also induce roughening of the paper surface. Thus attention should be paid not only to the roughness of the paper after calendering, but also to the fact that the roughness of the uncalendered paper may contribute to the quality of the final product.

THE RUNNABILITY OF PAPER

Traditionally, the endurance of paper has been characterized by tensile and tear tests. The tensile strength (or the critical normal stress in the tensile loading mode) is indeed a clearly defined material property contributing to the runnability of paper. However, the mean value of tensile strength is hardly very informative; rather, the frequency of weak spots contributes to runnability. This is illustrated in **Fig. 3.** Local failure occurs if the local load exceeds local strength. It is obvious that the local strain and stress vary; some tensile failure criteria have been proposed with only moderate success *(29, 30).*

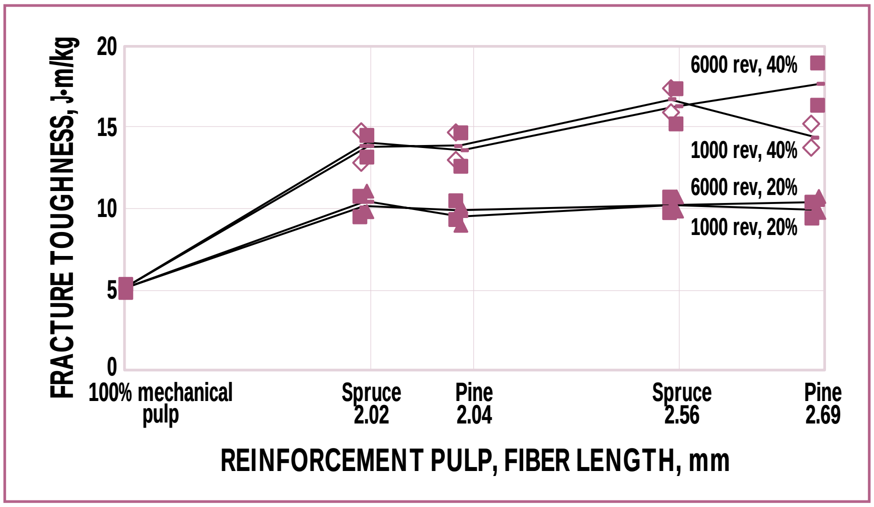
Since web breaks are rare events, it is difficult to find connections between paper properties and break frequency: Not only the material properties of paper, but also grammage, moisture content, and the manner of machine operation change with time. However, in some cases, a correlation has been found between break frequency and the fracture toughness of paper *(31).*

Griffith's seminal paper *(32)* proposes that the necessary condition for continuing crack propagation in an elastic body under load is that when the crack grows, the release rate G of elastic energy exceeds the rate γ, at which energy is needed to create new molecular surfaces, or

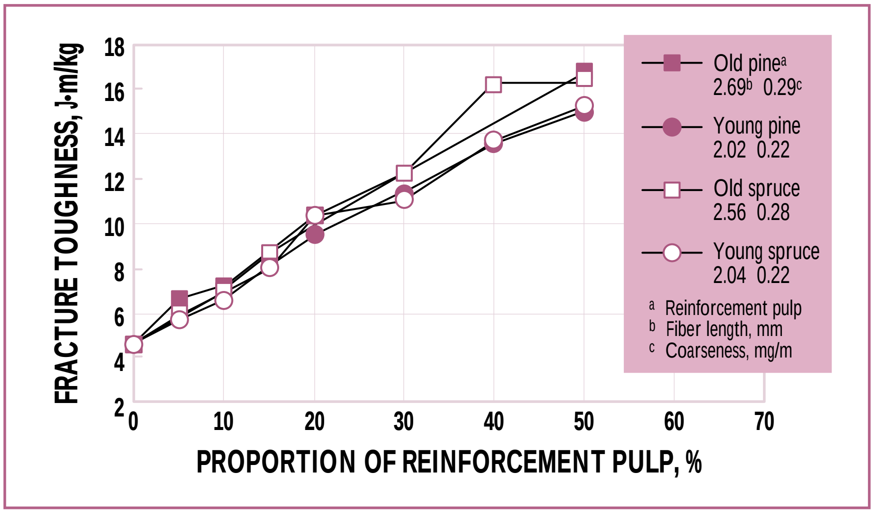
$$G \geq 2\gamma \qquad (2)$$

Here γ is the property describing the material's ability to carry flaws, its toughness. Toughness experiments are ideally designed to extract the critical value of G that fulfills Eq. 2. This value is the measured fracture toughness. However, if one simply measures G in some experimental setup, the result may be completely different from fracture toughness, because the rate of energy dissipation may actually be much greater than the minimum needed for crack propagation, as is the case in tear tests. One measures the total tearing work without any guarantee that all the work done is really needed for crack propagation.

Ideally, the toughness and the macroscopic load determine the critical size of a flaw that the web can tolerate. Further, variation of the strength within the web determines the probability density function of the appearance of weak spots of different dimensions. Unfortunately, as far as we know, a fracture criterion that would account for both of these effects has not been established. Thus the best we can do at the moment is to characterize the runnability of a paper web by means of the toughness of the paper.



5. Fracture toughness of reinforced sheets; mean values with 95% confidence limits.



6. Effect of the proportion of reinforcement pulp on the toughness of the paper. All reinforcement pulps are beaten to a dewatering resistance of 40–50° SR, and the papers are lightly calendered.

THE EFFECT OF FIBER PROPERTIES ON THE TOUGHNESS OF PAPER

A micromechanical theory on the effect of fiber properties and fiber bonding on the toughness of paper, which shows that the toughness should depend linearly on fiber length as long as fiber breakage is not very extensive, was recently introduced *(33)*. The toughness should also depend linearly on the breaking energy of individual fibers as long as the fibers are not very strong. The toughness should first increase, reach a maximum, and then decrease with increased interfiber bonding. These predictions agree with most experimental observations *(32-37)*.

The fracture toughness of 75 laboratory softwood kraft papers, analyzed with a J-integral method, which makes use of the work done at the Swedish Pulp and Paper Research Institute *(38)*, is shown in **Fig. 4** *(33)*. We find that the toughness of heavily beaten fibers appears to be a linear function of fiber length. In this experimental material, fiber length and coarseness are heavily correlated. When the fracture resistance is normalized according to the number of fibers, the lightly beaten papers also show a linear fiber length dependence *(33)*.

The fracture toughness of lightly calendered paper, where pressure groundwood has been reinforced with four different reinforcement pulps, is shown in **Fig. 5.** With reinforcement pulps made from the same chip samples as the pulps of Fig. 4, the toughness as a function of fiber length shows the same slope as the well-beaten fibers of Fig. 4. This is reasonable, since fracture resistance averages out over fiber properties, unlike tensile strength, for example.

We find such an agreement between Figs. 4 and 5 only in the case where the proportion of reinforcement pulp in the paper blend is relatively high (40%). Twenty percent of chemical pulp clearly reinforces the web, but the effects of different reinforcement pulps do not appear to differ. The authors find this somewhat surprising, since it indicates that the toughness of paper might be a nonlinear function of the proportion of the reinforcement pulp.

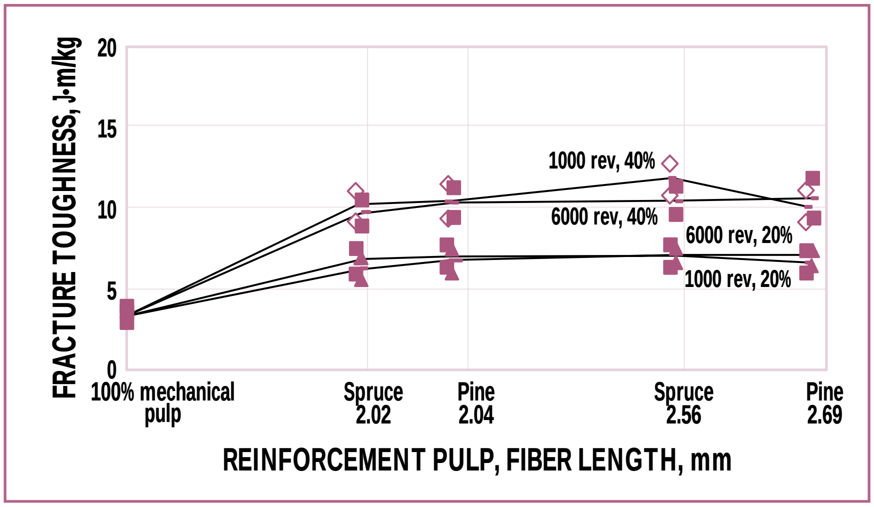
However, **Fig. 6** shows that the toughness of paper really is a linear function of the proportion of the reinforcement pulp, so no evidence of percolation transition is found *(39-41)*. It is obvious that, with long reinforcement fibers from old-growth forests, a specified toughness can be reached with about 20% less chemical pulp than in the case of fibers from younger trees. It is probable that the difficulty of distinguishing the reinforcing effects in Fig. 5 was due to random experimental variation.

THE EFFECTS OF PAPERMAKING TREATMENTS ON TOUGHNESS

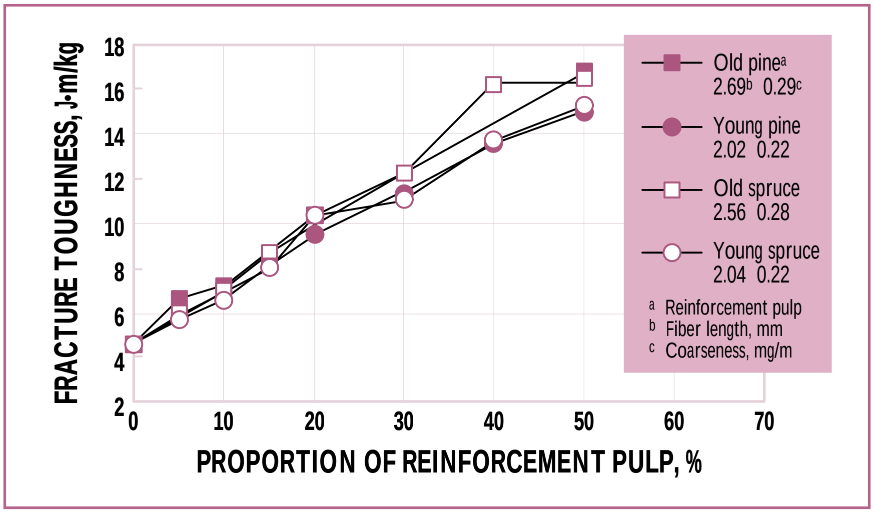
As mentioned previously, theory *(33)* suggests that the toughness should first increase, reach a maximum, and then decrease with increased interfiber bonding. These predictions agree with most beating experiments *(34, 35, 37)*. However, we find from Fig. 4 that beating only increased the toughness of kraft handsheets, and from Fig. 5 that the effect of the amount of beating of the reinforcement pulp on the toughness of paper is negligible, except in the case of the longest and coarsest fibers, where beating increases toughness. The authors are uncertain whether this is the ideal result or whether it depends on the method used to measure toughness.

With calendering, bond failure and particle splitting occur, but new contacts between particles may also be created. Thus Young's modulus and the tensile strength of paper often decrease but may remain almost unaffected or even increase *(15–17, 42–48).* Since bonds and fibers get damaged, we can expect the toughness of paper to decrease, at least in heavy hard-nip calendering. This is seen by comparing Fig. 5 and **Fig. 7**: Heavy calendering considerably decreases the toughness. It is somewhat remarkable that differences in the toughness of paper reinforced with different chemical pulps vanish with heavy calendering (Figs. 5 and 7). Fiber crushing may mean that the original length of the fibers no longer contributes to the endurance of the paper.

Increased moisture content of paper decreases strength but increases ductility *(49–57).* Thus tensile strength decreases with increased moisture, but tensile energy absorption, tear strength, and obviously toughness and runnability show a maximum as a function of moisture, probably at moisture contents of 15–20% *(31, 48–52, 54, 58).* Moisture content was not changed in this study, with all the samples being conditioned to 8–9% moisture content at 23°C and 50% relative humidity.



7. Fracture toughness of reinforced sheets after heavy calendering



8. Interrelationship of toughness and light-scattering power in papers reinforced with different proportions of kraft pulps. All reinforcement pulps are beaten to a dewatering resistance of 40–50° SR, and the papers are lightly calendered.

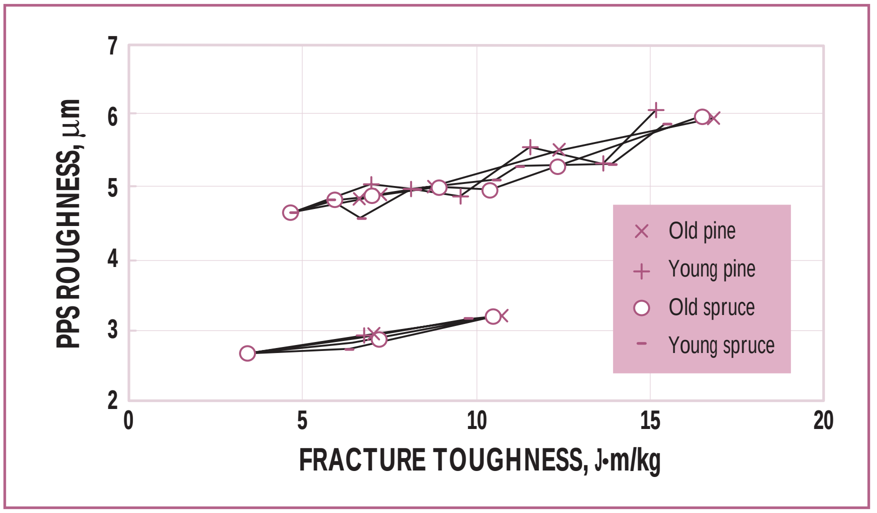
THE COMBINATIONS OF PAPER PROPERTIES ACHIEVABLE WITH DIFFERENT KINDS OF REINFORCEMENT PULPS

Because chemical softwood reinforcement pulp is often the most expensive furnish component, it is economically advantageous to reach a specified runnability with a small proportion of reinforcement pulp. We find from Fig. 6 that a specified toughness can be reached with about 20% smaller mass proportion of long softwood kraft fibers, although these fibers are also coarser.

The smaller the proportion of reinforcement pulp, the higher the light-scattering power of the paper. Thus, at a specified toughness, papers reinforced with long fibers from old-growth forests do have a greater light-scattering power, despite the greater coarseness of the reinforcement fibers themselves (**Fig. 8**).

In **Fig. 9**, the roughness of the paper is shown both after light and heavy calendering. Although surface roughening due to increased moisture content in coating or printing is most pronounced with mechanical fibers *(25–28),* this phenomenon makes the smoothness of uncalendered (or lightly calendered) paper important.

We find from Fig. 9 that increasing toughness by increasing the proportion of kraft pulp makes the surface somewhat rougher, but differences in the toughness–smoothness relationship between different rein-



9. Interrelationship of toughness and PPS roughness in papers reinforced with different proportions of kraft pulps. All reinforcement pulps are beaten to a dewatering resistance of 40–50° SR. The proportion of kraft pulp in lightly calendered sheets varies between 0 and 50%. There is 0, 20%, or 40% kraft pulp in the heavily calendered sheets.

forcement pulps are small. As was found already in Fig. 2, calendering considerably smooths the surface, but there is also a drawback in the toughness.

CONCLUSIONS AND DISCUSSION

The toughness of paper appears to be a linear function of fiber length. Long fibers from old-growth trees provide great toughness, despite their higher coarseness. This allows 20% less reinforcement pulp in the printing paper furnish, which in turn has positive effects on the opacity and the cost of the furnish.

The toughness of paper appears to be a linear function of the proportion of reinforcement pulp, thus no effect of percolation transition is found.

Differences between the reinforcement pulps appear to vanish with heavy hard-nip calendering, and thus the "best" pulps should perhaps be used in products where the process stages that are critical for runnability take place before calendering. This phenomenon is naturally affected by calendering equipment and conditions.

The reinforcement pulps used in this study were produced by mixing chips from sources introduced in an earlier study *(23),* resulting in 2.0–2.7-mm fiber length and 0.22–0.29-mg/m coarseness, expressed as length-weighted mean values for each pulp. These pulps can be assumed to be representative of those achievable by wood raw material classification in southern Finland.

There is no proof that the method used to measure the toughness of paper is ideal. For example, most observations and theoretical arguments indicate that the toughness should reach a maximum as a function of beating, but this method is not very sensitive to it. Further, it is not clear whether the toughness in itself is adequate in characterizing runnability. A parameter defining flaw size distribution or the variation of strength within the web might also be needed to establish a comprehensive fracture criterion for paper.

KEYWORDS

Alkaline pulps, bibliographies, chemical pulps, fiber dimensions, fiber length, kraft pulps, length, mechanical papers, mechanical properties, opacity, optical properties, paper grades, paper properties, physical properties, properties, pulp properties, pulps, reinforcement, smoothness, softwood pulps, surface properties, toughness.

EXPERIMENTAL

Four softwood reinforcement pulps were produced by laboratory kraft cooking of *Picea abies* and *Pinus silvestris* of different cambium age. Chip samples representative of the populations of young and old spruce and pine were created by mixing chips from sources introduced in an earlier study *(23).* The pulps were bleached with a chlorine dioxide-based sequence and beaten in a PFI mill with 35 g of pulp in each load. There were no major differences in the zero-span tensile indices of well-bonded kraft handsheets. Pressure groundwood-containing handsheets of 50 g/m^2 were produced with whitewater circulation, the groundwood having a freeness of 44 mL CSF.

Conditioned sheets were calendered in an 18-cm-diam. hard-nip laboratory calender roll at 23°C with a feeding speed of 10 m/min. Two nips and two alternative nip line pressures were used, 30 and 100 kN/m. Standard laboratory methods were used to evaluate sheet properties, but the toughness was evaluated with Lorentzen-Wettre's device, which makes use of the J-integral approach developed in the Swedish Pulp and Paper Research Institute *(38).* **TJ**

When this study was conducted, Kärenlampi was an associate professor, Rantanen was a graduate student, and Hämäläinen and Suur-Hamari were research scientists at the University of Helsinki, Department of Forest Resource Management, Box 24, FIN-00014, Finland. Kärenlampi is now with Champion International Corp., West Nyack, NY 10994. Hämäläinen is with Sunds Defibrator, Niementie, FIN-37600, Valkeakoski, Finland. Suur-Hamari is with Enso Publication Papers, Box 62, FIN-48101, Kokta, Finland.

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